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Architectural Design for Active Shooter Preparedness: A Simulation-Based Systematic Review

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Abstract

Active shooter incidents (ASIs) pose a grave threat to occupant safety in built environments. This systematic review methodically examines research on building design strategies to mitigate ASI risks and enhance occupant safety, with a particular emphasis on studies utilizing simulation modeling. Employing the PRISMA framework, we analyzed 75 relevant studies published since 2000. The review synthesizes findings across key themes, including: the impact of exit design and spatial configuration on evacuation efficiency; the effectiveness of security features such as access control, surveillance systems, and bullet-resistant materials; and the role of communication systems in facilitating information sharing and emergency response. We critically evaluate the strengths and limitations of different simulation modeling approaches, highlighting their contributions to understanding human behavior dynamics and informing evidence-based design strategies. The review also identifies knowledge gaps and future research directions for optimizing building design to enhance occupant safety and resilience during ASIs.

1. INTRODUCTION

Active shooter incidents (ASIs), characterized by individuals using firearms to inflict harm in populated areas, pose a growing and substantial threat to public safety worldwide [1, 2]. These incidents, tragically, have become more frequent and deadly in recent years, generating widespread fear and prompting urgent calls for enhanced prevention and preparedness strategies [3–5] While ASIs can occur in various settings, built environments—including schools, workplaces, healthcare facilities, and public spaces—have become increasingly common targets [3, 6, 7]. This alarming trend and the inherent vulnerability of occupants within these confined spaces underscores the critical need to examine how architectural design can contribute to occupant safety during these unpredictable and often rapidly unfolding events.

The design of buildings themselves, beyond conventional security measures like access control systems, surveillance technologies, and armed guards [8, 9], plays a pivotal role in shaping occupant behavior and influencing safety outcomes during ASIs. Research has shown that specific architectural features can either hinder or support effective evacuation and response. For example, exits' number, location, and visibility influence evacuation time and pedestrian flow [10–12]. Studies have demonstrated that strategic placement of exits, clear signage, and well-lit escape routes can significantly reduce congestion and facilitate faster evacuation [13, 14]. Similarly, corridor width and layout directly impact pedestrian flow rates and potential bottlenecks or crowd-crushing during emergencies [15, 16]. Wider corridors, thoughtfully planned circulation paths, and strategically placing obstacles to guide movement can improve pedestrian flow and enhance safety [17, 18]. Furthermore, the availability of secure spaces or well-concealed hiding places within rooms can offer occupants temporary refuge and increase their chances of survival [8, 19].

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Recognizing the complex interplay between human behavior, spatial configuration, and the dynamics of ASI events, researchers have increasingly turned to simulation modeling as a powerful tool for evaluating the effectiveness of different building design strategies [20–22]. Simulation modeling allows for creating virtual environments where various ASI scenarios can be tested, incorporating a range of factors such as attacker behavior, occupant characteristics, and building features [23, 24]. By simulating different evacuation and response strategies, researchers can gain data-driven insights into how design variations impact occupant safety outcomes, such as evacuation time, casualty rates, and the likelihood of survival [10, 23, 25].

This systematic review aims to thoroughly examine the growing body of research on building design strategies for mitigating ASI risks, emphasizing studies utilizing simulation modeling to evaluate the efficacy of different design approaches. By synthesizing findings from diverse simulation studies across various building types and occupant populations, we seek to provide a comprehensive overview of current knowledge and identify evidence-based design strategies for enhancing occupant safety during ASIs. The review will also address the strengths and limitations of different simulation modeling techniques, highlight key knowledge gaps, and propose future research directions for advancing the field of active shooter preparedness from an architectural design perspective. Ultimately, this review seeks to contribute to developing safer and more resilient built environments that can effectively protect occupants in the face of this evolving threat.

2. RESEARCH PROCESS AND METHODOLOGY

This systematic review embraced a systematic and meticulous approach, adhering to the well-established Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Systematic Reviews (PRISMA) framework [26]. This framework, specifically tailored for systematic reviews, provides a transparent and structured methodology for conducting and reporting research, ultimately enhancing the reliability and reproducibility of the findings. This commitment to a rigorous methodology ensured a comprehensive and unbiased exploration of the complex relationship between building design and occupant safety during active shooter incidents (ASIs).

The research process began with an extensive search for relevant studies, spanning multiple databases to capture diverse perspectives and research approaches. This multi-database approach recognized that knowledge on ASI preparedness is dispersed across various disciplines, including safety science, engineering, architecture, social psychology, criminology, and computer science. Specialized databases dedicated to safety science, such as SafetyLit and Transportation Research International Documentation (TRID), provided a focused lens on studies addressing building design for emergency preparedness and risk management [27]. In parallel, searches were conducted in databases specific to engineering and architecture, including Compendex and the Avery Index to Architectural Periodicals, capturing research on building design, construction, and technology that could potentially be applied to ASI mitigation [13, 28]. To further broaden the scope, multidisciplinary databases like Web of Science, Scopus, and Google Scholar were also included, encompassing research from diverse fields that could offer valuable insights into human behavior during emergencies and the effectiveness of simulation modeling for evaluating design strategies [29].

The search was deliberately limited to peer-reviewed journal articles, conference papers, and relevant book chapters published in English, prioritizing research that had undergone rigorous academic scrutiny and scholarly evaluation. This emphasis on peer-reviewed literature ensured the inclusion of high-quality research with robust methodologies and credible findings. Moreover, the search was conducted with a specific temporal focus, encompassing publications from January 1, 2000, to the present. This timeframe captured the significant advancements in ASI research and building design strategies that have emerged in recent years, reflecting the growing awareness of this threat and the increasing urgency to develop effective mitigation measures.

A carefully constructed keyword strategy was employed to refine the search further and identify the most pertinent studies within this vast body of literature. This strategy utilized Boolean operators (AND, OR, NOT) to effectively combine search terms and pinpoint studies focusing on the intersection of building design, simulation modeling, and ASI preparedness. General keywords, such as "active shooter," "mass shooting," "architectural design," "building design," "evacuation," "simulation," "security," and "safety," were combined with more specific terms, such as "exit design," "corridor width," "access control," "surveillance systems," "bullet resistant," "emergency notification," "real-time communication," "information sharing," and "occupant behavior." This multi-layered keyword strategy allowed for identifying studies that explored both broad concepts and specific design features, technologies, and behavioral considerations relevant to mitigating ASI risks. For instance, searches combined general terms like "active shooter" or "mass shooting" with specific terms like "exit design" and "evacuation time" to identify studies examining the impact of exit design on occupant safety during ASIs.

The next crucial stage involved a systematic screening process to select studies that met predefined inclusion and exclusion criteria. This rigorous screening process ensured that only the most relevant and methodologically sound studies were chosen for inclusion in the systematic review. Studies were carefully evaluated based on their focus, publication type, language, and publication date. To be included, studies had to explicitly examine building design strategies for ASI preparedness, either using simulation modeling or through empirical studies of occupant behavior during actual or simulated ASI scenarios. Furthermore, they had to be published as peer-reviewed journal articles, conference papers, or relevant book chapters in English from January 1, 2000, to the present.

Studies were excluded from the review if they focused solely on other types of emergencies, such as fire or earthquake, without a clear and explicit connection to ASIs. While these studies might offer valuable insights into general emergency preparedness and evacuation behavior, their relevance to the specific context of ASIs was deemed insufficient for inclusion. Additionally, opinions, editorials, news articles, and other publications lacking empirical data or a systematic analysis of building design strategies for ASI preparedness were excluded. This ensured that the review prioritized research grounded in empirical evidence and rigorous methodologies.

Once the relevant studies were selected, a standardized data extraction form was meticulously employed to gather pertinent information from each paper. This form captured essential details about the study, including the author(s), year of publication, study design, building type, occupant population, simulation modeling approach (if applicable), and key findings related to building design and occupant safety. This structured data extraction process ensured consistency and facilitated subsequent thematic analysis. Following data extraction, the collected information underwent a thorough thematic analysis to identify recurring concepts and patterns across the literature. Themes emerged inductively, based on the frequency and significance of specific findings related to building design strategies for ASI preparedness. This thematic approach allowed for a comprehensive and organized research synthesis, highlighting key areas of consensus, identifying knowledge gaps for future exploration, and revealing the overall landscape of knowledge on how architectural design can contribute to occupant safety during ASIs.

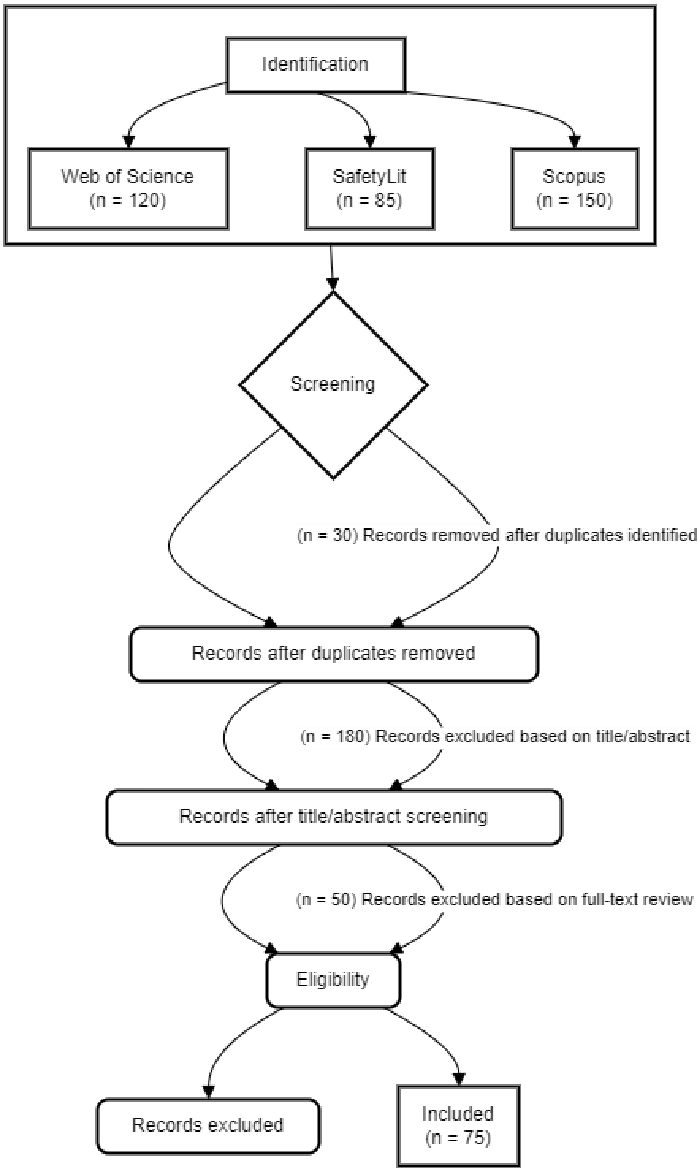

Figure 1. *PRISMA Flow Diagram for the Systematic Review*

This systematic and rigorous methodology, guided by the PRISMA framework, provides a robust foundation for exploring the multifaceted role of building design in enhancing occupant safety during active shooter incidents. By carefully selecting and analyzing relevant literature, this systematic review aims to contribute valuable insights to the field of ASI preparedness and inform the development of safer and more resilient built environments that can effectively protect occupants in the face of this evolving threat.

3. RESULTS AND THEMATIC ANALYSIS

The systematic search and screening process identified 75 studies meeting the inclusion criteria for this systematic review. These studies, spanning from 2000 to 2024, represent a diverse range of research approaches, building types, and occupant populations, reflecting the growing interest in understanding the role of architectural design in ASI preparedness. As illustrated in Table 1, simulation modeling has emerged as a dominant methodology, with agent-based modeling (ABM), social force models (SFM), and cellular automata (CA) being frequently employed to evaluate the effectiveness of different building design strategies.

Table 1. *Characteristics of Included Studies (see the whole Table in Appendix-A)*

Author(s)	*Year*	*Study Design*	*Building Type*	*Occupant Population*	*Simulation Model*	*Key Findings*
Arteaga & Park	2020	Simulation Study (Agent-Based Modeling)	School-like building	Students	Agent-Based Model (ABM)	Increasing hall and door widths improved evacuation efficiency and reduced casualties; narrower halls were more sensitive to higher occupant densities.
Zhu, Lucas, & Southers	2020	Qualitative Study (Focus Groups)	Various (schools, offices, hospitals)	Occupants	N/A	Security countermeasures must consider occupant behavior and trade-offs between security, cost, aesthetics, and daily operations; training and practice are crucial for effectiveness.
Doss & Shepherd	2015	Literature Review, Practical Guidance (Book Chapter)	Commercial buildings	Employees	N/A	Multiple communication platforms, clear message content, accessibility for diverse populations, and pre-scripted messages are essential for effective communication during ASIs.
Kellom & Nubani	2018	Simulation Study (Visibility Graph Analysis)	University classrooms	Faculty	Visibility Graph Analysis (VGA)	VGA measures predicted faculty preparedness levels and police response efficiency; visibility was crucial for both occupant safety and police response.
Shih, Lin, & Yang	2000	Simulation Study (Virtual Reality)	Metro Station	Passengers	Virtual Reality Simulation	VR simulations revealed discrepancies between traditional evacuation calculations and actual occupant behavior; exit signage and layout significantly influenced evacuation time.
Jin, Jiang, & Liu	2021	Empirical Experiment (Controlled Walking Trials)	Corridor	Pedestrians	N/A	Wider corridors improved pedestrian flow rates in both unidirectional and bidirectional movement; different corridor widths affected lane formation patterns.
Li & Xu	2020	Simulation Study	Limited-Space Building	Pedestrians	Social Force Model (SFM)	Exit width of 1.1m optimized evacuation time and construction costs; inward-opening doors were more efficient than outward-opening doors.
Lei, Li, & Gao	2013	Simulation Study (FDS + Evac)	Dormitory	Students	FDS + Evac	Corridor width of 3m and exit width of 2.5-3m were optimal for the dormitory; occupant density significantly influenced walking speed; evacuation time was not proportional to evacuation distance.
Hassanpour, González, & Cabrera-Guerrero	2024	Simulation Study (ABM)	University building	Students, Faculty	Agent-Based Model (ABM)	Integrating earthquake damage assessment into evacuation simulations informed the design of safe spaces and architectural layouts for post-earthquake evacuation.

Analysis of the included studies revealed several recurring themes related to building design for enhancing occupant safety during ASIs. These themes highlight the interconnectedness of architectural features, security systems, communication strategies, and human behavior in shaping safety outcomes during these critical events.

3.1 Exit Design and Spatial Configuration: Optimizing Egress and Movement

Exit design and spatial configuration are paramount considerations in ASI preparedness, as they directly influence evacuation efficiency and the potential for casualties. Effective exit design aims to minimize the time required for occupants to safely egress a building during an ASI, reducing their exposure to the threat and minimizing the risk of injury or death. Simulation studies have consistently demonstrated that the number, location, visibility, and design of exits significantly impact pedestrian flow, evacuation time, and the likelihood of successful escape [10–12].

Studies utilizing ABM and SFM have shown that increasing the number of exits, strategically placing them for optimal accessibility, and ensuring clear visibility and signage can considerably reduce congestion and facilitate faster evacuation [13, 14, 30]. These models allow researchers to explore how occupants navigate complex building layouts and make decisions about exit routes during emergencies.

For instance, research has shown that wider corridors and strategically placed doorways can create smoother pedestrian flows and reduce crowding [15, 16, 31]. Simulation studies have also demonstrated that the strategic placement of obstacles within corridors can, counterintuitively, improve pedestrian flow by directing movement and preventing congestion [17, 18].

Moreover, the availability of safe spaces or designated hiding places within rooms, offering temporary refuge from the threat, has emerged as a crucial design consideration, potentially increasing occupant survival rates [8, 19]. These spaces, ideally designed to be easily accessible, well-concealed, and resistant to forced entry, can provide occupants with a layer of protection while awaiting the arrival of law enforcement. Research has also highlighted the importance of integrating architectural design with emergency response protocols and occupant training programs [32]. By incorporating features that support lockdown procedures, such as reinforced doors and communication systems, buildings can be designed to facilitate a more coordinated and effective response to ASIs.

3.2 Security Features: Enhancing Protection and Delaying Access

Beyond exit design and spatial configuration, the incorporation of security features into building design is crucial for deterring attackers, delaying their access, and creating layers of protection for occupants. The goal is to create a "layered defense" [33], making it more difficult for attackers to reach their intended targets and providing occupants with additional time to evacuate or seek shelter. Studies have explored the effectiveness of various security features, including access control systems, surveillance technologies, and bullet-resistant materials, highlighting their potential to enhance building security and occupant safety.

Access control systems, such as locked doors, security checkpoints, and controlled entry points, have been shown to be effective in delaying or preventing attacker access [8, 34]. Research suggests that even relatively simple measures, such as requiring keycard access to enter buildings or individual rooms, can significantly increase the time it takes for an attacker to reach their targets, providing occupants with valuable minutes to escape or implement lockdown procedures [8]. However, it's crucial to balance security with accessibility and functionality, ensuring that security measures do not impede daily operations, create excessive inconvenience for occupants, or hinder emergency response efforts [8, 35].

Surveillance systems, including CCTV and other monitoring technologies, can play a vital role in enhancing situational awareness during ASIs, enabling faster detection of threats and supporting more effective response strategies [23, 36–38]. Strategically placed cameras, coupled with real-time monitoring systems, can provide security personnel with valuable information about the attacker's location, movements, and actions, allowing for a more informed and coordinated response [23]. Moreover, the integration of AI and machine learning into surveillance systems offers the potential for automated threat detection, identifying suspicious behavior and alerting security personnel to potential risks before an ASI occurs [39, 40]. This proactive approach to security, leveraging advanced technologies to identify and respond to threats early, could significantly reduce the likelihood of ASIs occurring and mitigate the severity of those that do.

Incorporating bullet-resistant materials into building construction, particularly in areas with high visibility or vulnerability, can offer an additional layer of protection for occupants, reducing the risk of injury or death from gunfire [41]. Research has examined the effectiveness of laminated glass, reinforced concrete, and composite materials in resisting ballistic impact, demonstrating their potential applications in building components such as windows, doors, and walls. However, while bullet-resistant materials offer enhanced protection, the cost-benefit analysis of implementing them must be carefully considered, considering factors such as building type, occupancy, perceived risk level, and budgetary constraints.

3.3 Communication Systems: A Lifeline for Information Sharing and Emergency Response

Effective communication systems are not merely technological tools; they are lifelines for occupant safety during active shooter incidents (ASIs), facilitating rapid information sharing, coordinated responses, and ultimately, saving lives. These systems play a critical role in mitigating the chaos and uncertainty inherent in ASIs, empowering occupants to make informed decisions and take appropriate actions, even in the face of extreme stress and fear. Research has repeatedly demonstrated the crucial role of communication in enhancing situational awareness, guiding evacuation, and supporting a swift and coordinated response from both occupants and emergency personnel [42, 43].

Emergency notification systems (ENS) serve as the foundation for effective communication during ASIs, acting as a central nervous system for disseminating critical information rapidly and widely [42]. These systems leverage diverse communication channels to reach occupants quickly and effectively, ensuring message redundancy and maximizing reach. Traditional methods, such as public address systems and audible alarms, remain vital for broad, immediate alerts within a building, particularly when power outages or internet disruptions may affect digital communication [44]. However, the digital age has expanded the communication toolbox significantly, incorporating SMS messages, emails, mobile alerts, social media platforms, and digital signage into the ENS repertoire [43, 45, 46]. This multi-channel approach, strategically combining traditional and digital methods, increases the likelihood of reaching occupants and creates redundancy, ensuring message delivery even if one or more channels fail [47].

While reaching occupants quickly is paramount, the effectiveness of ENS hinges on the messages' clarity, conciseness, and actionable nature [48]. Research has shown that vague or ambiguous messages can lead to confusion, hesitation, and inappropriate responses, potentially increasing the risk of harm to occupants [49, 50]. Therefore, emergency notifications must be carefully crafted, providing clear and specific instructions, location-based details (e.g., the location of the attacker, safe evacuation routes, designated safe spaces), and guidance on appropriate actions, such as evacuation procedures, lockdown protocols, or, as a last resort, defensive tactics [48, 51]. Furthermore, effective communication extends beyond initial alerts. Real-time communication and information sharing systems, utilizing mobile devices, two-way radios, and interactive digital displays, can further enhance occupant safety during ASIs [52, 53]. These systems create a dynamic information loop, providing ongoing updates about the situation, enabling two-way communication between occupants and first responders, and fostering a sense of shared awareness [23]. By knowing the attacker’s location, movements, and actions, occupants can make more informed decisions about evacuation routes, hiding places, or whether to engage in defensive actions [54, 55].

Integrating these real-time communication systems with building design is crucial for maximizing their effectiveness [23, 55]. Strategically placed communication hubs, incorporating two-way radios or internet-connected devices, can provide occupants with access to critical information and enable them to communicate with authorities even if cellular networks are disrupted [55]. Interactive digital displays, strategically positioned throughout the building, can provide real-time updates, evacuation maps, and safety instructions, supplementing audible alerts and enhancing situational awareness [23]. Furthermore, incorporating communication systems into building automation systems can enable automated responses, such as locking doors, activating alarms, or adjusting lighting to guide evacuation [56].

While technology plays a crucial role in facilitating communication during ASIs, it's paramount to acknowledge the profound influence of human factors. Occupants’ responses to emergency notifications are shaped by their perceptions of risk, trust in information sources, and the social dynamics unfolding around them. Research has shown that individuals in crisis situations often prioritize information from their peers and social networks, even if it is unverified or inaccurate [49, 57]. This "social contagion" [58] can rapidly spread misinformation, hindering effective response and potentially increasing the risk of harm. Therefore, building design and communication strategies should consider these social influences, promoting a culture of preparedness that fosters trust in official information channels and encourages occupants to verify information before sharing it. Regular drills, educational programs, and clear communication protocols can help build occupant confidence in emergency procedures and enhance their ability to act decisively and responsibly during ASIs [59].

3.4 Human-Building Interactions and Behavioral Aspects: A Complex Interplay of Design, Stress, and Social Dynamics

While well-designed exits, robust security features, and sophisticated communication systems form the physical and technological foundation of ASI preparedness, understanding and incorporating human behavior is paramount. Occupants are not simply passive entities moving through a building; they are active agents, making decisions, reacting to their surroundings, and influencing the dynamics of the event in profound ways. Research in crowd dynamics, social psychology, and human factors has revealed a complex interplay between individual characteristics, social influences, environmental cues, and the inherent stressors of ASI situations. Ignoring these human factors in building design and emergency planning risks creating environments that, despite technological sophistication, may fail to protect occupants effectively during these critical events.

One of the most challenging aspects of modeling occupant behavior during ASIs is the profound influence of panic and anxiety on human cognition and decision-making [60, 61]. Confronted with the sudden and unexpected threat of an active shooter, individuals may experience a cascade of physiological and psychological responses, including elevated heart rate, rapid breathing, hypervigilance, fear, and a sense of overwhelming dread [62, 63]. These stress responses, while evolutionarily adaptive for preparing the body to fight or flee, can significantly impair cognitive function, leading to delayed reactions, poor judgment, and an increased likelihood of making irrational or counterproductive choices [64, 65].

Studies have shown that under extreme stress, individuals may experience tunnel vision, auditory exclusion, time distortion, and a decline in fine motor skills [66, 67]. These stress-induced impairments can hinder occupants' ability to perceive information accurately, process instructions, locate exits, or effectively implement learned safety protocols [29]. Therefore, simulation models used to evaluate building designs must account for these psychological effects, incorporating realistic representations of human decision-making under stress to accurately predict evacuation patterns, identify potential bottlenecks, and guide the development of design strategies that can mitigate the negative impacts of panic [14, 30].

Furthermore, occupant behavior is significantly influenced by social factors, such as group dynamics, herd behavior, and information-sharing patterns. Research has consistently shown that individuals in emergencies often look to others for cues on how to behave, particularly when faced with ambiguity or uncertainty [68]. This "social proof" or "herd behavior" can be amplified during ASIs, as the chaotic and unpredictable nature of the event creates a heightened sense of urgency and a need for immediate action [69]. The tendency to follow the crowd can rapidly spread helpful and harmful behaviors, impacting evacuation efficiency, potentially contributing to congestion or panic, and hindering effective responses [58].

For example, research has shown that in crowded environments, the behavior of a few individuals can quickly cascade through the crowd, leading to mass movements towards exits, even if those exits are blocked or unsafe [70]. Simulation models can be powerful tools for incorporating these social dynamics, allowing researchers to explore how group behavior, leadership roles, and information sharing patterns influence exit choice, evacuation route selection, and overall crowd movement patterns during ASIs [22, 70]. By simulating different crowd compositions, social network structures, and communication strategies, researchers can gain insights into optimizing building design and emergency protocols to mitigate the negative impacts of herd behavior and promote more orderly evacuations.

Beyond social dynamics, building design itself can profoundly influence occupant behavior during ASIs. The arrangement of space, the visibility of exits, the clarity of signage, and the overall spatial configuration can either guide or hinder wayfinding, impact decision-making, and affect the perceived level of safety [8, 71]. Studies have demonstrated that well-lit corridors, clear signage indicating exit routes, and open spaces that provide a sense of visibility and control can reduce anxiety, improve wayfinding, and facilitate more efficient evacuation [8, 13, 71]. These design features can create a sense of predictability and control within the environment, supporting occupants' ability to make rational decisions and follow established safety protocols. Conversely, poorly lit areas, confusing layouts, narrow corridors, obstructed exits, and limited visual access can exacerbate panic, lead to poor decision-making, and increase the risk of congestion, bottlenecks, and injury [10, 16].

Finally, the effectiveness of training programs and emergency preparedness measures is intrinsically linked to occupant behavior and human-building interaction. Research on evacuation drills, active shooter training, and other preparedness initiatives has highlighted the importance of considering human factors, individual differences, and social dynamics in developing and implementing effective training programs [20, 32]. Traditional "lockdown" drills, while intended to enhance safety, have been found to increase anxiety and stress among participants, particularly children, without necessarily improving their ability to respond effectively during an actual ASI [72]. Therefore, there is a growing need to develop training programs that are not only informative but also psychologically sensitive, incorporating strategies for stress management, empowering occupants with a sense of agency, and addressing the diverse needs of different populations, such as children, individuals with disabilities, and those with pre-existing mental health conditions [73, 74].

Simulation models can be invaluable tools for evaluating the impact of different training strategies on occupant behavior, identifying areas for improvement, and informing the design of more effective preparedness measures [32]. By simulating occupants' cognitive and emotional responses during ASIs, researchers can assess the effectiveness of different training scenarios, communication methods, and building design features in supporting a calm and coordinated response [75].

By recognizing and integrating the multifaceted nature of human behavior into building design and ASI preparedness strategies, we can move beyond a purely technological approach and create built environments that are truly safer and more resilient for occupants. By considering the impact of stress, social dynamics, and the interplay between occupants and their surroundings, we can design buildings that facilitate swift evacuation and empower occupants to respond effectively, mitigate panic, and ultimately, increase their chances of survival.

4. DISCUSSION: SYNTHESIZING INSIGHTS, BRIDGING GAPS, AND SHAPING FUTURE DIRECTIONS

This systematic review, by systematically examining the burgeoning body of research on building design strategies for mitigating ASI risks, offers valuable insights into the complex interplay between architectural design, security features, communication systems, and human behavior. It unveils a landscape of knowledge where technological advancements intersect with human vulnerabilities, requiring a nuanced understanding of how people perceive and respond to threats within the built environment. While the review highlights promising avenues for enhancing occupant safety through informed design, it also unveils critical knowledge gaps. It underscores the need for further research to address the multifaceted challenges of ASI preparedness.

4.1 Connecting the Threads: A Holistic Perspective on Design for Safety

Synthesizing findings across the thematic categories reveals a clear and undeniable interconnectedness between the various aspects of building design for ASI preparedness. Effective mitigation requires a holistic approach, recognizing that exit design, security features, communication systems, and occupant behavior are not isolated elements but intricately interwoven components of a comprehensive safety strategy. This interconnectedness demands that architects, engineers, security professionals, and policymakers collaborate to create built environments that are physically secure and support informed decision-making, rapid response, and psychological resilience during ASIs. The need for this integrated approach is further amplified by the inherent unpredictability of ASIs, requiring buildings to be adaptable and responsive to a range of potential scenarios.

For instance, optimizing exit design for ASI preparedness extends far beyond simply providing sufficient exits and adhering to building codes [76, 77]. It necessitates a deep understanding of how occupants, under the extreme stress of an ASI, will perceive their environment, navigate complex building layouts, and make decisions about evacuation routes. Simulation modeling, particularly using approaches like ABM and SFM, allows researchers to explore these dynamics, considering factors such as exit visibility, signage clarity, corridor width, bottleneck potential, and the psychological and social influences on occupant behavior [10, 11, 16]. Research has shown that strategic placement of exits, ensuring their visibility from multiple vantage points, providing clear and intuitive signage, and designing wide and well-lit escape routes can significantly reduce congestion and facilitate faster evacuation [13, 14, 30]. Moreover, exit design must be carefully integrated with security measures to ensure that locked doors, security checkpoints, or other access control systems do not create unintended bottlenecks, trap occupants, or hinder emergency responders from accessing the building [8, 35]. This integration requires a nuanced understanding of how security features might alter occupant movement patterns during an ASI, necessitating a collaborative approach between security professionals and building designers.

As highlighted throughout this review, communication systems play a vital role in supporting a coordinated and effective response to ASIs. Beyond their function in quickly alerting occupants to the threat, these systems can provide real-time information about the attacker's location, guide occupants towards safe exits or designated safe spaces, and facilitate communication between occupants and first responders [42, 43, 52]. However, implementing effective communication systems requires more than just installing technology; it demands careful consideration of message content, delivery methods, accessibility for diverse populations, and the social dynamics of information sharing during emergencies [49, 50, 57, 78].

For instance, research has shown that emergency messages' clarity, conciseness, and actionability significantly influence occupant behavior [48, 51]. Vague or ambiguous messages can lead to confusion, hesitation, and inappropriate actions, potentially putting occupants at greater risk. Moreover, messages should be tailored to the specific context, audience, and communication channels being used, considering factors like language, cultural norms, literacy levels, and the potential for misinformation to spread through social networks [49, 78].

4.2 Simulation Modeling: A Lens into Complex Interactions, But Not a Crystal Ball

Simulation modeling has emerged as a powerful tool for exploring the complex interplay of factors influencing occupant safety during ASIs. These models allow researchers to create virtual environments, incorporating diverse building designs, occupant characteristics, attacker behaviors, and emergency response strategies [22–24]. By manipulating these variables and running multiple simulations, researchers can gain valuable insights into how different design choices impact occupant outcomes, such as evacuation time, casualty rates, and the likelihood of survival [10, 23, 25]. This data-driven approach offers a unique lens into the complex dynamics of human movement, decision-making, and social interaction within the built environment, providing valuable information for evidence-based design.

However, while simulation modeling offers a powerful approach to exploring ASI preparedness, it's essential to acknowledge its inherent limitations and critically evaluate the validity of simulation findings. As with any model, simulations simplify reality, based on assumptions and generalizations about human behavior, environmental conditions, and the unpredictable nature of ASI events. Oversimplifying these complex factors or relying on inaccurate assumptions can lead to misleading predictions, potentially misinforming design decisions, and creating a false sense of security [79]. Therefore, researchers utilizing simulation modeling must be transparent about the limitations of their models, clearly articulate the assumptions made, and strive to validate their findings through empirical data, real-world observations, or expert input whenever possible [79].

For example, many existing simulation models excel at capturing the physical aspects of evacuation, such as pedestrian flow rates, density distributions, and congestion patterns. Approaches like the Social Force Model (SFM) and Cellular Automata (CA) have been successfully used to simulate crowd movement, identify bottlenecks, and evaluate the impact of different exit designs on evacuation time [30, 80, 81]. However, accurately representing the psychological and social dimensions of human behavior during

ASIs remains a significant challenge [79]. While some models incorporate basic behavioral rules, such as following the shortest path to an exit or avoiding collisions with others, these rules often fail to capture the nuances of human decision-making under extreme stress, social dynamics' influence, and communication's impact on occupant behavior.

Models that fail to adequately account for the impacts of stress, panic, fear, herd behavior, social influence, information-sharing patterns, and individual decision-making biases may produce inaccurate results, particularly in high-stress, chaotic scenarios [49]. For instance, research has shown that occupants under stress may exhibit "freezing" behavior, delaying their evacuation or hindering their ability to make rational decisions. Social contagion can lead to the rapid spread of misinformation or panic through a crowd, influencing exit choices and evacuation routes in unpredictable ways [49, 58]. These findings underscore the need for ongoing research to develop more sophisticated simulation models incorporating a richer understanding of human cognition, emotion, and social dynamics, drawing on insights from psychology, sociology, and human factors research [82].

Furthermore, validating simulation models by comparing their results with empirical data from real-world events or controlled experiments is crucial for ensuring the accuracy and reliability of these models [83, 84]. Field observations of evacuations post-incident analyses of ASI events, controlled evacuation drills, and virtual reality experiments can provide valuable data for calibrating model parameters, testing the predictive power of simulations, and identifying areas where model refinements are needed [32, 85]. By grounding simulation models in real-world data, researchers can enhance their credibility and improve their ability to inform effective building design strategies.

4.3 A Holistic Framework for Building Resilience

While specifically focused on the urgent issue of Active Shooter Incidents (ASIs), this systematic review underscores the crucial need to connect its findings to the broader principles and frameworks of safety science. By integrating concepts such as human factors, risk assessment, control measures, and safety culture, we can transcend a purely event-specific approach and foster the creation of built environments that are not only prepared for ASIs but also inherently safer and more resilient in the face of diverse threats. This holistic perspective acknowledges that safety is not merely about reacting to specific hazards but about proactively designing and managing a system that anticipates, mitigates, and responds to risks across a spectrum of scenarios.

Human Factors: Weaving Human Behavior into the Fabric of Design

Human factors engineering, a discipline dedicated to understanding and optimizing the interaction between people, systems, and their environment, provides a crucial lens for examining building design for ASI preparedness [86]. Recognizing that occupants are not simply passive recipients of design but active agents interacting with their surroundings is essential for creating effective safety strategies. This requires going beyond compliance with building codes and prescriptive measures, delving into the complexities of human perception, cognition, decision-making, physical capabilities, and social behavior [29, 87]. Moreover, designers must understand how these human factors are influenced by the acute stress, anxiety, and fear inherent in ASI situations, recognizing that occupants under duress may not always behave rationally or follow established protocols.

For instance, research has shown that during emergencies, individuals may experience tunnel vision, auditory exclusion, time distortion, and a decline in fine motor skills, impacting their ability to perceive critical information, process instructions, locate exits, or effectively implement learned safety protocols [29, 66, 67]. These stress-induced impairments underscore the need for exit design that is not only compliant with building codes but also intuitive and easily navigable under duress. Clear lines of sight, strategically placed and well-lit signage, and wide, unobstructed evacuation routes can significantly reduce confusion and facilitate faster, more orderly egress [8, 11, 71, 88, 89].

Similarly, integrating security features must be carefully balanced with considerations for usability, accessibility, and the potential psychological impact on occupants [8, 35]. While locked doors, security checkpoints, and surveillance systems can deter attackers and enhance physical security, they can also create a sense of confinement, amplify anxiety among occupants, or even deter individuals from reporting suspicious activity if they feel intimidated or overly monitored [90]. The challenge lies in creating a secure environment without fostering a culture of fear or compromising the building's functionality and aesthetic appeal. Simulation modeling, incorporating realistic representations of human behavior under stress, can be a valuable tool for evaluating the impact of security features on occupant behavior and identifying potential unintended consequences.

Risk Assessment: Informing Design with Data and Foresight

A fundamental principle of safety science is the need for a systematic and data-driven approach to risk assessment. In the context of ASIs, this involves a multi-faceted process of identifying potential threats, analyzing vulnerabilities within the built environment, and quantifying both the likelihood and potential consequences of different ASI scenarios. Risk assessment should extend beyond a simple checklist of potential hazards, considering the interplay of factors such as building type, occupancy patterns, the profile of potential attackers, local crime rates, the accessibility of firearms, and the existing security measures in place [4, 91, 92]. This comprehensive approach provides a more nuanced understanding of ASI risks, allowing for the prioritization of mitigation strategies, the effective allocation of resources, and the development of informed design decisions.

Simulation modeling can be a powerful tool for supporting risk assessment, enabling researchers to explore various ASI scenarios and test the effectiveness of different design choices in mitigating risk [91, 93]. By incorporating data on building occupancy, attacker profiles, weapon characteristics, and potential escape routes, simulations can estimate potential casualties, predict evacuation times, and identify areas of vulnerability within a building [23, 24]. However, using simulation models judiciously is crucial, recognizing their inherent limitations and ensuring that the assumptions made align with real-world conditions and the complexities of human behavior [79].

Moreover, integrating real-time data from building systems, such as occupancy sensors, access control systems, and surveillance technologies, can significantly enhance situational awareness and support dynamic risk management [23, 94]. By continuously monitoring factors such as occupant density, movement patterns, access control breaches, and environmental conditions, intelligent systems can detect emerging threats, identify anomalies, adjust security protocols in real-time, and provide occupants with more targeted and timely information during an ASI. This dynamic risk management approach allows buildings to adapt to changing conditions and respond more effectively to evolving threats.

Control Measures: A Work of Design, Technology, and Human Action

Safety science emphasizes implementing control measures to prevent, mitigate, and respond to hazards. In the context of ASIs, building design strategies can be viewed as a set of architectural control measures orchestrated to minimize risks and enhance occupant safety. These measures encompass diverse approaches, blending physical design elements, technological systems, and administrative protocols to create a multi-layered defense against active shooter threats. However, these control measures' effectiveness hinges on their thoughtful design, meticulous implementation, and seamless integration with other safety systems and emergency protocols.

- **Engineering Controls:** These controls involve physical environmental modifications to reduce risk. Examples abound within the scope of this review, showcasing how architectural design features can act as robust control measures. Strategically designing effective exit routes, incorporating security features like access control systems and bullet-resistant materials, and implementing intelligent communication systems that enhance situational awareness and guide evacuation are all examples of engineering controls with the potential to significantly improve occupant safety during ASIs [8, 10, 42].

- **Administrative Controls:** These controls focus on policies, procedures, and training programs to manage human behavior and promote a culture of preparedness. They address the crucial human element in safety, recognizing that technology and design alone are insufficient without a well-trained and informed occupant population. Developing comprehensive emergency response plans, conducting regular and psychologically sensitive drills, providing active shooter training that empowers occupants with a sense of agency, and establishing clear communication protocols are all examples of administrative controls that can significantly enhance ASI preparedness [32, 50].
- **Personal Protective Equipment (PPE):** While not typically considered within the realm of architectural design, PPE can play a role in specific high-risk settings or for designated occupant groups. Security personnel, for example, might be equipped with bulletproof vests or helmets to enhance their personal protection during an ASI. In certain contexts, such as schools or government buildings, providing designated areas with readily accessible PPE for occupants could be considered as part of a comprehensive safety strategy.

As illustrated throughout this review, the effectiveness of control measures depends on their individual merits and careful integration and coordination. For instance, access control systems, while valuable for delaying attacker entry, must be designed to avoid creating unintended bottlenecks during evacuation or hindering first responders' access. This requires close collaboration between security professionals and building designers, using simulation modeling and real-world data to test the functionality of access control systems under various ASI scenarios [8].

Similarly, surveillance systems should be strategically placed while enhancing situational awareness to maximize coverage of vulnerable areas while minimizing privacy concerns [95, 96]. Integrating surveillance data with real-time communication systems can enable more targeted and timely information dissemination to occupants, guiding them toward safety based on the evolving situation. As highlighted earlier, emergency notification systems are only as effective as the messages they convey. Clear, concise, and actionable instructions, delivered through multiple channels and tailored to the audience's specific needs, are essential for minimizing confusion, reducing panic, and promoting a swift and coordinated response [42, 49].

4.4 Cultivating a Safety Culture: Empowering Occupants and Fostering Resilience

A truly resilient built environment goes beyond design's physical and technological dimensions, encompassing a deeper understanding of human behavior, social dynamics, and the importance of cultivating a proactive safety culture. A safety culture, as defined by the International Atomic Energy Agency (IAEA), is "the assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance". This concept, readily applicable to ASI preparedness, emphasizes that safety is not merely a set of rules or procedures but a collective mindset, a shared responsibility, and a commitment to continuous improvement.

Cultivating a safety culture within a building or organization involves fostering a shared awareness of potential risks, empowering occupants to take ownership of their safety, and creating a climate of trust and communication. This requires a multi-faceted approach, encompassing:

- **Education and Training:** Regular training programs, such as active shooter drills, emergency preparedness workshops, and educational materials on safety protocols, can enhance occupant knowledge, build confidence in responding to ASIs, and mitigate the negative impacts of stress and panic [32, 50]. However, these programs must be designed with sensitivity to the psychological impact of ASIs, particularly on vulnerable populations like children or individuals with pre-existing mental health conditions [72, 97]. Utilizing simulation modeling and virtual reality technologies can create more immersive and engaging training experiences while allowing occupants to practice different response strategies in a safe environment [20, 75].
- **Clear Communication and Information Sharing:** Establishing open and transparent communication channels is vital for fostering trust and ensuring that occupants receive accurate

and timely information during an ASI [78]. This includes providing clear instructions, addressing concerns promptly, and actively countering misinformation or rumors that may spread through social networks [49, 57]. Building design can support effective communication by incorporating features like strategically placed digital displays, interactive maps, and communication hubs that provide access to real-time information [23, 55].

- **Empowerment and Shared Responsibility:** A strong safety culture empowers occupants to take ownership of their safety, recognizing that everyone has a role to play in preventing, mitigating, and responding to ASIs [98]. This can be achieved by encouraging occupants to report suspicious activity, participate in training programs, familiarize themselves with emergency procedures, and build evacuation routes. Building design can support empowerment by creating intuitive environments, providing clear lines of sight, and minimizing the sense of confinement or vulnerability [8, 13].
- **Continuous Improvement and Evaluation:** A safety culture is not static but continuously evolving, requiring ongoing assessment, feedback, and adaptation to ensure its effectiveness [99]. Regularly evaluating emergency plans, conducting post-incident analyses, and soliciting feedback from occupants can identify areas for improvement and inform the design of more effective safety strategies. Simulation modeling can play a valuable role in this process, allowing for testing new protocols, evaluating design modifications, and exploring different scenarios to identify potential vulnerabilities or areas for optimization [32].

By fostering a proactive safety culture, we can create built environments that are not only equipped to respond to ASIs but also cultivate a shared commitment to safety, empower occupants to act decisively and responsibly, and enhance the community's overall resilience in the face of this evolving threat.

5. CONCLUSIONS: SHAPING A FUTURE OF SAFER AND MORE RESILIENT BUILDINGS

This systematic review highlights the critical role of architectural design in mitigating active shooter incidents (ASIs) and enhancing occupant safety. By synthesizing findings from 75 studies, we have identified key strategies related to exit design, security features, communication systems, and human behavior modeling. Our analysis underscores the necessity of integrating these elements into a cohesive design approach that balances security, functionality, and occupant well-being.

A key takeaway from this review is that no single design intervention can fully eliminate the risks associated with ASIs. Instead, a multilayered approach—combining strategic spatial planning, access control, surveillance, and effective communication systems—offers the most robust defense. Additionally, simulation modeling has proven valuable in assessing design effectiveness, though future advancements must better incorporate real-world behavioral dynamics under stress.

While our review provides a comprehensive synthesis, several gaps remain. Future research should explore cost-effective security implementations, the psychological impact of security measures on occupants, and the development of adaptable design strategies for diverse building types. Furthermore, validating simulation models with empirical data will strengthen their predictive capabilities.

Ultimately, integrating evidence-based design principles with evolving technological solutions can help create safer, more resilient built environments. Addressing these challenges will require continued collaboration among architects, security professionals, policymakers, and researchers to ensure that safety remains a foundational consideration in building design and management.

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Appendix A: Comprehensive Version of Table 1 (Sorted by Year)

Author(s)	*Year*	*Study Design*	*Building Type*	*Occupant Population*	*Simulation Model (if applicable)*	*Key Findings*
Shih et al.	2000	Simulation Study (Virtual Reality)	Metro Station	Passengers	Virtual Reality Simulation	VR simulations revealed discrepancies between traditional evacuation calculations and actual occupant behavior; exit signage and layout significantly influenced evacuation time.
Purser & Bensilum	2001	Evacuation Experiments, Incident Investigations	Various Building Types	Occupants	N/A	Quantified pre-movement time during evacuations and provided strategies for applying behavioral data to design standards and escape time calculations.
Saloma et al.	2003	Empirical Study	N/A	Pedestrians	N/A	Investigated self-organized queuing and scale-free behavior in real escape panic, demonstrating the rapid spread of behavior patterns through a crowd.
Seeger et al.	2003	Textbook	N/A	N/A	N/A	Provided a comprehensive overview of communication and organizational crisis, emphasizing the importance of effective communication strategies, rumor management, and stakeholder engagement.
Mawson	2005	Literature Review	Various	N/A	N/A	Provided a comprehensive overview of mass panic and collective responses to threats and disasters, emphasizing the need to understand human behavior in emergencies.
Parisi & Dorso	2005	Simulation Study (Social Force Model)	Single Room with Exit	Pedestrians	Social Force Model (SFM)	Showcased the benefits of SFM for capturing contact forces and pedestrian parameters, finding that increasing exit size reduced the probability of blockages.
Pinizzotto, Davis, & Miller	2006	Qualitative Study (Interviews)	N/A	Police Officers	N/A	Investigated police officers' experiences during violent encounters, documenting physiological and psychological responses to stress and their impact on performance.
Moussaid et al.	2010	Experimental Study	N/A	Pedestrians	N/A	Demonstrated the impact of social groups on crowd dynamics, finding that groups can facilitate lane formation and improve flow in bidirectional streams.
Sattler et al.	2011	Experimental Study (Text & Email Messages)	University Campus	Students	N/A	Evaluated the effectiveness of text and email warning messages during simulated ASIs, finding them effective in providing clear instructions and promoting appropriate responses.
Lei, Li, & Gao	2013	Simulation Study (FDS + Evac)	Dormitory	Students	FDS + Evac	Corridor width of 3m and exit width of 2.5-3m were optimal for the dormitory; occupant density significantly influenced walking speed; evacuation time was not proportional to evacuation distance.
Stephens et al.	2013	Empirical Study	University Campus	Students	N/A	Examined the use of multiple channels for emergency communication during crises, emphasizing the need to combat noise and capture attention through diverse communication sources.
Zarrinmehr et al.	2013	Simulation Study (Agent-Based Modeling, Genetic Algorithm)	Building (General)	Pedestrians	Social Force Model (SFM), Genetic Algorithm	Optimized building layout to minimize danger during evacuations, demonstrating the potential of combining SFM with optimization techniques.
Jungert, Hallberg, & Wadströmer	2014	Short Communication	Critical Infrastructure	N/A	Surveillance System	Proposed a system design for surveillance systems protecting critical infrastructures, offering insights into principles of integration with emergency response.
Lang	2014	Case Study	University Campus	Students, Staff	N/A	Described a layered approach to emergency notifications and crisis response, emphasizing empowerment and a four-module training program for crisis coordinators.
Layne	2014	Practical Guidance (Book Chapter)	Cultural Properties	Visitors, Staff	N/A	Emphasized the importance of workplace violence prevention strategies, including access control, employee training, and collaboration with emergency responders.
Doss & Shepherd	2015	Literature Review, Practical Guidance (Book Chapter)	Commercial buildings	Employees	N/A	Multiple communication platforms, clear message content, accessibility for diverse populations, and pre-scripted messages are essential for effective communication during ASIs.
Jungert & Chang	2015	Research Article	Critical Infrastructure	N/A	Surveillance System	Described a surveillance system for incident handling using a situation-based Recommendations Handbook, providing insights into how surveillance data can inform decision-making during

						emergencies.
Zhou et al.	2015	Simulation Study	Hall	Pedestrians	Fuzzy Logic Model	Investigated pedestrian evacuation under the influence of attackers, using a fuzzy logic approach to model avoidance and escape behaviors.
Ahn, Kim, & Lee	2016	Simulation Study (Agent-Based Modeling)	Complex Shopping Center	Shoppers, Employees	Agent-Based Model (ABM)	Human conflict and spatial design significantly influenced evacuation time; wider exits near high-density areas improved evacuation efficiency.
Malekitabar, Ardeshir, & Stouffs	2016	Risk Analysis (BIM-Based)	Construction Sites	Construction Workers	Building Information Modeling (BIM)	Identified safety risk drivers detectable during the design phase, advocating for BIM-based risk assessment tools to prevent construction accidents.
Jones et al.	2017	Survey, Twitter Data Analysis	University Campus	Students	N/A	Conflicting information and reliance on social media for updates during a campus lockdown increased acute stress; highlighted the need for reliable, timely communication.
Kaji & Inohara	2017	Simulation Study (Cellular Automata)	Corridor	Pedestrians	Cellular Automata (CA)	Simulated pedestrian flow in a corridor, reproducing the velocity profile of Hagen-Poiseuille flow, demonstrating the applicability of CA for studying pedestrian dynamics in specific architectural settings.
Douma	2018	Discussion, Case Study	Public Spaces (general)	N/A	Automated Video Surveillance, Machine Learning	Highlighted the potential of using existing surveillance infrastructure and machine learning for real-time detection of emergencies and activating response.
Kellom & Nubani	2018	Simulation Study (Visibility Graph Analysis)	University classrooms	Faculty	Visibility Graph Analysis (VGA)	VGA measures predicted faculty preparedness levels and police response efficiency; visibility was crucial for both occupant safety and police response.
Kim & Han	2018	Simulation Study	Virtual Environment	Occupants	Active Route Choice Model	Developed an active route choice model for crowd evacuation, incorporating human characteristics and communication between occupants for realistic evacuation simulations.
Liu	2018	Simulation Study (Social Force Model)	Public Building (General)	Pedestrians	Social Force Model (SFM)	Dedicated exits for different pedestrian groups (e.g., those with mobility limitations) can improve evacuation efficiency, highlighting the need for inclusive design strategies.
Munn et al.	2018	Methodological Guidance	N/A	N/A	N/A	Provided guidance on choosing between systematic and scoping review approaches, emphasizing the importance of aligning the review methodology with the research question.
Payne et al.	2018	Interviews	Schools (K-12)	School Administrators, Crisis Teams	N/A	Identified communication challenges faced by schools during crises, emphasizing the need for media plans, relationship building with media outlets, and strategies for communicating reassurance and reunification.
Tordeux et al.	2018	Simulation Study	Urban Area	Pedestrians	Mesoscopic Model	Developed a mesoscopic pedestrian model for large-scale simulations, describing movement using aggregate density-flow relationships and capturing population heterogeneity and behavioral variability.
Trivedi & Rao	2018	Simulation Study (Agent-Based Modeling)	Building (General)	Occupants	Agent-Based Model (ABM)	Investigated the influence of door placement on evacuation efficiency, finding that doors located in the middle of walls rather than corners improved evacuation times.
Cho et al.	2019	Simulation Study (Agent-Based Modeling)	Indoor Building (general)	Occupants	Agent-Based Model (ABM)	Even low levels of real-time location tracking of the shooter can improve evacuation safety and reduce casualties.
Nissen et al.	2019	Longitudinal Study	Workplace	Employees	N/A	Employee perception of safety after a terrorist attack was influenced by security measures and evacuation procedures; highlighted the need for employer prioritization of security and clear communication.
Pilkington & Zhang	2019	Literature Review	N/A	N/A	N/A	Examined research trends and challenges in pedestrian and evacuation dynamics, emphasizing the need for data-driven models that incorporate social and behavioral factors.
Purpura	2019	Textbook	Various Buildings	N/A	N/A	Covered principles of life safety, fire protection, and emergency preparedness in various building contexts, emphasizing the need for a multi-faceted approach to safety.
Ronchi et al.	2019	Review Article	N/A	N/A	N/A	Examined the use of simulation modeling for evaluating evacuation

						performance in tunnel fires, highlighting the importance of model validation and the need for multi-model approaches to address uncertainties.
Zhu et al.	2019	Simulation Study (Virtual Reality)	Office Building	Occupants	Virtual Reality (VR)	Identified information requirements for virtual environments to study human-building interactions during ASIs, highlighting the potential of VR for research and training.
Arteaga & Park	2020	Simulation Study (Agent-Based Modeling)	School-like building	Students	Agent-Based Model (ABM)	Increasing hall and door widths improved evacuation efficiency and reduced casualties; narrower halls were more sensitive to higher occupant densities.
Gao, Medjdoub, & Sheng	2020	Simulation Study	Museums	Visitors	Constraint-Based Model, Branch and Bound Algorithm	Proposed a constraint-based design approach to optimize evacuation door positions for minimizing escape route length and evacuation time.
Gwynne, Amos, & Ronchi	2020	Review Article	Various Buildings	Occupants	N/A	Explored the limitations of traditional evacuation drills and proposed a framework for assessing and enhancing evacuee performance using emerging technologies, advocating for evidence-based approaches.
Li & Xu	2020	Simulation Study	Limited-Space Building	Pedestrians	Social Force Model (SFM)	Exit width of 1.1m optimized evacuation time and construction costs; inward-opening doors were more efficient than outward-opening doors.
Lu et al.	2020	Simulation Study (Agent-Based Modeling)	Public Square	Civilians, Attackers	Agent-Based Model (ABM)	More exits and diverse exit distributions reduced casualties during simulated terrorist attacks; highlighted the importance of public facility design for crowd management.
Moore-Petinak et al.	2020	Survey (National)	Schools (K-12)	Students	N/A	Active shooter drills were found to have negative impacts on student emotional health, raising concerns about their effectiveness and the need for less traumatic alternatives.
Schildkraut & Nickerson	2020	Review Article	Schools	Students, Staff	N/A	Examined the effects of lockdown drills and training on school emergency preparedness, emphasizing the need for clearly defined procedures and best practices.
Schonfeld et al.	2020	Policy Statement	Schools (K-12)	Children, Adolescents	N/A	Outlined considerations for involving children in live crisis drills, emphasizing the need to eliminate high-intensity drills, prohibit deception, and ensure appropriate accommodations.
Wang, Liu, & Wang	2020	Questionnaire Survey	Ro-Ro Passenger Ship	Passengers	Multinomial Logistic Regression	Analyzed passengers' likely behaviors during emergency evacuations, finding demographic differences in responses to alarms, instructions, and social influences.
Zhu et al.	2020	Qualitative Study (Focus Groups)	Various (schools, offices, hospitals)	Occupants	N/A	Security countermeasures must consider occupant behavior and trade-offs between security, cost, aesthetics, and daily operations; training and practice are crucial for effectiveness.
Bonaretti & Fischer-Preßler	2021	Survey, Analysis of SMS Warning Systems	University Campus	Students	N/A	SMS warnings often lack sufficient spatial awareness, hindering occupant comprehension and compliance; recommendations for improving message design provided.
Jin, Jiang, & Liu	2021	Empirical Experiment (Controlled Walking Trials)	Corridor	Pedestrians	N/A	Wider corridors improved pedestrian flow rates in both unidirectional and bidirectional movement; different corridor widths affected lane formation patterns.
Menn, Payne-Purvis, & Chaney	2021	Data Article (Survey Data)	University Campus	Students	N/A	Provided an open-access dataset on university emergency notification systems, including student perceptions and experiences, offering insights into communication effectiveness and areas for improvement.
NFPA	2021	Building Code	Various Buildings	N/A	N/A	Established life safety codes and standards for building design, including requirements for exits, fire protection, and emergency egress.
Omilion-Hodges & Edwards	2021	Experimental Study	University Campus	Students	N/A	Students acted as information responders during a simulated ASI, highlighting their role in crisis communication and the need for universities to engage with students as partners in emergency preparedness.
Rusho et al.	2021	Social Media Analysis (Twitter)	N/A	General Public	N/A	Analyzed social media responses to active shootings, revealing initial panic

						followed by informed public responses; demonstrated the evolving influence of social media on crisis communication.
Sadri, Ukkusuri, & Ahmed	2021	Review Article	N/A	N/A	N/A	Examined social influence in crisis communication and evacuation decision-making during extreme weather events, highlighting the role of social networks in information dissemination and behavioral influence.
Scott, Andersen, & Kobayashi	2021	Survey (Questionnaire)	Private University	Undergraduate Students	N/A	Explored student perceptions of safety and preparedness for ASIs, finding that participation in emergency preparedness activities increased awareness of susceptibility and preparedness and enhanced perceptions of safety.
Shi et al.	2021	Experimental Study, Model Validation	Controlled Environment	Pedestrians	Social Force Model (SFM)	Verified the applicability of SFM in simulating crowd egress at exits, highlighting limitations in reproducing emergency conditions and the need for further research.
Tang, Zhao, & Li	2021	Simulation Study	Passenger Terminal Building (Ro-Pax Terminal)	Passengers	Simulation Models (SM-PTO & SM-PE)	Developed a framework for evaluating evacuation performance in passenger terminals, simulating operation processes and passenger movement to identify bottlenecks and optimize design for emergency evacuation.
Zhuang et al.	2021	Simulation Study (Cellular Automata)	Public Space (General)	Pedestrians	Cellular Automata (CA)	Investigated self-organized queuing behavior at bottlenecks, finding that moderate orderliness can improve evacuation efficiency.
Fu et al.	2022	Controlled Experiment	Corridor	Pedestrians (incl. simulated disabilities)	N/A	Examined bidirectional flow with individuals simulating disabilities; helping behavior improved movement efficiency; congestion levels were higher at low densities compared to crowds without disabilities.
Saini, Kalra, & Sood	2022	Simulation Study	Smart Building	Occupants	IoT, Fog Computing, Cloud Computing	Developed an intelligent evacuation system using IoT, fog computing, and cloud services, demonstrating its efficiency in guiding occupants to safety during simulated emergencies.
Haghani	2023	Review Article	N/A	N/A	N/A	Differentiated crowd experiments based on purpose and critically assessed their validity; argued for a balance between controllability and realism in experiment design.
Jin et al.	2023	Simulation Study (Modified Social Force Model)	Ring Road, Straight Corridor	Pedestrians	Modified Social Force Model (SFM)	Addressed limitations of the traditional SFM in simulating bidirectional flow at high densities, successfully capturing lane formation even at high densities.
Lancel, Chapurlat, & Martin	2023	Behavioral Experiments, Computer Simulations	Supermarket	Shoppers	Agent-Based Model (ABM)	Active guidance (flashing lights at emergency exits) influenced exit choice during a simulated terrorist attack; demonstrated the impact of environmental cues on decision-making in emergencies.
Liu et al.	2023	Experimental Study	Office Building	Occupants	Virtual Reality (VR), Video	VR-based training improved response performance and perceived preparedness for ASIs compared to traditional video-based training; immersion and interactivity were key factors in VR training effectiveness.
Lu et al.	2023	Simulation Study (Agent-Based Modeling)	Bar	Civilians, Police, Attacker	Agent-Based Model (ABM)	Modeled ASI scenarios with police intervention, identifying optimal police force size and response times for minimizing civilian and police casualties.
Lyu, Wang, & Wang	2023	Evacuation Experiment, Model Validation	Large Underground Railway Station Plaza	Occupants	EVACNET 4, Composite Occupant Evacuation Model	Validated evacuation models using real-world data; direct access to outdoor exits significantly reduced evacuation time; highlighted the importance of accurate models for predicting evacuation performance.
Mirzaei-Zohan, Gheibi, & Behzadian	2023	Simulation Study (BIM-Based)	Multi-Story Commercial Building	Occupants	Revit, MassMotion	Different stair designs significantly impacted evacuation efficiency; two individual stairs per floor were optimal; identified key factors influencing evacuation performance (density, visibility, agent count).
Ray	2023	Review Article	N/A	N/A	N/A	Explored the background, applications, and limitations of ChatGPT, highlighting ethical concerns, data biases, and safety issues associated with AI technologies.
Templeton, Nash, & Spearpoint	2023	Qualitative Study (Focus Groups)	High-Rise Residential Buildings	Residents	N/A	Explored information sharing and support among residents during fire incidents, highlighting the influence of social dynamics, collective self-

						organization, and trust in peer information during evacuations.
Yakhou, Thompson, & Ronchi	2023	Framework Development, Prototype System	Various Buildings	N/A	Revit, Pathfinder (Evac4BIM)	Proposed a framework for integrating fire evacuation models into BIM, enabling comprehensive assessment of building designs and evacuation data; demonstrated the benefits of two-way data flow between BIM and evacuation tools.
Yang & Ding	2023	Experimental Study, Machine Learning Model	Classroom	Students	Random Forest, SHAP	Identified key factors influencing evacuation outcomes in classroom attacks, emphasizing distance from the attacker, preparation time, and seating position.
Barten, Janssen, & Mortelmans	2024	Cross-sectional Survey (Questionnaire)	Hospitals	Hospital Staff	N/A	Assessed threat awareness and counter-terrorism preparedness, highlighting potential vulnerabilities and security practices in healthcare settings.
Di & Gong	2024	Development of AI-Based Approach	School Buildings	N/A	AI, Point Cloud Data	Proposed an AI-powered method for creating spatial inventories of safety-related features, including access control points, to identify vulnerabilities and enhance response planning.
Hassanpour et al.	2024	Simulation Study (Agent-Based Modeling)	University building	Students, Faculty	Agent-Based Model (ABM)	Integrating earthquake damage assessment into evacuation simulations informed the design of safe spaces and architectural layouts for post-earthquake evacuation.
Lin & Zhou	2024	Simulation Study (Pathfinder)	Geriatric Hospital High-Rise	Elderly Patients, Staff	Pathfinder	Hierarchical crowd organization, vertical functional zoning, and congestion mitigation strategies reduced evacuation time; proposed an integrated evacuation strategy.
Menzemer, Vad Karsten, & Ronchi	2024	Survey, Semi-Structured Interviews	N/A	General Public	N/A	Investigated public perceptions and attitudes towards fire evacuation training, highlighting the importance of early-age education and the need for realistic and engaging training scenarios.