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Human-building-emergency interactions and their impact on emergency response performance: A review of the state of the art

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ABSTRACT

Human behavior is fundamental to human safety and the outcomes of building emergencies. It is correlated with social environments, building environments and emergency situations. This study presents a review about *human-human interactions* (i.e., interactions among people or groups of people and their influence on behavior during emergencies), *human-building interactions* (i.e., how buildings influence human behavior and how human behavior impacts the building performance during emergencies), *human-emergency interactions* (i.e., how emergency situations impact human behavior and people's coping strategies with emergencies), and second-order interactions among humans, buildings, and emergencies. The review reveals that while various human-human interactions among building occupants have been investigated, some of them (e.g., grouping behavior, information sharing) are less understood, and the interactions between building occupants and staff members need further explorations. With regard to human-building interactions, prior studies have been limited to certain types of buildings and building attributes, while the aggregate impact of a combination of building attributes should be more studied. Moreover, building fires were the most frequently examined emergency type, while other types of emergencies, such as earthquakes and acts of extreme violence, received less attention. Additionally, second-order interactions among humans, buildings and emergencies have not been widely studied. This paper also puts forward recommendations for future research, including validating prior findings when transforming them into real-world applications, leveraging the strength of different data collection and interpretation methods, as well as collaborating more closely with researchers and practitioners in related areas.

1. Introduction

Emergencies, either natural (e.g., earthquakes) or man-made (e.g., acts of extreme violence), could occur and cause damages in a wide spectrum of civil infrastructure, including buildings (Sheeba and Jayaparvathy, 2019), transportation systems (Dulebenets et al., 2019a, 2019b), and industrial facilities (Phark et al., 2018). During emergency situations, available time and capacity of evacuation routes are both limited, hence developing effective emergency evacuation plans is pivotal for ensuring human safety and reducing emergency damages (Dulebenets et al., 2019b). Various operational strategies, such as contraflow lanes, priority traffic signals and dynamic routing have been employed to improve the efficiency of emergency evacuation (Han et al., 2007). Among a variety of influencing factors for effective emergency evacuation, human behavior is a critical one (Pan et al., 2006). Prior studies have looked into various aspects of human factors during emergency evacuation, such as cooperative and competitive behavior (Cheng and Zheng, 2019; Yang et al., 2018), crowd density (Rendón Rozo et al., 2019), evacuees' usage of emergency exits (Liang et al., 2018), and how these human factors could influence emergency evacuation. Compared with other types of emergencies, building emergencies are particularly important, as buildings play a key role in people's life (e.g., people in the U.S. spend 90% of their time in buildings (Klepeis et al., 2001)), and hence building emergencies can result in disastrous consequences. For example, in 2018 alone, there were 363,000 home structure fires in the U.S., causing 2720 civilian deaths (Evarts, 2018). Past emergency events have demonstrated how various building attributes could impact human behavior during emergencies. It was reported that locked doors, poor lighting and poor or missing signage constrained the evacuation during the 2001 World Trade Center (WTC) attack (Averill et al., 2013). On the other hand, human behavior can also greatly influence building performance during emergencies. For example, in the 2003 Rhode Island station nightclub fire, evacuees simultaneously headed towards the main exit and

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ignored other available exits, probably because of high stress brought about by the emergency. This behavior caused severe blockage at the main exit and resulted in dozens of fatalities (Aguirre et al., 2011). Thus, a thorough understanding of the relation between human behavior and building performance during emergencies is crucial for both emergency preparedness and response.

The behavior of an individual during building emergencies is interrelated with other people (e.g., other occupants, staff members, adversaries), building attributes (e.g., location and visibility of signage, stairs, exits, etc.), and emergency attributes (e.g., fires, smoke, explosions) (Kobes et al., 2010b). When there are others in the surrounding environment, people persistently interact with others during building emergencies. For example, mutual aid and cooperation are common in building emergencies, even among strangers (Mawson, 2005). Nevertheless, competing and selfish behavior can also happen, due to increased stress and loss of personal space (Moussaïd and Trauernicht, 2016; Pan et al., 2007). Moreover, human behavior and buildings are two interwoven elements. Building layout (e.g., location and number of rooms, space adjacency, and location and number of exits) impacts people's evacuation time (Ha and Lykotrafitis, 2012); Stairway design in high-rise buildings influences people's movement during emergencies (Peacock et al., 2017); and people's knowledge of the building could affect evacuation efficiency (Kobes et al., 2010b). Emergency attributes are another factor that are correlated with human behavior and building performance during emergencies. For example, in building fires, the presence of smoke imposes physiological impact and influences people's evacuation strategies (Gwynne et al., 2001) and people's abilities of using spatial knowledge (Cao et al., 2019). Moreover, human behavior varies depending on the types and attributes of emergencies (e.g., fires, earthquakes, and acts of extreme violence) (Bernardini et al., 2016b).

Interaction defined as "reciprocal action or influence" of people and/or things on each other (Rusbult and Van Lange, 2002), is the driving force of human behavior and response performance during building emergencies, with human-human interactions, human-building interactions, human-emergency interactions, and human-building-emergency interactions contributing to its formation. Thus, this paper specifically focuses on these important interactions. Specifically, *human-human interactions* refer to the collective behavior among building occupants and their interactions with people in specific roles, such as staff members and emergency response teams. In this paper, unless otherwise pointed out, the terms "people" and "human behavior" represent building occupants and their behavior, respectively. *Human-building interactions* refer to how various building attributes (e.g., signage, exits, stairs) impact human behavior and how human behavior (e.g., using familiar exits, choosing stairs or elevators) impacts a building's performance during emergencies. *Human-emergency interactions* refer to how emergency situations (e.g., presence of fire and smoke) impact human behavior and how people cope with emergencies (e.g., extinguishing fire, fight with adversaries). *Human-building-emergency interactions* refers to second-order interactions among the three factors: humans, buildings, and emergencies.

Several studies have discussed the relations among humans, buildings, and emergencies (Bernardini et al., 2016a; Kobes et al., 2010b; Lin et al., 2020a; Proulx, 2001; Ronchi and Nilsson, 2013; Shipman and Majumdar, 2018). Nevertheless, these studies were limited to certain types of emergencies (e.g., fires and earthquakes) and did not formally analyze the human-human, human-building, human-emergency, and human-building-emergency interactions in detail. Since all of these interactions play an essential role during building emergencies, it is crucial to provide a comprehensive understanding of these interactions to make appropriate decisions related to building design and emergency preparedness. The rest of this paper is organized as follows: Section 2 presents the objectives and methodology of the review. A holistic review of the existing body of literature is presented in Section 3. Section 4 discusses the findings of the review, including the accomplishments and limitations of current research, and recommendations for future research. Section 5 states the limitations associated with this review. Finally, Section 6 concludes the paper.

2. Research objectives and methodology

The first *objective* of this review is to improve our understanding of human behavior and response performance during building emergencies from an interaction perspective. Specifically, to analyze the literature comprehensively, four types of interactions during building emergencies were investigated, namely (1) human-human interactions, (2) human-building interactions, (3) human-emergency interactions and (4) human-building-emergency interactions. Since prior studies might have focused on distinct aspects (e.g., only human-emergency interactions or only human-building interactions), the second *objective* of this review is to establish a comprehensive view of the interactions during building emergencies and analyze how these interactions influence emergency response performance. The third *objective* of this review is to identify gaps in this research area and put forward suggestions for future research.

The topic of human behavior and response performance during building emergencies is highly interdisciplinary. Hence, to investigate what has been studied in this area, an extensive search of literature was performed. In line with the above-mentioned objectives, electronic databases of scientific publications that are acknowledged as leading resources with high quality and cross-disciplinary nature, including "Web of Science" and "Scopus," were used to search for relevant articles. No specific publishers were excluded from the search. Since the main objective of this review is to understand interactions among humans, buildings and emergencies, the search "TS = (human behavio*) AND TS = (building OR indoor OR built environment) AND TS = (emergency OR disaster OR extreme event OR extreme environment)" was conducted to search in the articles' title, abstract, and keywords (TS = Topic). It needs to be noted that since phrases were used in the search items (e.g., human behavior), if a single word in the phrase (e.g., human or behavior) appeared in the articles' title, abstract or keywords, the article would be included in the search results as well. By doing so, articles that used synonyms for the search items (e.g., "crowd behavior" for "human behavior") could be included in the search results. Moreover, as the research on human behavior during building emergencies originated in the 1950s (Fritz and Marks, 1954) and various research methods (e.g., emergency drills, interviews, simulations, etc.) have been used in this area, the search did not exclude any particular period or research method. Finally, forward and backward snowballing method was used to complement the search results (Wee and Banister, 2016), which enabled us to include more relevant articles that were not in the above search results (e.g., articles that used "crowd interaction" instead of "human behavior"). First, the authors quickly reviewed each individual article by reading the title and abstract to verify its relevance to the scope of this review and excluded irrelevant ones, based on the criteria below. If needed, a second round of screening was performed by reading the full paper. To be included in this review, an article had to (1) be written in English and (2) address at least one type of human-human, human-building, human-emergency, and human-building-emergency interactions. Articles that did not meet the above inclusion criteria were excluded from this review. Specifically, studies that were (1) not focused on emergencies in buildings (e.g., aircraft emergencies and city/region scale disasters), (2) aimed at emergency training (i.e., transferring knowledge to occupants and/or security personnel) or emergency management (e.g., navigation models) without exploring human behavior during building emergencies were considered out of scope.

As a result, a total of 136 articles were included in the review, which formed the basis of the analyses summarized in this paper. Among these articles, 86% were journal articles, 13% were published in conference proceedings, and 1% were book chapters. The earliest one was published in 1951, and 74% of these articles were published during the last decade. It can be seen that despite the relatively long history of this research area, there is an apparent increase in the number of publications in recent years. Moreover, the articles were published in a variety of sources. The venues in which most of the articles were published are: Safety Science (22), Fire Safety Journal (12), Fire Technology (11), Fire and Materials (9), and Fire Safety Science (5). The top publishers where the reviewed articles were published are: Elsevier (73), Springer (16), Wiley (9) and Sage (5). Commonly used research methods in the literature included simulations (45), emergency drills (26), virtual reality (VR) experiments (18), surveys (17), interviews (13), laboratory experiments (8), and non-human animal experiments (4).

3. Review of interactions during building emergencies

This section provides a comprehensive review of the literature following the *interaction* perspective described earlier. The first subsection focuses on human-human interactions among building occupants, their interactions with people in different roles and the impact of these interactions on the response performance. The second subsection discusses how people interact with various building attributes and the corresponding impact on the response performance. The third subsection focuses on the interactions between people and emergency attributes and again the impact of these interactions on the response performance. Finally, the last subsection focuses on the second-order interactions among humans, buildings, and emergencies.

3.1. Human-human interactions

In many circumstances, people are not alone during building emergencies. They may be accompanied by others, such as their families, coworkers, or strangers. Human-human interactions are one of the most important aspects that determine how people behave and the overall evacuation time and pattern (Chu and Law, 2013). Table 1 summarizes the studies discussed in this subsection, in which the studies are listed in chronological order based on their year of publication.

3.1.1. Occupant-occupant interactions

Human-human interactions are crucial determinants of human behavior during building emergencies. Especially in large public buildings, people tend to observe others' responses and behave accordingly (Proulx, 2001). Typical types of human-human interactions include herding, avoiding, grouping, helping and competing, leader-following, and information sharing (Lin et al., 2020a; Pan et al., 2007; Shipman and Majumdar, 2018; Zheng et al., 2009). Herding behavior is a type of interactive behavior. It refers to a person following what others are doing, even though the perceived situational information suggests otherwise (Banerjee, 1992). In respect to emergency evacuation, herding behavior refers to an evacuee choosing the most congested route because that route is the most popular choice, instead of alternative routes with less people (Lovreglio et al., 2016b). In the early 2000s, it was suggested that herding behavior would occur when people experience high levels of stress (Helbing et al., 2000). However, subsequent studies revealed that herding behavior could be a result of rational decision-making process and it is related to the lack of information that people need to understand the situation and make a decision (Lovreglio et al., 2016b). Recent studies further evidenced that herding behavior is impacted by both environmental factors (e.g., number of evacuees near exits, exit visibility, crowd density) and personal factors (e.g., herding attitudes) (Haghani and Sarvi, 2017a; Lovreglio et al., 2016b; Moussaïd et al., 2016). With regard to its influence, on the one hand, herding behavior may facilitate the evacuation of those who are not familiar with the building, representing a type of cooperation in which people share their knowledge (Alavizadeh et al., 2008). On the other hand, it may also lead to inefficient exit choice and decrease evacuation efficiency (Haghani and Sarvi, 2019; Pan et al., 2007). In addition to following the crowd, prior research also pointed out that people might prefer to have personal space and avoid physical contact with others during emergencies (Pan et al., 2007). Avoiding behavior is also related to building attributes and environmental factors. Studies that conducted laboratory experiments illustrated that in highly crowded places with low uncertainty (e.g., no obstacles blocking visibility), people would avoid choosing the same direction as the majority (Haghani and Sarvi, 2017a). Moreover, when exits with shorter distance were overcrowded, the majority of people would tend to choose further exits to avoid excessive delays due to heavy congestions (Haghani and Sarvi, 2017b).

Similar to the herding and avoiding behavior, grouping behavior is another type of interactive behavior that involves multiple people. While herding and avoiding behavior may occur among crowds of strangers, grouping behavior is usually based on some form of social connectedness (Drury et al., 2009a). When people are with families, close co-workers or friends, they tend to move as a group and even reenter the building to search for missing members (Bryan, 2002; Johnson, 1987). Grouping behavior frequently occur in real-world emergencies, including the Beverly Hills Supper Club Fire (Cocking et al., 2009), which demonstrated that the group size had an influence on evacuation efficiency. Additionally, grouping behavior has been incorporated in simulations to analyze its impact on the evacuation process. It was found that the evacuation time would be significantly prolonged if evacuees travelled back and forth and took detours to seek group members (Chu and Law, 2013).

Compared with the grouping behavior, helping and competing behavior are also related to people's pre-existing social, as well as their emergent collective identities during building emergencies (Cocking et al., 2009). Contrary to the panic theory, people often exhibit helping behavior during building emergencies, which is observed in many real-world building emergencies, such as the July 7th London bombings in 2005 (von Sivers et al., 2016) and the Rhode Island station nightclub fire (Aguirre et al., 2011). Collective bonds among people might be strengthened and even created through the experience of an emergency, and higher collective identification increases cooperation among people, while higher level of danger decreases the amount of help (Drury et al., 2009b). On contrary, competing and selfish behavior can also happen, due to increased stress and loss of personal space (Moussaïd and Trauernicht, 2016; Pan et al., 2007). The presence of competing behavior could result in more physical collisions, clogged exits, and inefficient evacuations, as reported in several studies that conducted simulated evacuations (Pan et al., 2007; Sharma, 2009). Additionally, based on the survey data from 1134 respondents in a train station in Melbourne, summarized in a study published in 2017, it was shown that men were more likely to behave competitively than women (Shiwakoti et al., 2017). However, the case study of the Beverly Hills Supper Club Fire demonstrated that men helped women more often than women helped men (Best, 1978), which may suggest a change in human behavior over time.

Apart from pre-existing or emergent social relationships, people's behavior is influenced by their social roles in their daily life as well (Canter, 1980). Thus, people can take roles of leaders and followers when emergencies happen based on their personality, knowledge and experience, and their social roles in daily lives. Most people adopt the role of followers during emergencies and respond after others' actions (Kobes et al., 2010b). Leaders may be authority figures, individuals and social groups, and they can lead followers to perceive environmental cues as well as to guide their evacuation process (Averill et al., 2013; Lin et al., 2020a). Moreover, queuing behavior can be observed when a leader slows down or stops and followers form a waiting line (Fang et al., 2016). Leader-following and helping behavior can also have coupled effects: when altruistic leaders slow down to help injuries, followers reduce their speed accordingly, which slows down the evacuation process (Pluchino et al., 2015).

Situational information plays an important role in emergencies and

Table 1
Summary of studies on human-human interactions.

Author(s) (Year)	Methodology	Attributes			Investigated phenomena	Metrics	Main findings
		Type of subjects	Type of emergencies	Type of buildings			
Helbing et al. (2000)	Simulation	Unspecified	Unspecified	Unspecified	The influence of individual and collective behavior on emergency evacuation performance	– Evacuation time – Exit choice	Both individual and herding behavior can decrease evacuation performance
Pan et al. (2007)	Simulation	Unspecified	Unspecified	Unspecified	Represent and investigate people's social behavior during emergency evacuation	– Route choice – Exit choice	A multi-agent based framework to represent people's social behavior during emergencies
Alavizadeh et al. (2008)	Simulation	Unspecified	Unspecified	Unspecified	The influence of individual's decision-making on emergency evacuation	Evacuation time	Herding can help people evacuate from emergency faster when people are unfamiliar with the building
Galea et al. (2008a)	Interview	Unspecified	Act of extreme violence	Office building	Investigate human behavior during the evacuation process of the 2001 WTC attack	– Pre-movement time – Evacuation speed – Stoppage during evacuation	The development of High-rise Evacuation Evaluation Database
Cocking et al. (2009)	Interview	Unspecified	Unspecified	Unspecified	– Investigate the occurrence of mass panic during emergencies – Investigate whether helping behavior predominate during emergencies	– Feeling of panic – Feeling of common unity – Presence of helping and competing behavior	– There is little evidence of mass panic during emergencies – Helping behavior is common during emergencies – People often feel common unity with others during emergencies
Drury et al. (2009a)	Interview	Unspecified	Unspecified	Unspecified	Investigate the formation of crowd solidarity, helping and competing behavior during emergencies	– Feeling of crowd solidarity – Presence of helping and competing behavior	– Crowd solidarity can be formed during emergencies even without pre-existing social bonds – Crowd solidarity can induce helping behavior
Drury et al. (2009b)	VR experiment	Students	Unspecified	Train station	Investigate the formation of crowd solidarity, helping and competing behavior during emergencies	– Feeling of crowd solidarity – Presence of helping and competing behavior	– Crowd solidarity can be formed during emergencies even without pre-existing social bonds – Helping behavior occurs more frequently in high-identification groups than low-identification groups
Sharma (2009)	Simulation	Unspecified	Unspecified	Unspecified	Represent and simulate people's social behavior during emergencies	– Evacuation time – Route choice	The development of a prototype multi-agent system integrating people's social behavior during emergencies
Averill et al. (2013)	Interview	Unspecified	Act of extreme violence	Office building	Investigate human behavior during the evacuation process of the 2001 WTC attack	– Presence of information sharing behavior – Presence of grouping behavior – Presence of helping behavior	A discussion of social and physical factors that influenced the evacuation process of the 2001 WTC attack
Chu and Law (2013)	Simulation	Unspecified	Unspecified	Unspecified	Develop a simulation framework that represents people's social behavior during emergencies	– Evacuation time – Route choice – Exit choice	– A simulation framework that represents people's social behavior during emergencies – Grouping behavior has a significant effect on total evacuation time
Huo et al. (2014)	– Survey – Emergency drill	Staff	Fire	Retail store	Understand people's evacuation process in an underground retail store	– Evacuation time – Evacuation speed – Exit choice	Staff who have emergency drill experience can behave more properly and help others
Pluchino et al. (2015)	Simulation	Unspecified	Unspecified	– Train station – Museum	Develop an agent-based simulation of emergency evacuation integrating people's social behavior	Evacuation time	Helping behavior can affect the evacuation time during building emergencies
Fang et al. (2016)	Simulation	Unspecified	Unspecified	Unspecified	Represent and simulate people's social behavior during emergencies	– Evacuation time – Route choice – Exit choice	The development of simulation that can represent people's social behavior during emergencies

(*continued on next page*)

Table 1 (*continued*)

Author(s) (Year)	Methodology	Attributes			Investigated phenomena	Metrics	Main findings
		Type of subjects	Type of emergencies	Type of buildings			
Lovreglio et al. (2016b)	– Survey – Interview – Simulation	Mostly students	Unspecified	Unspecified	Investigate the occurrence of herding behavior in exit choice during emergency evacuation	Exit choice	The occurrence of herding and avoiding behavior is related to both environmental and personal factors
Moussaïd et al. (2016)	VR experiment	Unspecified	Unspecified	Unspecified	Investigate the influence of stress on collective behavior during emergency evacuation	– Evacuation time – Route choice – Exit choice	Herding behavior results from the level of crowdedness instead of the change of an individual's herding tendency
Moussaïd and Trauernicht (2016)	Survey	Unspecified	Unspecified	Unspecified	Investigate the occurrence of helping and competing behavior during emergencies	– Pre-movement time – Presence of helping and competing behavior	– Helping behavior is common during emergencies – Prosocial people become more cooperative with the increase of emergency – Individual people become more selfish with the increase of emergency
Tancogne-Dejean and Laclémence (2016)	– Survey – Interview	– Vulnerable occupants – Healthcare professionals	Fire	– Residential building – Hospital	Investigate the occurrence and influence of people's risk perception during fire evacuation	– Risk perception – Decision to evacuate – Trust in others	The identification of risk perception factors and importance of trust during fire evacuation
von Sivers et al. (2016)	Simulation	Unspecified	Act of extreme violence	Train station	Simulate the influence of social identity and helping behavior during emergency evacuation	Evacuation time	The representation of social identity and helping behavior in computer simulations
Gerges et al. (2017)	– Survey – Interview	Unspecified	Fire	Residential building	Investigate human behavior during fire emergencies in high-rise residential buildings	Decision to evacuate	People tend to ask others and gather with family members before evacuation during fire emergencies in high-rise residential buildings
Haghani and Sarvi (2017a)	Laboratory experiment	Unspecified	Unspecified	Unspecified	The influence of social interactions and physical environments on herding behavior during emergency evacuation	– Route choice – Exit choice	The assumption of herding behavior is not necessarily applicable to all contexts and situations of evacuation
Haghani and Sarvi (2017b)	– Interview – Laboratory experiment	Unspecified	Unspecified	– Unspecified – Train station	– Investigate factors that affect herding and avoiding behavior with regard to exit choice during emergency evacuation – Compare behavioral results obtained from hypothetical and real choice experiments	Exit choice	– Herding and avoiding behavior are influenced by both social and physical factors – The behavioral data from hypothetical and real choice experiments are consistent
Kinateder et al. (2018)	VR experiment	Mostly student	Unspecified	Museum	Investigate the influence of exit familiarity and neighbor behavior on exit choice during emergency evacuation	Exit choice	People are more likely to follow their neighbors' exit choice during emergency evacuation
Rahouti et al. (2018)	Emergency drill	– Patients – Staff	Unspecified	Hospital	Investigate human behavior during emergency evacuation in hospitals	– Pre-movement time – Evacuation time – Exit choice	– The identification of staff's and patients' pre-movement time during emergency evacuation in hospitals – Staff and patients both make exit choices based on their habits with the building
Haghani and Sarvi (2019)	Simulation	Unspecified	Unspecified	Unspecified	Investigate the influence of herding behavior on the efficiency of emergency evacuation	– Evacuation time – Route choice	Herding behavior can decrease evacuation efficiency, at least when people are familiar with the building

sometimes acts as a medium in human-human interactions. During building emergencies, people are "information hungry" and make efforts to gain more information about the emergency situation, such as consulting others and forming a group to discuss the situation (Kuligowski and Gwynne, 2010). A survey targeting at human behavior in fires in high-rise residential buildings also revealed that most responders would warn others and/or ask neighbors if there was a fire (Gerges et al., 2017). Information sharing acts as a determinant of people's evaluation of the situation, intention to act, and evacuation route choices. It enables people to share situational information during emergencies (e.g., infeasible evacuation path), so that they can take more appropriate actions accordingly. Nevertheless, information sharing could also prolong the pre-movement time (i.e., the delay time from the perception of emergency cues to the movement to a safe place, typically to an exit) and delay the evacuation process (Averill et al., 2013).

3.1.2. Occupant-staff interactions

Staff, such as security personnel and first responders, are often present in building emergencies and play important roles (Ronchi and Nilsson, 2013). Sime, in his study of affiliative behavior (Sime, 1983), highlighted the difference between staff behavior and occupant behavior. During emergency evacuations, staff and building occupants tend to follow different egress routes due to different levels of familiarity with the building (Tan et al., 2015). Therefore, occupant-staff interactions have different characteristics compared with the interactions among occupants. It was demonstrated that many people tend to seek information or wait for directions from staff members before taking actions during emergencies (Shiwakoti et al., 2017). Occupants with disabilities particularly trust and rely on staff members when an emergency occurs (Tancogne-Dejean and Laclémence, 2016). It was also noted that staff, who have more emergency drills and training experiences, could respond properly and inform building occupants to evacuate immediately (Huo et al., 2014; Rahouti et al., 2018). Moreover, staff could involve in many alternative activities that facilitate evacuation, such as directing occupants to exits, giving out supplies (e.g., water), and helping the injured (Averill et al., 2013; Bernardini et al., 2016b). In the Rhode Island station nightclub fire, seven of the twelve staff, including bartenders, bouncers and waitresses, were involved into helping the occupants (Aguirre et al., 2011). Nevertheless, while staff can provide help to occupants and guide them to behave appropriately, it has been noted that counter-flow may also be caused by the movement of staff and building occupants (Averill et al., 2013). For example, fire fighters and rescuers who run into the buildings and move against evacuees may cause evacuation delays (Proulx, 2007; Ronchi and Nilsson, 2013).

3.2. Human-building interactions

Buildings provide primary conditions for the possibility of surviving an emergency (Kobes et al., 2010b). There exist complex interactions between humans and various building attributes, which could impact human safety and a building's performance during emergencies. Thus, this section presents the interactions between building occupants and various building attributes (e.g., signage, corridors, exits, stairs, elevators and alarms) and overall building characteristics during emergencies. Table 2 summarizes the studies discussed in this subsection, in which the studies are listed in chronological order based on their year of publication.

3.2.1. Human-signage interactions

Signage systems have long been regarded as one of the most important building attributes in both normal conditions and during emergencies (Raubal and Egenhofer, 1998; Tang et al., 2009). However, the effectiveness of signage systems does not always reach expectations. A study demonstrated that only 38% of people perceived signage systems and used the information for evacuation (Xie et al., 2012). Thus, how to improve the effectiveness of signage during building emergencies have been widely studied, such as changing color and location of signage, and using dissuasive exit signage (Kinateder et al., 2019; Occhialini et al., 2016; Olander et al., 2017). It was found that people rarely perceived signage installed at the ceiling level, while signage located at the floor level were more effective, especially with dense smoke (Kobes et al., 2010a). Additionally, the interactions between people and signage systems are related to cognitive factors (e.g., interpretation of the information conveyed by the signage) and psychological factors (e.g., desire to believe the information) (Xie et al., 2012). Cultural and local implications are thus an important consideration, as there are different signage configurations worldwide, which might cause people from different cultures and locations interpret the meaning of signage differently. For instance, most international building codes prescribe exit signage to be green, whereas certain codes also allow users to choose between green and red exit signage (Kinateder et al., 2019). Green and red exit signage were found to have similar connotations for both Chinese and European participants during emergency evacuation (Troncoso et al., 2015). Moreover, compared with local exposure (e.g., signage color in the local environment where people reside), semantic association (e.g., green = exit) was found more influential to people's exit choice (Kinateder et al., 2019). To further magnify the effectiveness of signage systems, researchers developed active dynamic signage that could provide adaptive information (e.g., fire propagation), exclude unsafe routes and guide people to safe places (Xie et al., 2014). Galea et al. (2017) found that the active dynamic signage could be correctly interpreted by most of the respondents from across the world and was able to direct most people to a distant exit and keep them away from a closer but non-viable exit.

3.2.2. Human-exit interactions

Exits are one of the most fundamental building attributes, especially during emergencies. Earlier research have set several basic engineering features for exits, such as maximum flow rate capacity and required number of exits (Kobes et al., 2010b). Thereafter, many studies adopted a more behavioral perspective and examined how people interact with exits during emergencies. Some researchers concluded that the unbalanced usage of exits during emergencies was related to exit locations (Oven and Cakici, 2009). If exits are open and people can see the outside, these exits are more attractive and likely to be chosen more frequently (Benthorn and Frantzich, 1999). Moreover, exit choice is related to an individual's role. Compared with staff members, building occupants mostly egress through the main building exits instead of the emergency exits, due to their insufficient knowledge of the building and lack of prior emergency training experience (Sime, 1983). Moreover, People tend to evacuate the building using exits that they are most familiar with (e.g., the main entrance of the building) since routes leading to familiar exits are often perceived as the shortest (Kinateder et al., 2018; Kobes et al., 2010b). That being said, another study that conducted emergency evacuation experiments in a two-dimensional virtual environment found that participants did not have any preference for their familiar exits (Bode and Codling, 2013). Whether this result can amount to occupant behavior in real-world emergencies, however, is debatable, as the participants only had a top-down view of the virtual environment and no hazard was included. Furthermore, the combined effect of exits and other building attributes was studied. It was suggested that to facilitate the evacuation process, obstacles near exits should be cleared, gathering places should not be close to exits and more signage is needed near exits (Huo et al., 2014).

3.2.3. Human-corridor interactions

Corridors are essential components for horizontal accessibility during building emergencies. The flow rate of a corridor is a significant indicator of evacuation performance (Kobes et al., 2010b). Many aspects of corridor configuration have been studied. For example, if a

Table 2
Summary of studies on human-building interactions.

Author(s) (Year)	Methodology	Attributes			Investigated phenomena	Metrics	Main findings
		Type of subjects	Type of emergencies	Type of buildings			
Proulx and Pineau (1996)	Emergency drill	Unspecified	Fire	– Office building – Residential building	Compare human behavior and evacuation time between office and residential buildings	– Pre-movement time – Evacuation time – Evacuation speed	More structured evacuation plans, presence of fire wardens and easier access to fire safety information contribute to the efficiency of emergency evacuation in office buildings
Benthorn and Frantzich (1999)	Survey	Unspecified	Fire	Warehouse	Investigate the influence of fire alarm on people's exit choice during emergency evacuation	Exit choice	– People prefer to use open exit that they can see the outside – Spoken message is more effective than ring signal as fire alarms during building emergencies
Helbing et al. (2000)	Simulation	Unspecified	Unspecified	Unspecified	The influence of individual and collective behavior on emergency evacuation performance	Evacuation speed	Congestions can occur at widenings of escape routes
Olsson and Regan (2001)	– Emergency drill – Simulation	Mostly students	Unspecified	Educational building	Compare human behavior and evacuation time between emergency drill and computer simulated evacuation	– Pre-movement time – Evacuation time	– Pre-recorded message alarms are more effective than siren type alarms – Pre-evacuation time varies because of the dissimilar activities performed in buildings
Gershon et al. (2007)	Interview	Unspecified	Act of extreme violence	Office building	Investigate individual, organizational, and environmental factors that influenced the evacuation process of the 2001 WTC attack	Evacuation behaviors	The identification of various factors at the individual, organizational, and environmental levels that affect evacuation during building emergencies
Galea et al. (2008b)	Simulation	Unspecified	Unspecified	Unspecified	Investigate the merging process at the floor-stair interface during emergency evacuation	– Evacuation time – Evacuation speed	The flow rate of floor occupants onto the stairs can be maximized by connecting the floor to the landing adjacent to the incoming stair
Oven and Cakici (2009)	Simulation	Unspecified	Fire	Office building	– Investigate human behavior during emergency evacuation in high-rise office buildings – Evaluate the use of computer simulation to study the emergency evacuation process	– Evacuation time – Exit choice	– People's exit knowledge can significantly influence emergency evacuation process – Failure in the activation of sprinkler system can have disastrous effect on the loss of life – Computer simulation is an effective method to analyze human behavior during emergency evacuation
Tang et al. (2009)	VR experiment	People from different professions	Unspecified	Unspecified	Investigate the influence of signage on people's evacuation behavior during emergency evacuation	– Evacuation time – Route choice	– The presence of signage can facilitate emergency evacuation – Construction workers and fire safety personnel do not have better evacuation performance than those with less prior experience with building layouts and evacuation procedure
Kobes et al. (2010a)	– Emergency drill – VR experiment	Unspecified	Fire	Hotel	Investigate the usage of virtual reality to study human behavior during building fires	– Pre-movement time – Exit choice – Evacuation behaviors	– The presence of smoke has an impact on people's exit choice during fire evacuation – The influence of signage is stronger when no smoke is perceptible – The use of virtual reality can be a valid method to study human behavior during building fires
Heyes and Spearpoint (2012)	Survey	Unspecified	Fire	Office building	Investigate people's use of elevators during emergency evacuation in high-rise buildings	Elevator usage	The percentage of occupants likely to use elevators to evacuate is dependent on floor level
Kinsey et al. (2012)	Survey	People from different cultural backgrounds	Unspecified	Unspecified	Investigate people's use of elevators in both normal and emergency conditions	Elevator usage	– People's use of elevators is dependent on floor level, crowd density, and expected elevator waiting time during emergency evacuation – There is a difference of people's use of elevators according to country

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Table 2 (*continued*)

Author(s) (Year)	Methodology	Attributes			Investigated phenomena	Metrics	Main findings
		Type of subjects	Type of emergencies	Type of buildings			
Peacock et al. (2012)	Emergency drill	Unspecified	Fire	Office building	Collect people's movement data during fire evacuation in office buildings	– Pre-movement time – Evacuation time – Evacuation speed	– The identification of people's movement data during fire evacuation in office buildings – Staircase configuration and crowd density can influence people's movement speed during fire evacuation in office buildings
Xie et al. (2012)	– Emergency drill – Simulation	Unspecified	Unspecified	– Educational building – Retail store	Investigate how occupants perceive, interpret and use the information conveyed by signage during emergency evacuation	– Decision-making time – Evacuation time – Evacuation distance – Route choice – Exit choice	– Only a small portion of people detect signage during emergency evacuation – If detected, signage can facilitate people's decision-making process during emergency evacuation
Averill et al. (2013)	Interview	Unspecified	Act of extreme violence	Office building	Investigate human behavior during the evacuation process of the 2001 WTC attack	Evacuation time	A discussion of social and physical factors that influenced the evacuation process of the 2001 WTC attack
Bode and Codling (2013)	VR experiment	Unspecified	Unspecified	Unspecified	Investigate people's exit and route choice during emergency evacuation	– Pre-movement time – Route choice – Exit choice	People do not have an inherent preference for familiar routes during emergency evacuation
Vilar et al. (2013)	VR experiment	Students	Unspecified	Unspecified	Investigate the influence of corridor configuration on people's route choice during emergency evacuation	Route choice	People are more likely to use wider and brighter corridors during emergency evacuation
Dias et al. (2014)	– Laboratory experiment – Animal experiment	Unspecified	Unspecified	Unspecified	Investigate the influence of turning angle on human collective behavior during emergency evacuation	– Evacuation time – Evacuation speed	Higher turning angles can significantly reduce flow rate during emergency evacuation
Huo et al. (2014)	– Survey – Emergency drill	Staff	Fire	Retail store	Investigate the emergency evacuation process in an underground retail store	– Evacuation time – Evacuation speed – Exit choice	– Unbalanced exit choice can occur during emergency evacuation – Obstacles near exits should be removed to facilitate evacuation
Vilar et al. (2014)	VR experiment	Students	Fire	Hotel	Investigate the relative influence of corridor configuration and signage on people's route choice during normal and emergency conditions	Route choice	– Without the presence of signage, people rely on the corridor width and brightness for emergency evacuation – People's route choices have disagreement with the direction indicated by signage during emergency evacuation
Xie et al. (2014)	Emergency drill	Unspecified	Unspecified	Educational building	Evaluate the effectiveness of dynamic signage during emergency evacuation	– Decision-making time – Evacuation time – Signage interpretation – Route choice – Exit choice	The dynamic signage can be understood by most people
Chu et al. (2015)	Simulation	Unspecified	Unspecified	Museum	Evaluate the evacuation performance in a museum using agent-based simulation	– Evacuation time – Route choice – Exit choice	– Grouping behavior can cause additional congestion during emergency evacuation, especially at corridor intersections – People's pre-evacuation delay can significantly affect overall evacuation time
Tan et al. (2015)	Simulation	Unspecified	Fire	Educational building	Investigate the influence of spatial accessibility change on emergency evacuation	– Evacuation time – Exit choice	Predictable spatial accessibility change can improve the efficiency of emergency evacuation
Troncoso et al. (2015)	VR experiment	Unspecified	Fire	Unspecified	Evaluate the influence of green and red signage on emergency evacuation for people from different cultural backgrounds	Exit choice	– Green and red signage have similar connotations for Chinese and European participants – Green is perceived by most of the people as meaning safety in case of an emergency

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Table 2 (*continued*)

Author(s) (Year)	Methodology	Attributes			Investigated phenomena	Metrics	Main findings
		Type of subjects	Type of emergencies	Type of buildings			
Occhialini et al. (2016)	– Emergency drill – VR experiment	Unspecified	Fire	Unspecified	Evaluate the effectiveness of signage during emergency evacuation in terms of type and position	– Signage interpretation – electroencephalography	EEG tool can be used to assess the effectiveness of signage
Tancogne-Dejean and Laclémence (2016)	– Survey – Interview	– Vulnerable occupants – Healthcare professionals	Fire	– Residential building – Hospital	Investigate the occurrence and influence of people's risk perception during fire evacuation	Decision to evacuate	The identification of risk perception factors and importance of trust during emergency evacuation
Galea et al. (2017)	– Survey – Emergency drill	Unspecified	Unspecified	– Unspecified – Train station	Evaluate the effectiveness of active dynamic signage during emergency evacuation	– Signage interpretation – Exit choice	– The active dynamic signage can be understood by most people – The active dynamic signage can direct most people to targeted exits
Gerges et al. (2017)	– Survey – Interview	Unspecified	Fire	Residential building	Investigate human behavior during fire emergencies in high-rise residential buildings	– Decision to evacuate – Route choice	– People tend to ignore the fire alarm and they usually investigate if the alarm is true or false in high-rise residential buildings – Using stairs is the top evacuation method during fire emergencies in high-rise residential buildings
Olander et al. (2017)	Survey	Unspecified	Fire	Unspecified	Evaluate the characteristics of dissuasive emergency signage during emergency evacuation	Signage interpretation	Characteristics that clearly negate the message of the original positive emergency signage are most effective
Peacock et al. (2017)	Emergency drill	– Unspecified – People with mobility impairment	Fire	– Office building – Residential building	Collect people's movement data during fire evacuation in office and residential buildings	– Pre-movement time – Evacuation time – Evacuation speed	The identification of people's movement data during fire evacuation in office and residential buildings
Shiwakoti et al. (2017)	Survey	Unspecified	Unspecified	Train station	Investigate the likely behaviors of passengers in transport hubs during emergency evacuation	Route choice	People are less likely to use elevators, escalators and tunnels to escape during emergencies
Zhang et al. (2018)	Emergency drill	Students	Unspecified	Office building	Investigate the influence of grouping behavior and visibility condition on people's evacuation speed on stairs	Evacuation speed	People's evacuation speed drops with reduced visibility
Kinateder et al. (2018)	VR experiment	Mostly student	Unspecified	Museum	Investigate the influence of exit familiarity and neighbor behavior on exit choice during emergency evacuation	Exit choice	People are more likely to choose the familiar over unfamiliar exit during emergency evacuation
Kinateder et al. (2019)	VR experiment	Unspecified	Fire	Unspecified	Investigate which colored signage are most likely to be perceived as exit signage during emergency evacuation	Exit choice	Semantic association is more influential than local exposure for people's exit choice during emergency evacuation
Shahhoseini and Sarvi (2019)	Laboratory experiment	Unspecified	Unspecified	Unspecified	Investigate the influence of corridor configuration and movement speed on people's evacuation performance	– Evacuation time – Evacuation speed	Corridor configuration can influence people's evacuation efficiency during emergency evacuation

corridor contains a widening, it could result in disturbances instead of increasing the flow rate, in that people would increase the distance from each other and squeeze in at the end of the widening (Helbing et al., 2000). Empirical data from human and ant experiments showed that with the presence of high-density crowd, higher turning angles of corridors were inefficient because they reduced the flow rates during evacuations. When stress level is high, the reduction of flow rates was more significant due to the stress-induced competing behavior (Dias et al., 2014). With regard to merging corridors, a laboratory-controlled evacuation experiment found that a symmetric angle was more efficient than an asymmetric setup with equal angles when the participants were merging to a third corridor from two different corridors (Shahhoseini and Sarvi, 2019). VR-based studies also showed that people preferred to follow brighter and wider pathways, and their egress route choice was subject to the intersection type of corridors (e.g., T-type) when a signage system was absent (Vilar et al., 2014, 2013). In addition, corridors with more turns and unfamiliar routes were perceived to be longer, which decreased the probability of the corridor being chosen as part of the evacuation route (Kobes et al., 2010b). Due to the grouping behavior (e.g., waiting to stay close to group members), congestions may be built up at the intersection of corridors, which lengthens the overall evacuation time (Chu et al., 2015).

3.2.4. Human-vertical accessibility interactions

Stairs, elevators, and escalators are common building attributes for vertical accessibility. Movement rates on stairs have been studied extensively in relation to the configuration of stairs (e.g., effective width, spacing on stairs, etc.) (Peacock et al., 2017, 2012). The investigations on the 2001 WTC attack revealed that adequate lighting on stairs, marked handrails, and steps with reflective tapes facilitated the evacuation process, whereas debris on stairs and locked stair doors were barriers for efficient evacuation (Gershon et al., 2007). Meanwhile, human behavior can impact the efficiency of movement on stairs as well. A slow person entering the stairs and counter-flow are likely to decrease the overall movement speed (Proulx, 2007; Zhang et al., 2018). Merging streams of evacuees in the floor-stair intersection are also a significant issue during evacuations. It was suggested that landing doors should be connected opposite the incoming stairs instead of adjacent to the incoming stairs to improve the efficiency of merging streams (Galea et al., 2008b). Apart from the stairs, using elevators and escalators is an alternative choice, especially for those with disabilities or medical conditions. With more high-rise buildings built in the recent years, a combined use of elevators and stairs is deemed practical to improve evacuation efficiency (Heyes and Spearpoint, 2012). However, prior studies have found that people's tendency of using elevators and escalators was low, due to the belief that it is safer to use stairs during emergencies (Kinsey et al., 2012; Shiwakoti et al., 2017). Thus, instead of assuming that people will use elevators to evacuate during emergencies, human behavior must be taken into consideration when designing building evacuation systems that utilize elevators. Significant differences in elevator/stairs choice during emergencies were found between the U.S. and Chinese respondents: 52.5% of the U.S. respondents considered using elevators during emergencies, which was around twice the proportion of Chinese responders (21.5%) (Kinsey et al., 2012). The difference indicates there might be cultural impacts in terms of using elevators during emergencies, thus further cross-cultural investigations are necessary.

3.2.5. Human-alarm interactions

Emergency alarms and announcements are important information sources during emergencies, especially at the early stage when only ambiguous information is perceivable (Proulx, 2001). In the last century, emergency announcements were seldom used to provide emergency information because of the false belief that people would behave irrationally if they knew there was an emergency. However, it was revealed by more recent studies that telling the truth about the emergency could in fact motivate people to start evacuating more quickly and shorten the pre-movement time, which accounts for a large proportion of the total evacuation time (Proulx, 2001). Nevertheless, in real-world emergencies, accurate notifications might not always be present or possible (Fahy and Proulx, 2001). For example, during the 2001 WTC attack, a building-wide announcement in WTC 2 assured that the building was safe and asked people to return to their offices (Averill et al., 2013). Moreover, many people tend to ignore alarms instead of taking immediate actions, particularly when they are not near the hazard (Purser and Bensilum, 2001), when they have past experience of false alarms or frequent drills (Gwynne et al., 2017), when they need more situational information, and when they are committed to other tasks (Hofinger et al., 2014). An evaluation of different alarm types showed that announcements providing timely instructions are more effective than siren alarms (Olsson and Regan, 2001). Additional alarm modes need to be redesigned, especially for people with disabilities, since the signal type may not be adequate for them and can instead result in undesired effects (Tancogne-Dejean and Laclémence, 2016).

3.2.6. Other human-building interactions

Beyond the specific building attributes, several building characteristics that influence emergency evacuations have been identified. These are: (1) visual access, (2) degree of architectural differentiation (i.e., unique building characteristics that can be used for orientation/wayfinding purposes) and (3) plan configuration (Raubal and Egenhofer, 1998). Changes of spatial accessibility (i.e., caused by activated fire shutters) were also found to have negative impacts if people do not have enough awareness of the change of spatial accessibility during emergencies (Tan et al., 2015). In addition, as the environments get more complex with more visual and aural noise, the more it becomes difficult for people to identify emergency cues due to more amount of irrelevant environmental stimuli (Kinateder et al., 2014a). Different building types might also influence the interaction results. For example, a study that used evacuation drills found that people in apartment buildings tended to delay their evacuation compared with office building occupants because they needed longer preparation time (e.g., gathering family and valuables) and they could not hear the alarm well (e.g., poor audibility of alarms) (Proulx and Pineau, 1996). Moreover, the difference in activities being carried on (e.g., more people may be asleep in apartment buildings than other types of buildings) and the lack of formal evacuation plan for apartment buildings are another two factors that could contribute to delayed evacuation in apartment buildings. Another example is hospitals, where some patients have limited mobility, hence the efficiency of evacuations is likely to be compromised as well (Gerges et al., 2017).

3.3. Human-emergency interactions

Human behavior is dependent on the emergency situation. While all building emergencies share certain common characteristics (e.g., causing stressful situations), the results of human behavior studies specific to one type of emergency situation may not always be directly applicable to other types of emergencies (Bernardini et al., 2016b). It is necessary to study how people interact with different types of emergency situations. Therefore, this subsection presents human-emergency interactions in several emergency situations that can occur in buildings and the influence of these interactions on the response performance. Table 3 summarizes the studies discussed in this subsection, in which the studies are listed in chronological order based on their year of publication.

3.3.1. Human-fire interactions

Fire is a widely studied type of emergency in buildings. Several fire attributes, including perceptual attributes (visual, audible, tangible features and smell), fire growth rate, heat, smoke yield, and toxicity

Table 3
Summary of studies on human-emergency interactions.

Author(s) (Year)	Methodology	Attributes			Investigated phenomena	Metrics	Main findings
		Type of subjects	Type of emergencies	Type of buildings			
Jin and Yamada (1989)	Laboratory experiment	Unspecified	Fire	Unspecified	Investigate people's behavior and emotional instability during evacuation in smoke-filled environments	– Evacuation speed – Performance of arithmetic task	Smoke can influence people's thinking power and movement speed during emergency evacuation
Gwynne et al. (2001)	Simulation	Unspecified	Fire	Unspecified	Simulate the interaction between occupants and smoke during evacuation in building fires	– Evacuation time – Route choice – Exit choice	The representation of more complex and realistic interactions between occupants and smoke during evacuation in building fires
Khiun Then and Loosemore (2006)	Survey	Facility manager	Act of extreme violence	Unspecified	Investigate risk and crisis management of facility managers in response to terrorist attacks	Risk perception	Facility managers tend to underestimate the vulnerability of buildings to terrorist attacks
Zhao et al. (2009)	Survey	Unspecified	Fire	Office building	Investigate people's pre-evacuation behavior during building fires	Decision to evacuate	The identification of factors that might influence people's behavior at the recognition and response stage in building fires
Yuan and Tan (2011)	Simulation	Unspecified	Fire	Unspecified	Investigate the influence of smoke-induced visibility reduction on emergency evacuation	– Evacuation time – Route choice	People tend to follow the crowd with limited level of visibility during emergency evacuation
Prati et al. (2013)	Survey	Unspecified	Earthquake	Unspecified	Investigate human behavior during the 2012 Northern Italy Earthquakes	Response to earthquake	– The most frequent responses during the earthquake are moving to another room of the house, escaping from home, and waiting in bed – Perceived risk is associated with evacuation behavior during the earthquake
Lindell et al. (2016)	Survey	Unspecified	Earthquake	Unspecified	Investigate earthquake response of people from different cultural backgrounds	Response to earthquake	– There are similar emotional and behavioral earthquake responses of occupants in New Zealand and Japan – Freezing is the most frequent earthquake response of occupants in both New Zealand and Japan
Liu et al. (2016)	Simulation	Unspecified	Earthquake	Office building	Investigate the influence of human behavior and building damage on earthquake evacuation	– Evacuation time – Exit choice	– Social behavior plays a significant role during earthquake evacuation – Heavily-damaged buildings can cause longer evacuation time due to building damage and injured people
Gunn et al. (2017)	Simulation	Unspecified	Act of extreme violence	Recreational building	Develop a guidance optimization method to help people to evacuate during active shooter incidents	– Evacuation time – Exit choice	The guidance optimization method is effective to guide evacuees to safety during active shooter incidents
Li et al. (2017a)	Simulation	Unspecified	Act of extreme violence	Unspecified	Develop simulation to represent people's behavior and decision-making process at the onset of a terrorist attack	Route choice	The representation of people's decision-making process when dealing with fuzzy information at the onset of a terrorist attack
Li et al. (2017b)	– Laboratory experiment – Simulation	Unspecified	Act of extreme violence	Unspecified	Investigate and simulate people's behavior in response to moving threats	Route choice	The representation of individual's behavior in response to moving threats
Cao et al. (2018)	– Survey – Emergency drill – Simulation	Unspecified	Fire	Retail store	Investigate human behavior under good and limited visibility conditions during emergency evacuation	– Evacuation time – Evacuation speed – Route choice – Exit choice	People are more likely to follow and help others, and walk along obstacles under limited visibility during emergency evacuation
Liu (2018)	Simulation	Unspecified	Act of extreme violence	Unspecified	Investigate the interactions between terrorists' attack behavior and people' evacuation behavior	Exit choice	– The number of deaths in a terrorist attack increases with the number of terrorists and density of occupants – Adding the number of exits can reduce the number of deaths in a terrorist attack
Shapira et al. (2018)	Survey	Unspecified	Earthquake	Unspecified	Investigate people's response patterns to earthquakes	Response to earthquake	– Evacuating buildings is the most commonly adopted strategy during earthquakes – People's level of earthquake preparedness is correlated with their responses to earthquakes

have been identified to impact people's emergency response performance (Kobes et al., 2010b). However, people often ignore ambiguous fire cues (e.g., fire alarms) and continue with their activities instead of starting to evacuate (Kobes et al., 2010b). Typical coping strategies with fire include: extinguishing fire, taking shelter to avoid fire, and evacuation (Tong and Canter, 1985). Depending on the severity of fire, both fighting the fire and avoiding the fire have been observed during fire emergencies (Zhao et al., 2009). In addition, smoke is a critical attribute that is often present in fire emergencies. However, people do not always perceive smoke as evidence of fire. They may interpret smoke as a normal phenomenon, such as smoke coming from a restaurant kitchen (Benthorn and Frantzich, 1999). Through an experiment in smoke-filled corridors, it was reported that high smoke density could significantly reduce evacuees' speed, as well as their thinking power (Jin and Yamada, 1989). Smoke also imposes influence on spatial visibility. If the visibility range is limited, people tend to follow the crowds (Cao et al., 2018; Yuan and Tan, 2011). However, contrary to the conception that people are reluctant to move through smoke, studies of major incidents showed that people were actually willing to move through smoke when they believed that they were heading towards safety (Proulx et al., 2008). In dramatic fire emergencies, there are three situations that people do not have to move through smoke: (1) they are located below the fire floor in a high-rise building; (2) they are remote from the fire site in a large horizontal structure; and (3) they start the evacuation early (Proulx et al., 2008). When confronted with dense smoke, people may also redirect their paths in order to avoid breathing difficulty, lack of visibility, and out of fear (Gwynne et al., 2001).

3.3.2. Human-earthquake emergency interactions

During earthquake emergencies, people's common responses include freezing in place, evacuating the building immediately, taking cover, and protecting others and property (Lindell et al., 2016). An investigation of the 2012 Northern Italy Earthquakes, which occurred at night, showed that escaping from home, moving to another room of the house, going down the stairs, and getting dressed were the most frequently reported behaviors in the immediate aftermath of the earthquake (Prati et al., 2013). Moreover, the earthquake magnitude greatly influences the emergency situation, and human behavior is influenced by the post-earthquake damaged environments and their level of earthquake preparedness (Shapira et al., 2018). Several earthquake attributes have been identified to have direct interference with human behavior, namely (1) buildings shaking, (2) ruins and "high building" influence (i.e., avoid areas surrounded by high buildings after evacuating buildings), and (3) presence of visible damage (Bernardini et al., 2016a). Post-earthquake building modifications can provoke several human behaviors, such as fear of buildings (i.e., running out of buildings and keeping a distance from them) and social attachment (e.g., helping behavior) (Bernardini et al., 2016a). Impediments to egress routes, other physical damages (e.g., fallen ceiling tiles), and injured individuals blocking the routes were found to delay earthquake evacuation based on the results of a simulated evacuation (Liu et al., 2016).

3.3.3. Human-violence interactions

In the acts of extreme violence (mass shootings, terrorist attacks, etc.), various weapon types may be used (e.g., bombs, firearms, incendiary). Adversaries also evolve their techniques, such as using more advanced weapons and strategies (Khiun Then and Loosemore, 2006). The 2001 WTC attack, as an act of extreme violence, has been extensively investigated around the world and generated many behavioral data. However, since no adversaries were present after the planes hit the WTC, how people interact with adversaries have not been studied. There are few studies that looked into adversary behavior during attacks. However, the existing studies that simulated adversary behavior tended to ignore the decision-making procedure of adversaries, and instead considered their behavior as essentially random (Gunn et al., 2017), or simply choosing the nearest person as the target (Liu, 2018). In fact, unlike other emergencies, adversaries (such as shooters in an attack) are essential attributes in acts of extreme violence, thus closer examination of the adversaries is of critical importance. Moreover, suggested responses to acts of extreme violence have not been well defined (Federal Emergency Management Agency, 2011). While some studies simulated people's movement in the presence of adversaries (e.g., people try to keep away from adversaries) (Li et al., 2017b, 2017a), more studies concerning fine-grained interactions between building occupants and adversaries are needed to understand the influence of interactions on human safety.

3.4. Human-building-emergency interactions

In addition to the three types of interactions reviewed above, second-order interactions among humans, buildings, and emergencies also play a significant role. In the context of different emergencies, human-building interactions could have distinct patterns (Bernardini et al., 2016a; Lindell et al., 2016). Similarly, when building characteristics are different, human-emergency interactions might also change (Olsson and Regan, 2001; Thompson et al., 2018; Zhu et al., 2020). In prior studies, how people interact with various building attributes under normal and emergency situations have been studied, including elevators (Kinsey et al., 2012), exits (Haghani and Sarvi, 2016), signage and corridors (Vilar et al., 2014). Other than the investigations on human-building interactions in normal and emergency situations, some studies also looked at how people cope with the emergency situation in different buildings, such as apartment buildings vs. office buildings in fires (Proulx and Pineau, 1996). However, overall speaking, the investigations on second-order interactions are rather limited in the literature, and more future research in this area is necessary. Table 4 summarizes the studies discussed in this subsection, in which the studies are listed in chronological order based on their year of publication.

4. GAPS and recommendations for future research

4.1. Interactions should be further studied

4.1.1. Human-human interactions

Human-human interactions in the context of various types of emergencies were investigated by around 43% of the reviewed articles. As shown in Table 5, the majority of the articles did not specifically study any type of human-human interactions. Among the various types of human-human interactions studied in the reviewed articles, herding and avoiding behavior were the most frequently investigated. While the frequency of investigation does not necessarily imply herding and avoiding behavior are the most important behaviors, possible reasons that contributed to their popularity in the literature are discussed here. People's evacuation route and exit choice are largely shaped by their herding and avoiding tendencies, which could fundamentally determine the total evacuation time (Lovreglio et al., 2016a). In the building design and engineering domain, performance-based design is a widely used approach, which depends on the comparison of Required Safe Escape Time (RSET) and Available Safe Escape Time (ASET) (Purser, 2003). Thus, an understanding of herding and avoiding behavior is indispensable. Nevertheless, even though prior studies have investigated various factors contributing to herding and avoiding behavior, a comprehensive understanding of the influencing factors through a quantitative approach, such as what level of crowd density would trigger herding/avoiding behavior and what building attributes would mediate herding/avoiding behavior is lacking. Grouping behavior is another type of human-human interactions explored in the literature. Past studies have observed grouping behavior and analyzed its influence on evacuation performance (Chu et al., 2015; Cocking et al., 2009). Nevertheless, as grouping behavior is highly related to social

Table 4
Summary of studies on human-building-emergency interactions.

Author(s) (Year)	Methodology	Attributes			Investigated phenomena	Metrics	Main findings
		Type of subjects	Type of emergencies	Type of buildings			
Proulx and Pineau (1996)	Emergency drill	Unspecified	Fire	– Office building – Residential building	Compare human behavior and evacuation time between office and residential buildings	– Pre-movement time – Evacuation time – Evacuation speed	Pre-evacuation time is longer in residential buildings than office buildings
Kinsey et al. (2012)	Survey	People from different cultural backgrounds	Unspecified	Unspecified	Investigate people's use of elevators in both normal and emergency conditions	Elevator usage	People's elevator usage is significantly less during emergencies than normal conditions
Vilar et al. (2014)	VR experiment	Students	Fire	Hotel	Investigate the relative influence of corridor configuration and signage on people's route choice during normal and emergency conditions	Route choice	The influence of signage on people's route choice is lower during emergencies than normal conditions
Haghani and Sarvi (2016)	Interview	Unspecified	Unspecified	Train station	Investigate the differences of people's exit choice in normal and emergency conditions	Exit choice	– In normal conditions, the proximity of exits is the most influencing factor for people's exit choice – In emergency conditions, crowd flow is a more decisive factor for people's exit choice

relationships, comparison of more specific grouping behavior among different social groups (e.g., between parents and children, coworkers, and friends) is necessary. Apart from these, other human-human interactions (e.g., information sharing, leader-following) were studied relatively less in prior studies. However, they are also crucial for the formation of human behavior and their influences on the outcomes of building emergencies may vary in different scenarios. In addition, people's backgrounds, such as age (e.g., elderly, kids, etc.), education levels and cultural backgrounds might affect their interactions with others (BeSeCu-group, 2012). With the exception of few studies, these variables have not been studied. Furthermore, only around 11% of the reviewed studies, which mostly targeted public buildings (e.g., train stations and office buildings), specifically examined the interactions between occupants and staff members. Since social interactions among people with different roles, as discussed in the above section, can influence on the emergency outcome, future research should involve other roles, such as building managers, police officers, fire fighters, medical personnel and rescuers.

4.1.2. Human-building interactions

Building types and building attributes along with their connection, studied in the reviewed articles, are shown in Table 6. Around 46% of the studies did not specify the targeted building type. Meanwhile, office buildings, educational buildings, and residential buildings were among the most studied types of buildings (around 32% of all studies), whereas the remaining studies sparsely focused on a variety of building types. In fact, some types of buildings may have specific building attributes (e.g., sky-bridges in high-rise buildings and ticket booths in train stations), and different buildings could be faced with different emergency risks (e.g., active shooter incidents in schools in the U.S.) (Thompson and Bank, 2007). In addition, buildings differ in their usage and occupancy types: educational buildings are usually occupied by teachers and students, and office buildings are for office workers and visitors. Distinct interaction patterns are expected due to different building usage and people's commitment to activities that take place in buildings (Proulx, 2001).

In terms of building attributes, according to Table 6, interactions between occupants and many individual building attributes have been examined (e.g., signage, exits, corridors, etc.). However, other building attributes, such as furniture, barriers, or environmental factors, such as lighting, color, noise, etc., could also impact human behavior during building emergencies, both physically (e.g., impacting flow rate, causing congestions, etc.) and psychologically (e.g., impacting occupants' route choices, decisions to start evacuation, etc.). These attributes as well as combined impact of building attributes, however, were insufficiently investigated. Additionally, interactions are reciprocal actions or influences. While the influence of building attributes on human behavior is studied, the influence of human behavior on building attributes is not well studied with the exception of a few studies, in which dynamic signage was explored (e.g., the change of signage based on human behavior).

4.1.3. Human-emergency interactions

With regard to the types of building emergencies, unspecified emergencies and fires were examined by the majority of prior studies, as shown in Table 5. How people interact with other emergency types that can occur in buildings, such as earthquakes, acts of extreme violence, chemical, biological and radiological incidents/attacks were much less investigated. Specifically, there have been very few empirical findings of human-violence interactions. Even though more research has been focused on acts of extreme violence with the occurrence of the 2001 WTC attack and the increasing number of active shooter incidents in the U.S. (Federal Bureau of Investigation, 2018), the research focus has been lying in designing anti-terrorism buildings, developing responding procedures, and educating people the recommended behavior (Coaffee et al., 2008; Federal Bureau of Investigation, 2016; Federal

Table 5
Types of human-human interactions and emergencies studied in the reviewed articles.

Human-human interactions	Types of emergency: Acts of extreme violence	Earthquake	Fire	Unspecified	Sum
Grouping	1	1	4	4	10
Helping and competing	2	1	3	12	18
Herding and avoiding		1	5	25	31
Information sharing	1	1	2	1	5
Leader-following			1	7	8
No specific human-human interaction	8	8	38	40	94
Sum	12	12	53	89	166

Emergency Management Agency, 2011; Khiun Then and Loosemore, 2006), rather than investigating human-violence interactions. Furthermore, the large amount of prior studies that focused on unspecified emergencies indicates that these studies assume the similarities or common rules of human behavior during building emergencies. In fact, human-emergency interactions may vary in different situations due to different emergency characteristics and evacuation goals. For example, during active shooter incidents, the recommended response is "run, hide, fight"; whereas in earthquakes, people are suggested to follow the "drop, cover, hold" procedure (Bernardini et al., 2016a; Federal Bureau of Investigation, 2016). Thus, there is a need to study human behavior during specific and different types of emergencies. Even though human behavior during building fires have historically been commonly studied (Bryan, 2002), with the change in climate, socioeconomic and political environment, other types of building emergencies (e.g., active shooter incidents) are likely to occur, which necessitates to focus on building emergencies other than just fires to transform and apply research findings in this area.

4.1.4. Human-building-emergency interactions

In addition to the three types of interactions discussed above, how collective interactions among the three factors (humans, buildings, and emergencies) determine emergency response performance should be further explored. To the best of our knowledge, only a few studies investigated interactions between people and certain building attributes, such as corridors and signage (Vilar et al., 2014), elevators and stairs (Kinsey et al., 2012), and exits (Haghani and Sarvi, 2016) in normal and emergency situations. In fact, knowing people's responses are highly dependent on emergency scenarios, the patterns of interactions between two of the three factors are likely to vary when introducing a third factor at different levels. For example, as presented above, different types of emergencies provide different conditions, which can shift people's goals and impact their interactions with the building. Similarly, people's tackling strategies with the emergency also hinge on the building environments because various factors, such as building layouts, surrounding people, as well as activities happening in buildings can influence people's responses to building emergencies. As a result, humans, buildings, and emergencies should be considered altogether to further evaluate the interactions between any of the two or among these three types of factors (Zhu et al., 2020).

4.2. More validation is needed to transform state-of-the-art research and state-of-the-art practice

As discussed in the last subsection, human behavior depends on many factors. It is challenging, if not impossible, to consistently identify all types of interactions for all population and building types, as well as emergency scenarios (Lochhead and Hedley, 2018). This challenge is

Table 6
Building types and building attributes studied in the reviewed articles.

Building types	Building attributes: Alarm	Corridor	Elevator	Escalator	Exit	Floor plan	Signage	Stairs	Unspecified	Sum
Airport					1				1	2
Educational building	2				5	1	3	4	1	16
Hospital					1		1		1	3
Hotel			1				2	1	2	6
Museum					1	1			2	4
Office building	2		1		2		1	10	8	24
Recreational building					3		1			4
Residential building	3							4	5	12
Retail Store	1				3					4
Stadium					1					1
Theater	1						1			2
Train station			1	1	3		1		1	7
Warehouse	1				1		1			3
Unspecified		9	6		19	2	6	6	26	74
Sum	10	9	9	1	40	4	17	25	47	162

evident when prior studies are reviewed and some discrepancies are found among different studies focusing on the same type of interactions. For example, in one study, it was revealed that cooperation was common during emergencies and it helped facilitate the egress process, whereas another study that used evacuation drills showed that behaving cooperatively would lengthen the egress time of the crowd, since participants were too careful not to push each other (Heliövaara et al., 2012). Similarly, findings showed that herding behavior occurred since people tended to follow others blindly in stressful situations (Helbing et al., 2000). However, the results of another study that conducted VR experiments demonstrated that following occurred as a result of density effect without the need to assume an increase of the tendency to follow others (Moussaïd et al., 2016).

The review of prior studies points to a long-standing challenge in this area, namely the context dependency of research findings. In other words, findings of these studies may be valid for the specific context in which they were examined. The research findings depend on the characteristics of participants or responders, effectiveness of research methods, as well as scenarios examined in the studies (e.g., level of crowd density, environmental settings, etc.). First, the representation of emergency scenarios could influence the reliability of research findings. Over-simplified environments (e.g., empty rectangular rooms, temporary setups in laboratory environments), which were adopted by the majority of prior studies, may not be representative enough to support investigations and predictions on human behavior, because various building attributes and activities can influence occupants' decision-making and actions during emergencies (Proulx, 2001). Likewise, the inclusion of emergency attributes is a crucial influencing factor as well. Even in the same type of emergency, attributes may be different (e.g., different smoke levels in building fires).

Second, different research methods should also be considered, for which prior studies have compared their advantages and disadvantages (Haghani and Sarvi, 2017c; Lin et al., 2020a). Based on the review of prior studies, it was shown that most studies did include human subjects (e.g., by running emergency drills and VR experiments, and conducting post-emergency surveys and interviews, etc.) to examine the formation, characteristics, and influencing factors for certain types of interactions, which could be used to compare with research findings in prior studies and validate existing knowledge (e.g., by using actual behavioral data obtained from post-emergency reports) (Haghani and Sarvi, 2017c). Nevertheless, a major limitation for these methods is the lack of capability to provide participants with a strong sense of presence, thus participants may behave or respond differently than in real emergencies (Kuligowski, 2016; Muir, 1996). Particularly, the experience of frequent emergency drills may inhibit the perception process in real emergencies and cause danger (Gwynne et al., 2017). Additionally, for VR experiments, a major limitation is the ecological validity – whether or not one can generalize from observed behavior in the laboratory to natural behavior in the world (Schmuckler, 2001). To enhance ecological validity of VR experiments and validate the research findings, future studies could provide more stimuli channels (e.g., thermal, olfactory, and haptic feedback) (Lawson et al., 2019). Moreover, most prior studies that used VR-based methods asked participants to perform certain tasks individually without the presence of other evacuees (Zhu et al., 2018). Therefore, future VR-based studies could focus more on social influence (Kinateder et al., 2014b; Lin et al., 2020b), for which plausible or credible behavior of non-playable characters (NPCs) from a participant's point of view in the virtual environment is indispensable.

There are, however, a few studies that used simulation methods (without inclusion of human subjects) to understand the formation of individual human behavior. For example, game theory has been combined with simulation methods to understand the influence of emergency level and environmental uncertainty on people's helping behavior during building emergencies (Cheng and Zheng, 2019; Guan and Wang, 2020); Belhaj et al. (2014) used simulation methods to study people's emotional generation process during building emergencies. Whether the findings from these studies are reliable are debatable, as they did not rely on empirical human behavioral data. Thus, future research could develop simulations based on the support of more empirical behavioral data, instead of theoretical assumptions from other fields (e.g., physics). Moreover, future simulation methods could incorporate more fine-grained building attributes (e.g., effect of visual access), which are typically lacking in current simulations. That being said, simulation methods have been most widely used to study how different types of interactions affect response performance during building emergencies. This is a more reliable usage of simulation methods, because of their capability of generating quantifiable results (e.g., evacuation time, congestion level, etc.). Moreover, non-human animal (e.g., mice and ants) experiments have been used to study the influence of building attributes (e.g., exits and corridors) on the collective evacuation process (Dias et al., 2013; Saloma et al., 2003). While this method can avoid exposing human subjects to dangerous conditions, behavioral similarities between humans and non-human animals need to be validated (Parisi et al., 2015).

Apart from the above methods, augmented reality (AR) is a real-time view of a physical real-world environment with added virtual computer-generated information (Azuma, 1997). There are two stages in the mechanism of AR applications: detecting the surrounding environment and align virtual contents to real environments, which are two of the biggest problems in building effective AR systems (Azuma, 1997). In the area of building evacuation, AR has mainly been used for evacuation training, navigating building occupants during evacuations, and visualizing building evacuation simulations (Lovreglio, 2018), while the application of AR technology in exploration of human behavior during building emergencies is still missing. For future research, AR can be used together with emergency drills and laboratory experiments by imposing virtual emergency scenarios to the physical environments, which could potentially increase ecological validity of these experiments and further validate existing research findings.

Furthermore, when behavioral data are collected, different approaches can be used to interpret the data. In the prior studies that adopted interviews and surveys, narrative analysis was frequently used based on the interviewees' responses (Peacock et al., 2013). Statistical analyses (both descriptive and inferential) have been used to analyze data from VR experiments (Lin et al., 2019; Tucker et al., 2018), emergency drills (Chen et al., 2013; Galea et al., 2017), surveys (Kinsey et al., 2012), and non-human animal experiments (Dias et al., 2014), in order to identify group differences and analyze the impact of changes of investigated factors. Additionally, probabilistic choice modeling has been applied on behavioral data gathered from laboratory experiments and surveys (Haghani and Sarvi, 2017a; Lovreglio et al., 2016a) to quantitatively predict people's responses (e.g., exit choices) as a function of environmental and personal factors. More recently, machine learning approaches has also began to be used in this research area. Wang et al. (2019) used machine learning methods to study people's stepwise movement patterns during evacuation. Compared with the above-mentioned approaches, machine learning approaches have the strength to tackle more complex emergency scenarios. Nevertheless, machine learning approaches heavily rely on data for training algorithms, and the results could be biased based on the input data. Certain machine learning models (e.g., neural networks) also generate results that cannot be easily interpreted by humans.

It is indeed unlikely to eliminate context dependency of the research findings. Therefore, instead of holding universal assumptions about interactions during building emergencies (e.g., herding with the crowd), existing research findings should be used with caution (e.g., examine research finding with different human subjects) to extract the commonality of human behavior during emergencies, that is independent of a particular experimental setup (Haghani and Sarvi, 2017c). Several studies have been conducted to compare behavioral data collected using different methods or validate research findings using different methods (e.g., surveys, simulations, laboratory experiments) (Haghani and Sarvi, 2017b; Li et al., 2017a; Moussaïd et al., 2016). Even though direct validations may be challenging, alternative validating approaches, such as comparing research finding generated from different population and research methods, as well as internal validations (e.g., evaluating participants' level of stress in VR experiments and emergency drills) are needed.

4.3. More comprehensive investigations are needed for transformation of research findings to improved human safety

Undoubtedly, the ultimate goal of this research area is to use the domain knowledge to improve human safety during building emergencies. Two approaches have been proposed to enhance human safety during building emergencies (Lovreglio et al., 2018). The first one is to improve human preparedness for emergencies by training (i.e., teach building occupants recommended responses to emergencies); the other one is to use "behavioral design" approaches to implement risk-reduction strategies in new and existing buildings based on how people actually respond during building emergencies (Bernardini et al., 2016a). To implement the second approach, it is a prerequisite to examine human behavior during emergencies comprehensively. However, due to the context dependency of the research findings, several challenges still remain for applying knowledge that have developed so far.

First, even with the decades-long efforts in this research area, our knowledge is still far from being comprehensive. Nevertheless, it is necessary to adopt a holistic view to derive the optimal strategy to improve human safety during emergencies. For example, many building attributes, such as corridors, stairs, and exits, are functionally interdependent, thus it is important to consider not only interactions between occupants and individual building attributes, but also their combined effects during emergencies. Hence, it is important for future research to consider what level of detail (e.g., building characteristics and occupancy types) should be included. Second, a building may suffer from various types of emergencies. Thus, a practical question is how to evaluate a design that aims to mitigate the risk of one emergency, given the possibility of the building being challenged by other types of emergencies? To tackle this issue, a promising research direction could be the "cross-examination" of building performance under different emergency scenarios. Third, there may be a conflict between meeting the requirement of daily usage of a building and improving its performance during emergencies. For example, occupants in office buildings are likely to use door stops to facilitate free movement in their daily usage, which cause fire doors to fail in fulfilling their role during building fires (Proulx, 2001). Atriums could promote fire propagation, whereas atriums are very common in current shopping centers for commercial purposes. Thus, to advance the application of research findings in real-world scenarios, coordination with different stakeholders and reconciliation on building performance in daily usage and emergencies are required to achieve a balance.

4.4. Cross collaboration among multiple disciplines should be strengthened

To further boost studies in this area, insights about the correlating factors that influence human behavior are necessary. First, regarding human-human interactions, future research also needs to understand and incorporate the behavior of first responders, police, and rescuers during building emergencies. To do so, future research could include these personnel who are directly involved in building emergencies (e.g., by conducting interviews and surveys), which not only enables us to learn how the behavior of the personnel would influence occupants' responses during building emergencies, but also how research findings in this area could be applied in real-world scenarios. Second, considering human-building interactions, law enforcement communities that develop building design standards and guidelines could provide information of what key building attributes would impact the outcome of building emergencies, which thereby could stimulate the study of human-building interactions. Third, in terms of human-emergency interactions, while building fires were widely studied (Kobes et al., 2010b), further exploration of human-emergency interactions could benefit from research focusing on specific types of emergencies. For example, a study developed VR serious games for building earthquake preparedness and claimed building damages could be realistically modeled by a qualitative approach (i.e., mimicking the damage based on existing datasets including videos and photos of building damage) (Lovreglio et al., 2018). The reliability of this approach, however, may need further validation and could be improved by collaborating with researchers working in the field of earthquake engineering. On a similar token, prior studies on human behavior during acts of extreme violence could collaborate with experts who focus on behavior, decision-making and strategies of adversaries to have more accurate representation of adversaries' behavior.

4.5. Recommendations for future research

Based on the discussions in the above subsections, the recommendations for future research are summarized as follows.

- Human-human interactions:
  - o Investigate interactions between occupants and people with different roles (e.g., staff members, fire fighters, etc.).
- Human-building interactions:
  - o Extend existing findings about human-building interactions to more building attributes (e.g., visual access, furniture, etc.) and building types (e.g., airports, governmental buildings, etc.).
  - o Examine the combined impact of several building attributes (e.g., signage, exits, corridors, etc.) on human behavior during emergencies.
- Human-emergency interactions:
  - o Investigate how people interact with emergencies (e.g., earthquakes, acts of extreme violence) other than fires.
  - o Examine the connections and disparities of human behavior in different types of building emergencies.
- Human-building-emergency interactions:
  - o Investigate how second-order interactions (i.e., interactions among humans, buildings and emergencies) affect the findings on first-order interactions (i.e., human-human interactions, human-building interactions, and human-emergency interactions).
- General recommendations:
  - o Further validate existing research findings before applying them in real-world scenarios.
  - o Leverage the strength of different research methods (e.g., VR experiments, laboratory experiments, simulations).
  - o Bridge the gaps between the state-of-the-art research and the state-of-the-art practice by collaborating with researchers and practitioners in related areas (e.g., interviewing with building emergency personnel).

5. Limitations

While the authors strived to present a comprehensive review in this study, as with any study, there were several limitations that were worthwhile to point out. First, as discussed in this study, the research findings in this research area are hinged on human subjects involved in the study, research methods being used, and experimental designs. Therefore, findings from different studies may differ in their soundness and credibility. A systematic method to set criteria to evaluate the quality of these research findings is still lacking and was not addressed by this study. Second, this study focused on emergencies in indoor buildings. However, in certain circumstances, evacuating buildings is not the end of people's emergency response. The connection of human behavior in indoor and outdoor environments was not discussed in this study, which could be further examined in the future.

6. Conclusions

To enhance human safety, an essential prerequisite is gaining a complete understanding of human behavior during emergencies. Various factors, such as behaviors of others, building attributes, and emergency attributes play a crucial role in the formation of human behavior. Therefore, this paper adopted an interaction perspective to review prior studies on human behavior during building emergencies. Human-human interactions, human-building interactions, human-emergency interactions and human-building-emergency interactions were analyzed and discussed. The results showed that while there have been many studies of human behavior during building emergencies, some aspects are insufficiently explored, and existing knowledge remains to be enriched. The interactions between building occupants and staff members (e.g., security personnel, first responders), how building configuration and functionality impact human behavior during emergencies, and how people interact with emergencies other than just building fires, as well as the second-order interactions among humans, buildings, and emergencies, need further investigation. Our review also indicates that more validations of prior research findings is needed, and how to transform prior research findings to practical applications remains unclear. Future research could explore the application of emerging technologies to facilitate the study of human behavior during building emergencies, utilize existing data of emergency incidents to develop building emergency scenarios, and strengthen cooperation among researchers in related research areas to advance the knowledge about the relationship among humans, buildings and emergencies.

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