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REVIEW

Pedestrian collision and future work in the restricted indoor space: A state-of-the-art review on influencing factors, behaviors, and methods

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Emergency evacuation involves rapid transfer of individuals from hazardous areas, where limited time and space can lead to collisions. Although the collision behavior of evacuees has been studied previously, there is a lack of systematic summaries. This study used the CiteSpace visualization software to analyze keywords in the evacuation collision literature. Based on the frequency of keyword occurrence, we determined the research trend; classified the keywords; and analyzed and summarized their influencing factors, behavioral characteristics, and research methods. Clearly, the evacuation environment and emergency guidance directly affect individual behavior and emotions, mainly affecting gait adjustment and decision-making processes, which in turn determine evacuation efficiency and collision risk. In the future, emphasis should be placed on post-collision psychological activities, coping strategies, and the application of virtual and mixed reality technologies to observe the interaction between individuals and the environment and to strengthen evacuation research.

Keywords: public safety, building structure, evacuation environment, individual collision, avoidance

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1. Introduction

Collisions are inevitable during evacuations.[1] Individual collision behavior refers to instances where individuals collide, push, step on, or rush against each other in crowded evacuation scenarios because of space limitations, heightened crowd density, inadequate room for movement, and emergencies.[2] These collision behaviors can induce psychological stress[3–5] and crowd confusion,[6,7] and can lead to fatalities.[8] Examples include the Mount Meron festival crowd crush in Israel in May 2021, which resulted in at least 45 deaths and more than 150 injuries,[9] and the mass crowd crush in Seoul, South Korea in 2022, which led to as many as 158 deaths and 196 injuries.[10] Pedestrian behavior typically involves collective or individual efforts to maneuver around conflicting pedestrians to avoid colliding with others and to respond to signals and pedestrian boundaries. For instance, transit stations and congested public transportation stops often breed circumstances in which pedestrians make biased judgments about their surroundings in fast-paced situations, heightening collision risks.[11] At intersections, where pedestrian movement requires coordination, individuals typically adjust their pace and movement in response to traffic signals, pedestrian signals, and other regulations to avert collisions and enhance the overall evacuation safety.[12] Furthermore, pedestrians are generally mindful of environmental boundaries, such as buildings and guardrails,[13] adjust their walking paths to sidestep obstacles and prevent collisions.

Understanding individual collision behavior is crucial for maintaining safety in crowded environments and ensuring the effectiveness of emergency evacuations. First, research into individual collision behavior helps comprehend how people behave in overcrowded settings, which is attributed to the design of building interiors, including the placement of exits and layout of access routes. Second, insights into individual collision behavior are the foundation for developing evacuation strategies and safety measures. By understanding how people react in crowded situations, authorities can implement measures to facilitate quicker and more orderly evacuations, thereby reducing the likelihood of crowd crushes and minimizing the risk of injuries. Overall, investigating the behavioral aspects of individual collision behavior holds significance both in theory and practice, as it positively impacts public safety and survival by enabling the creation of environments and protocols that enhance evacuation efficiency and mitigate the potential dangers associated with crowded spaces during emergencies.

Over recent decades, researchers have extensively investigated the collision behavior of evacuating individuals using experiments and models to simulate crowd dynamics in various scenarios and evaluate the impact of dif-

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ferent factors on evacuation efficiency and collision risk. Initially, the focus was placed on factors within evacuation environments, such as crowd density,[14–21] exit and access configurations,[22–27] escape routes,[1,28–35] building structures,[21,36–42] and emergencies.[40,42–46] During this period, limited technology constrained researchers to case observations, accumulated experiences, and rudimentary computer modeling to some extent. However, advancements in computer technology have led to significant improvements in research methodologies. Mathematical modeling and computer simulations have emerged as crucial tools for studying the collision behavior of evacuating individuals, enabling researchers to simulate various scenarios and predict evacuation processes and collision risks with greater precision. Beyond macroscopic factors, researchers have begun delving into micro-level studies, including the psychological state,[3,4] cultural background,[47,48] and individual pedestrian characteristics such as age[49,50] and cognitive ability.[51,52] In recent years, the development of virtual technology has garnered attention, prompting researchers to adopt a "real and virtual" combination approach to study collision behavior. By integrating more accurate evacuation environments into the simulation process, participants experience an immersive setting, facilitating the exploration of pedestrian collision behavior.

A systematic review of previous studies is essential to enhance the clarity, validity, and feasibility of studying individual collision behavior during evacuations. This requires a more comprehensive review of research findings, identification of existing trends, and addressing any shortcomings.[53] Based on this, this paper aims to systematically summarize the factors influencing collision behavior from various aspects, such as individual, environment, and guidance, to analyze the behavioral characteristics of individual collision behavior in depth. At the same time, it provides a comprehensive review of the various approaches involved in the current study, including their strengths and weaknesses. In addition, we explore the actual impact of these factors on evacuation outcomes to provide a reference for evacuation planning and emergency management. Finally, through a comprehensive summary of the findings, we propose directions and challenges for future research, which will provide essential guidance and insights for further development of the field.

2. Literature analysis

This section explores the bibliometric methods concerning individual evacuation collision behavior. By amalgamating the literature and unveiling the distribution of keywords in existing studies, this section thoroughly comprehends the critical themes and research directions in the field, gaining a comprehensive understanding of the overall development and trends in individual evacuation collision research. Furthermore, this paper delves deeper into cutting-edge issues and future challenges within research on individual evacuation collision behavior, which provides a richer perspective for understanding and addressing this issue.

2.1. Methods and tools

In this study, we mainly used the visual science software CiteSpace[54] to study the distribution, structure, quantity, and relationship of the selected literature, as well as to visually display the research status, research hot spots, and development trends of the selected literature in the form of images and tables by mining keywords. In the search data of this study, literature data were obtained from the Web of Science Core Data Collection. The research topic selection was TS (Topic) = ("individual evacuation" OR "crowd evacuation" AND "evacuation collision" OR "evacuation conflict"). A total of 1127 document records were retrieved, in which the selected language was English. The document types were articles and review articles, and the period was set from 2003 to 2024. The research directions were engineering, physics, transportation, computer science, environmental science ecology, science technology, mathematics, social science, automation control systems, and behavioral science. The retrieved documents were exported in the form of "full record" and "plain text file" and then converted into an executable format for visualization using the "Data/Import/Export" function of CiteSpace.

2.2. Literature search results

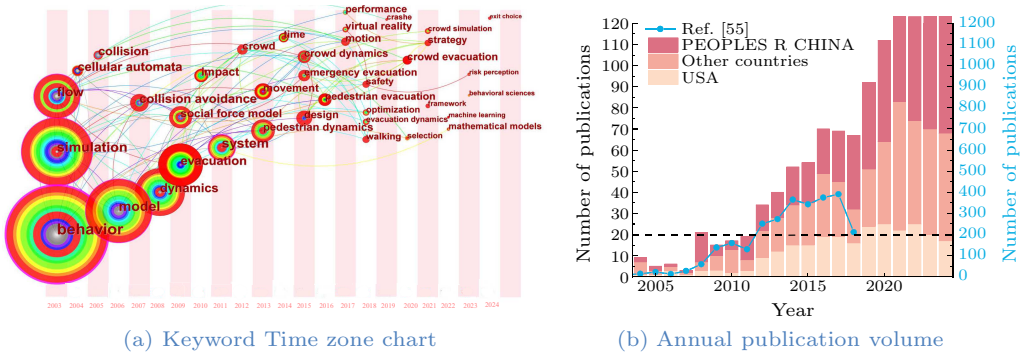
2.2.1. Evolution process

Figure 1 displays the annual publication volume and keyword time-zone chart of the literature in the field of evacuation and evacuation collision. Figure 1(a) shows the frequency of keywords in the research area over time. Each circle in the graph represents a keyword, and the horizontal axis (x-axis) represents the year in which each keyword first appeared in the analyzed literature set. If the keyword appears again in a later year, its frequency is superimposed on the position of the first appearance. The more times it appears, the higher the frequency, and the corresponding circle of the keyword also expands. The line connecting the keywords indicates their connection. If a certain keyword and a previous keyword appear together in the same article at a certain time, the line connecting the keywords indicates their coexistence in the same literature. As depicted in Fig. 1(a), "behavior" has always been a hot research topic, and research is mostly carried out through "simulation" and "model". In recent years, the focus has shifted to microscopic research on "strategy", "selection", and "evacuation dynamics".

Figure 1(b) shows the annual publication volume of literature in the field of evacuation and evacuation collision. The

left vertical axis in the figure represents the yearly publication volume of literature in the field of evacuation collision in China, the United States, and other regions. In contrast, the right vertical axis (blue axis) represents the annual publication volume of literature in the field of emergency evacuation, and these data are sourced from the research results of Liu *et al.*[55] By comparison, it can be found that the change in the annual publication volume of evacuation collision literature can be divided into two stages. In the first stage, before 2010, the publication volume of the literature on individual collision behavior during evacuation was relatively low, with an average annual publication rate of less than 20 articles. The second stage, after 2012, marked the peak of research on "collision behavior" during evacuation, as evidenced by an increasing number of publications in the literature. At this stage, the annual publication rate increased, accounting for over 10% of the yearly publication volume in the field of emergency evacuation literature. The black horizontal dashed line in the figure represents the proportion. Above the dashed line, this indicates that the proportion exceeds 10%. It is worth noting that the number of published studies has shown a downward trend in the past two years, which may be due to incomplete updates or retrieval biases in the literature database. Compared to other countries, China and the United States have conducted more extensive research in the field of individual collision evacuation. The change in this trend may be due to the continuous development of urbanization and the increase in population,[56] which has made large-scale gatherings increasingly common and has increased the potential risk of evacuation conflicts.[57]

Over time, research in this field has evolved to incorporate greater detail and complexity, enabling more accurate modeling and understanding of evacuation collision events.



(a) Keyword Time zone chart (b) Annual publication volume

Fig. 1. Keyword timezone chart of literature and annual publication volume in the field of evacuation and evacuation collision.

This can also be seen in Figs. 1(a) and 1(b) that, compared to the period before 2010, keywords such as "crowd dynamics" and "evacuation dynamics" emerged after 2010, which reflects a heightened focus among researchers on the role of group dynamics and collective behavior in evacuation collisions. The selection of research keywords has gradually shifted toward more specific domains, expanding the research focus from merely examining the evacuation process to encompassing crowd dynamics and the underlying dynamic laws and patterns of collective behavior. Remarkably, research on collision and avoidance indicates a growing emphasis on understanding the specific behaviors associated with evacuation collisions, and the shift may be driven by the recognition of the crucial role of collision events in actual evacuation scenarios, prompting researchers to urgently investigate the reasons behind such collisions and effective methods for their avoidance. Interestingly, although early research primarily focused on the macroscopic behavior of the evacuation process, there has been a shift toward examining the microscopic behavior of pedestrian collisions and evacuation processes over time. Moreover, researchers have delved into psychological activities, such as "choice" and "selection," signifying a transition toward more nuanced research to better understand individual and group behavior patterns in evacuation collision scenarios. In addition, based on the literature survey data, there appears to be a downward trend in the number of publications over the past two years, which could be attributed to incomplete updates of the literature database and search biases.

2.2.2. Analysis of research hot spots

Burst terms refer to keywords that appear frequently in articles published within a short period. Extracting and detecting burst terms can better understand the forefront of research in the field of individual collision evacuation, changes in research focus, and the latest research hot spots, and can help predict future development trends in this field.[55] After removing duplicates from the 1127 retrieved literature, the key keywords extracted using the CiteSpace software are shown in Table 1, where the top 30 keywords are presented with the highest frequency of occurrence in a short period in the literature data, where "year" represents the year when the corresponding keyword first appeared, and "strength" represents the burst intensity of a keyword, which is an indicator used to measure the frequency of a specific topic or keyword appearing over some time. This represents the activity level and sudden increasing trend of a topic during a certain period and can indirectly re-

flect its importance and attention in the research field. The higher the burst intensity, the greater the influence of the node is during that period. In Table 1, each year is represented by a hyphen "_", with a total of 22, representing the years 2003 to 2024, whereas the red horizontal line represents the period for maintaining the mutation, corresponding to the "begin" and "end" columns in the table. The longer the red horizontal line, the longer the duration of the popularity of the keyword and the stronger its research frontier. The dark blue horizontal line represents the year in which the keyword first appeared, and the light blue horizontal line indicates that the keyword has not yet appeared. The keyword with the highest frequency, as shown in Fig. 1(a), does not exhibit a higher burst intensity.

Table 1. Burst terms of keywords in the field of evacuation collision.

Keywords	Year	Strength	Begin	End	2003−2024
Numerical simulation	2005	2.38	2005	2009	
Group	2007	1.75	2007	2014	
Collective behavior	2008	1.61	2008	2014	
Simulation	2003	2.22	2012	2013	
System	2011	2.19	2013	2016	
Collective motion	2013	1.56	2013	2015	
Dynamics	2008	1.49	2013	2014	
Cellular automaton	2014	3.04	2014	2017	
Crowd dynamics	2015	4.14	2015	2018	
Pedestrian dynamics	2013	2.33	2015	2017	
Algorithm	2007	1.38	2015	2016	
Aggression	2016	1.42	2016	2019	
Motion	2017	3.78	2017	2022	
Movement	2013	2.33	2017	2018	
Safety	2018	4.15	2018	2020	
Collision risk	2012	2.15	2018	2019	
Walking	2018	1.4	2018	2019	
Crash	2019	2.2	2019	2020	
Design	2015	1.72	2019	2021	
Collision	2005	1.45	2019	2020	
Crowd	2012	2.61	2020	2022	
Crowd evacuation	2020	2.35	2020	2024	
Route choice	2020	2.1	2020	2021	
Selection	2020	1.6	2020	2021	
Collision avoidance	2007	5.27	2021	2022	
Strategy	2021	4.69	2021	2024	
Decision making	2010	1.54	2021	2022	
Tracking	2018	3.17	2022	2024	
Collective behavior	2010	1.4	2022	2024	
Virtual reality	2017	0.4	–	–	

As observed in Table 1, researchers have emphasized the keywords "collision avoidance" and "collective behavior", indicating that investigating obstacle avoidance behavior during evacuations is a primary research focus. Notably, from 2021 to 2024, attention substantially increased to the keyword "collision avoidance", making it a prominent research issue in evacuation scenarios. The attention garnered by "numerical simulation" since 2005 suggests its widespread application in simulating collision avoidance and related phenomena. Over time, researchers have sought more detailed and com-

prehensive modeling methods, such as "cellular automaton" and "algorithm", indicating a shift toward detailed and multilevel system modeling and behavioral simulation. This shift signifies the researchers' quest for a deeper understanding of the complex system behavior. Furthermore, "virtual reality" technology began gaining traction in individual evacuation and collision research in 2017. With ongoing technological advancements and widespread adoption, virtual technology is promising as a novel research method capable of enhancing and expanding existing research capabilities, thereby facilitating breakthroughs and advancements in future research and practice. The frequent occurrence of keywords such as "collision avoidance", "simulation", "decision making", "route choice", and "algorithm" suggests a recent focus on simulation and model-building methods. Regarding research content, there is a predominant emphasis on microlevel decision making and macrolevel individual behavior. Consequently, based on the emergence and impact of these keywords, it can be predicted that they will remain prominent in future research on individual evacuation and collision, with virtual technology likely retaining its status as a critical tool for advancing research in this field.

Based on the keyword analysis conducted using the CiteSpace software, we further classified all keywords into three categories: research factors, content, and methods, as detailed in Fig. 2. The analysis comprehensively explored the factors influencing pedestrian evacuation behavior, including individual, environmental, and guidance factors.

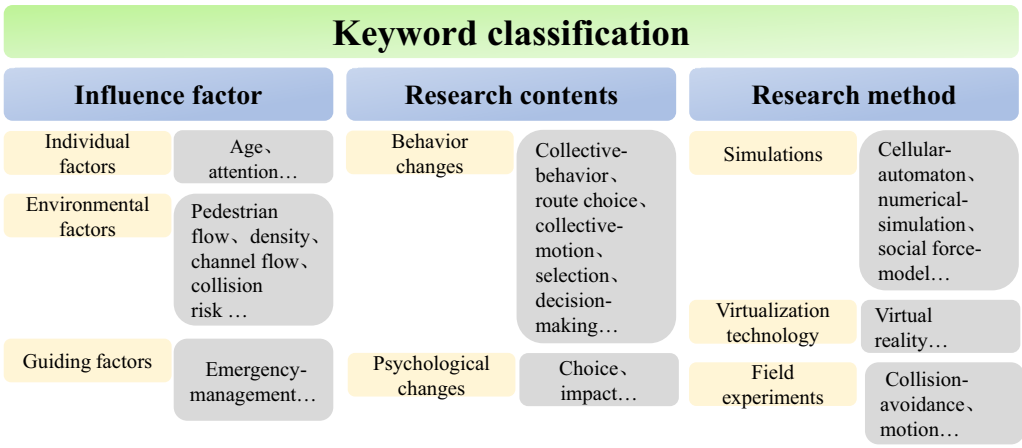


Fig. 2. Keyword classification in the field of evacuation and collision.

Among these factors, individual characteristics emerged as crucial considerations related to unique attributes, such as age[58–60] and attention,[61,62] which play pivotal roles in understanding individual athletic ability and decision-making processes. Investigating individual influencing factors facilitates a deeper understanding of individual behavior during evacuation collisions, which offers valuable insights for optimizing the evacuation process and enhancing individual safety. Additionally, environmental factors represent a significant component that influences the collision behavior of evacuated individuals. Research related to pedestrian flow,[4,63,64] density,[65,66] and channel flow[67,68] often involves actual evacuation site conditions, including environmental factors, such as crowd density, channel flow, and accident probability. Studying these environmental factors aids in better planning evacuation sites, designing more effective evacuation plans, enhancing site safety and adaptability, and reducing individual collision risk. Furthermore, the study of guiding factors offers a scientific basis for emergency management and provides more precise guidance for interventions and directions during evacuation. For instance, guidance factors within the emergency management[69–71] category directly influence the overall evacuation efficiency. Investigating the influencing factors enhances the understanding of macroscopic behavioral changes, such as pedestrian step length, speed, and acceleration, during evacuation collisions. This sheds light on microscopic behavioral changes in pedestrian psychology, including direction selection and decision-making processes.

Based on these influencing factors, researchers primarily focus on behavioral and psychological changes following individual collisions in terms of research content. These changes encompass aspects, such as collective behavior,[72,73] route choice,[68,74] decision making,[66,75–78] and impact.[79–81] This can be explained by the fact that in evacuation collision scenarios, individuals often face complex and urgent decisions that can significantly influence their behaviors and psychological states. Studying collective behavior aids in understanding how individuals affect and coordinate with each other during an evacuation. Studying route choice helps to understand the psychological change process of individuals, focusing on their decision-making processes when presented with different route options influenced by individual characteristics, perception cognition, and social factors. In addition, investigating decision-making processes unveils how individuals make

quick and effective decisions during emergencies, which also helps reveal how individuals suffer physical harm and psychological effects during an evacuation. Overall, studying behavioral and psychological changes post-collision enables the prediction of likely individual actions and facilitates the implementation of measures to reduce injuries. These measures include improving the visibility of emergency exits and providing more explicit escape guidance.

Among the research methods, cellular automaton,[64,82–85] numerical simulation,[86,87] and social force model[68,88–90] are frequently used as modeling and simulation techniques. These methods enable the simulation of evacuation behaviors across various scenarios, facilitating a deeper understanding of collision mechanisms. Virtual reality,[76,91] collision avoidance,[13,92], and motion[76,93] are methods for observing and studying the collision behavior of evacuated individuals through virtual technology and field experiments. These methods provide realistic and controllable experimental environments to simulate and observe individual behaviors more accurately and realistically, thus providing more intuitive and reliable data support for designing evacuation strategies and emergency management. The ongoing exploration of various experimental methods, such as simulations, virtual technology, and field experiments, holds the promise of obtaining richer and more realistic data, thereby advancing research on evacuation collision behavior to a more profound and comprehensive stage.

The comprehensive examination of keywords provides a broad perspective on the factors that influence the collision behavior of evacuated individuals (Section 2). Next, this study will further refine the discussion on individual, environmental, and guidance factors that influence evacuation collision behavior (Section 3). This section details the impact of these factors on individual behavioral characteristics in depth, mainly focusing on gait and decision making. At the same time, this study also explores the interaction of these factors that jointly determine pedestrian collision behavior and evacuation efficiency (Section 4). Finally, this study summarizes the commonly used research methods in this field and makes a more comprehensive and substantial contribution to the in-depth study of the collision behavior of evacuated individuals (Section 5). Ultimately, we attempt to provide scientific direction for future evacuation strategies and safety management. The framework of this study is illustrated in Fig. 3.

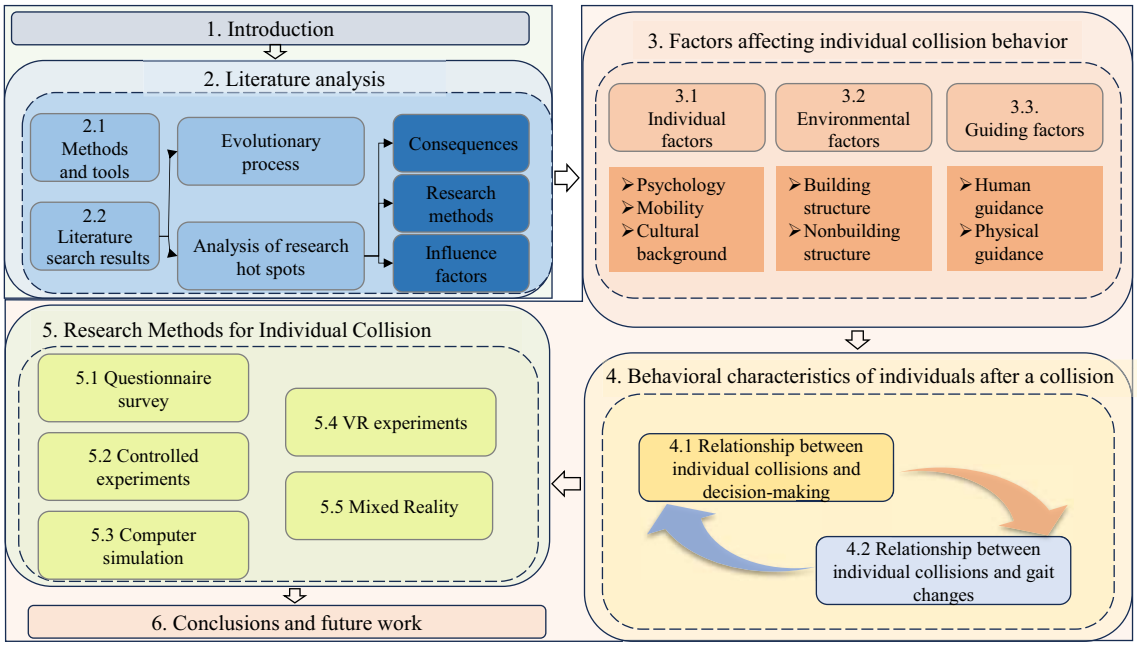


Fig. 3. Framework diagram of this study.

3. Factors affecting individual collision behavior

Over the past few decades, researchers have conducted extensive studies on the factors influencing individual collision behavior during evacuations to understand the characteristics of this behavior. Numerous studies have highlighted the close relationship between the occurrence of individual collision behavior and various factors, including crowd density,[83,94] exit conditions,[40] and individual behavioral characteristics.[29,95–97] It has also been pointed out that individual behavior is often influenced by multiple factors, encompassing cognitive traits,[51,52] emotional responses,[48] social relationships,[98] environmental conditions,[39,99] and information dissemination.[33,100–102] In this work, we will conduct a profound study on the mechanisms that govern evacuation collision behavior concerning individual, environmental, and guidance factors. Figure 4 illustrates the framework of this chapter, where individual factors constitute internal fac-

tors encompassing factors and characteristics related to the individual, such as psychological state, cultural background, and physical capabilities. On the other hand, environmental and guidance factors are extrinsic factors representing the characteristics of the evacuation environment itself, including environmental conditions, access conditions, and the presence of guidance. Understanding the mechanisms behind the roles of these factors facilitates the design of more effective evacuation plans, improves building design, enhances public awareness of evacuation procedures, and reduces collision risk.

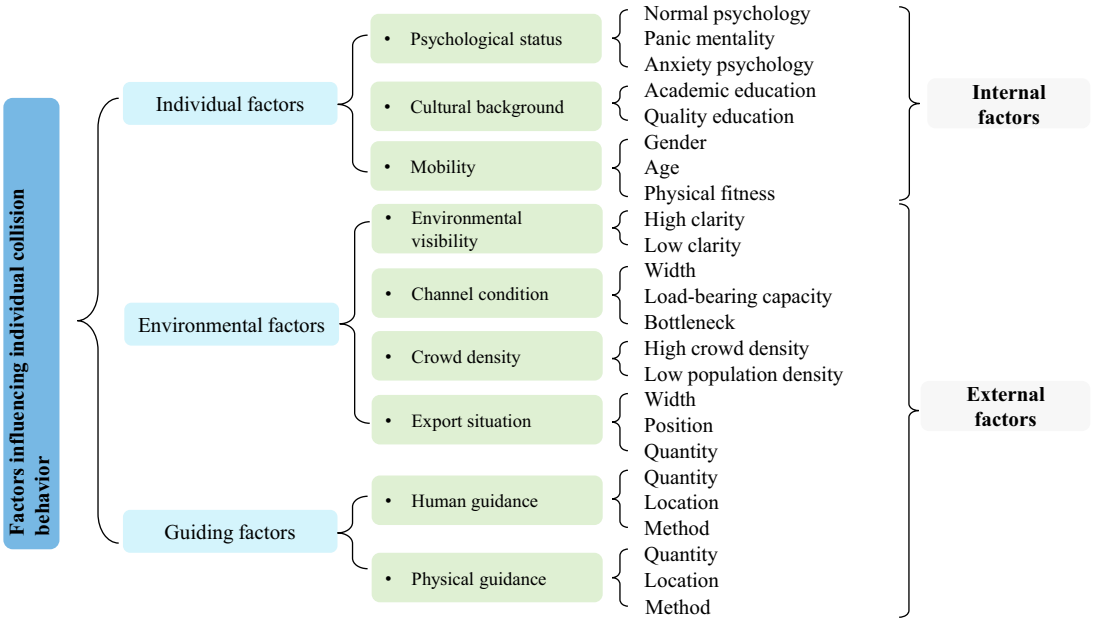


Fig. 4. Hierarchy diagram of factors affecting evacuation collision.

3.1. Individual factors

Among the individual influences, researchers have placed significant focus on psychological state,[3,4,103] individual mobility,[48,59,82,104–107] and cultural background.[47,48] An individual's psychological state is an essential factor affecting their behavior during an emergency evacuation. Research has shown that emotional fluctuations, such as anxiety, fear, and anger, are often amplified in crowded environments, which may lead to impulsive behaviors, such as running away and pushing, thereby increasing the risk of collisions and chaos.[108] Sudden events, such as violent attacks, emotional fluctuations, and panic reactions, significantly affect an individual's decision-making efficiency and speed of action. For example, in a violent attack scenario, factors such as panic coefficient, crowd structure, group proportion, and the location and number of attackers can significantly impact evacuation. Research has found that excessive panic prolongs evacuation time and exacerbates human casualties.[109] However, when individuals are in a relatively calm psychological state and have specific decision-making abilities, they are more inclined to adopt rational behavior, reduce conflicts with others, and optimize evacuation routes.[110] Some studies suggest that moderate "panic" reactions can accelerate crowd movement and help alleviate tension, but excessive panic often backfires, leading to delayed action and reduced evacuation efficiency. Therefore, effective management of the psychological state is crucial in emergencies. In addition, the nature and environmental characteristics of emergencies can significantly affect the emotional responses of individuals. For example, factors such as the significance of threats, effective guidance measures, and site structure can directly affect an individual's assessment of the surrounding environment, thereby influencing their emotional fluctuations and coping strategies.[103,111]

An individual's ability to act includes physiological health, physical fitness, and skills required to perform actions.[112] This directly affects their ability to respond to emergencies, making it an essential factor in determining an individual's ability to act. People with poor physical health or limited mobility often have difficulty moving quickly during emergencies, and their ability to adapt and respond to emergencies is weaker, making them more susceptible to collision risks in crowded environments during evacuation.[50] Special attention should also be paid to the mobility of special groups, such as older people, children, and wheelchair users, during evacuation. Owing to physiological decline, older adults may face more challenges during evacuation, especially in environments with higher floors or narrow spaces where evacuation speeds are slower and collisions are more likely to occur.[50,113] By contrast, young people are usually more flexible and able to react more quickly and avoid obstacles, reducing the risk of collisions with others.[114,115] Wheelchair users face particularly prominent challenges in densely pop-

ulated areas. Song *et al*. showed that as the proportion of wheelchair users increases, the overall mobility efficiency of the group significantly decreases, traffic congestion intensifies, and the evacuation time of wheelchair users prolongs, resulting in a decrease in evacuation efficiency,[116] which indicates that people with limited mobility may require more time and effort to complete evacuation and need additional support and guidance during the evacuation process to ensure they can safely and quickly evacuate during emergencies.

Differences in cultural backgrounds affect people's perceptions and responses to emergencies and their environments. In emergencies, the social environment, values, traditional habits, cultural background, and social experience in which individuals exist can profoundly influence their psychological state and behavioral choices.[117] Individuals often exhibit different behavioral patterns when faced with unexpected events in various cultural environments. For example, individuals prioritize safety in cultures that emphasize individualism and self-protection. They are more inclined to take independent actions, which may increase the risk of competing with others for resources.[118] In a culture that emphasizes collaboration and collective action, individuals are more concerned about the overall safety and well-being of the group and tend to work together to address risks and challenges through collaborative cooperation.[119,120] This response to differences reflects the profound influence of core cultural values and behavioral norms, including key factors, such as competition and cooperation and individualism and collectivism. These cultural differences not only affect the behavioral decisions of individuals during evacuation but also play an essential role in the overall response patterns of the group. In addition, knowledge and emotion also play a crucial role in emergency

Table 2. Analysis of individual influencing factors.

Factors	Contents	Related work	Method	Scenario	Findings
psychological condition	negative emotions such as psychological stress and anxiety	[122]	questionnaire survey	–	The impact of psychological factors on evacuation collisions is mainly reflected in psychological stress emotions and conflict costs. Moderate psychological stress can improve evacuation efficiency to a certain extent, while excessive psychological stress and high conflict costs can prolong evacuation time.
		[4]	simulation	building	
		[112]	simulation	public place	
		[43]	–	–	
mobility	health condition	[50]	simulation	building	Individuals with healthy physical conditions or strong physical fitness can take more effective measures. Often possessing good mobility, flexibility, and coordination skills, they can act more easily in emergencies, which is beneficial for avoiding collisions with others during evacuation. On the contrary, vulnerable groups such as children are unable to cope well with emergencies, which overall reduces evacuation efficiency.
		[116]	field experiments	funnel-shaped corridor	
		[49]	field experiments	long channel	
		[113]	virtual experiment	hospital	
		[50]	simulation	building	
		[49]	field experiments	long channel	
	physical power	[114]	simulation	public place	
		[112]	simulation	public place	
		[43]	–	–	
		[115]	field experiments	–	

Table 2. Continued.

Factors	Contents	Related work	Method	Scenario	Findings
cultural background	specific awareness, personal habits, and knowledge of hazards	[17]	simulation	rectangular room	Individuals with a sense of etiquette are more inclined to follow evacuation rules. Their good communication and cooperation skills can promote efficient information transmission and coordination, making the evacuation process smoother and more orderly and reducing conflicts in path selection. People who tend towards collectivism value teamwork, and moderate collaboration can improve evacuation efficiency. Still, excessive partnership may lead to crowds needing to be more concentrated, increasing the risk of crowding and collisions. In addition, knowledge and emotion also play essential roles in the evacuation process, with expertise influencing an individual′s direction of movement and emotion determining their speed. The combined effect of these two factors affects the efficiency and safety of evacuation.
		[121]	simulation	rectangular room	
		[118]	field experiments	school building	
		[119]	survey	–	
		[114]	simulation	–	

evacuation. Knowledge determines the direction of an individual's movement, whereas emotion directly affects movement speed.[121] Therefore, a deep understanding of the influence of cultural background on behavioral patterns is crucial for optimizing group behavior and improving evacuation efficiency and safety. This understanding helps to develop evacuation strategies that align with the population's characteristics and provides essential support for enhancing the scientific and practical nature of emergency management.

To better understand the individual factors influencing collision risk during emergencies, this section systematically reviews and synthesizes relevant research findings, presenting them in an apparent reference framework, as outlined in Table 2.

3.2. Environmental factors

Environmental factors play a pivotal role in shaping the behavior and decision making of individuals during emergency evacuations, significantly influencing safety and evacuation efficiency. Among various environmental considerations, the structure of passageways,[41,68] configuration of exits,[40,110,123] environmental visibility,[124] and crowd density[65,125–127] emerge as primary determinants affecting evacuation dynamics and collision risks. This section scrutinizes these four subfactors and elucidates their influence on the collision behavior and decision making of individuals in emergency evacuation scenarios.

The accessibility of evacuation routes encompasses various factors, including the distribution of boundary conditions and obstacles, such as the width, length, bottlenecks, and geometric features of evacuation paths.[22,94,128] Bottlenecks, which primarily involve their number and location, significantly impact the mobility of individuals and risk of collisions during evacuation. For instance, narrow and congested corridors hinder swift movements, resulting in congestion and potential collisions. In an experiment conducted by Helbing *et al.*,[128] the models simulated corridors, bottlenecks, and intersections to observe the effects of different passageway configurations on pedestrian flow. The findings revealed that geometric boundary conditions affect the capacity of pedestrian facilities and influence the distribution of pedestrian time intervals. Similarly, Chen *et al.*[21] explored the impact of corridor width and the number of aisles on evacuation time, demonstrating that reducing the number of aisles increased the evacuation time, whereas increasing the number of aisles in classrooms reduced the occurrence of collisions. Furthermore, Liu

et al.[94] found that individuals avoid collisions with pedestrians moving in the opposite direction and "follow" pedestrians moving in the same direction. Shahhoseini *et al.*[20] investigated the efficiency of crowd movement in channels with varying geometric features, highlighting that symmetric geometric features promote smoother crowd flow with a lower probability of collision and conflict compared to asymmetric features. Moreover, the smoothness of crowd mobility in channel situations influences an individual's ability to choose efficient movement paths and avoid collisions. Helbing[128] proposed that strategically placing "obstacles" can stabilize crowd flow patterns and enhance mobility, especially in narrow or crowded passages. When obstacles are kept at 1.0 m or 1.2 m from exits, they can reduce exit conflicts and improve the movement order of people near exits.[129] However, restricted movements caused by limited, crowded, or obstructed passages may lead to anxiety, psychological stress, and movement obstruction among evacuees.[5,22,128] Therefore, optimizing the design and conditions of evacuation routes is crucial for facilitating efficient evacuation and reducing the risk of collision during emergencies.

In emergency evacuation scenarios, the effective identification and accessibility of exits are crucial for ensuring personal safety when leaving hazardous areas. However, insufficient or unclear exit locations can easily lead to congestion and delays, thereby increasing the risk of collisions. The effectiveness and safety of evacuation largely depend on the number, location, and size of exits, and increasing the number of exits has been proven to be an effective means of reducing the evacuation time.[124] Wang *et al.*[123] explored pedestrian exit selection mechanisms using a game model and analyzed how exit arrangement, width, and decision firmness impact evacuation performance. Their findings underscored the significance of exit distance, suggesting that a limited field of vision and environmental cues may cause pedestrians to hesitate between exits, thereby increasing wandering time and congestion risks. Heliövaara *et al.*[130] investigated evacuee exit choices at various distances, highlighting the influence of cooperative and competitive behaviors on evacuation efficiency. Notably, they found that the "fast is slow" effect is more pronounced in competitive scenarios. Mehmood *et al.*[52] used an agent model to study the behavior of college students post-fire and observed high crowd densities at certain exits leading to congestion. Crowds exceeding 3.8 p/m were prone to congestion, which can put pedestrians under high psychological stress and further increase the likelihood of crowd crush incidents. Hu *et al.*[131] verified through experiments that in complex building scenarios, volunteers who have a clear understanding of the exit location make more decisive decisions and act more quickly during the evacuation process. These experiments underscore the importance of meticulously planning exit strategies to ensure adequate exit resources and optimal design, facilitating swift and orderly evacuation to minimize injuries and losses. Moreover, factors, such as the field of vision visibility, temperature, and presence of toxic gases, must be considered in exit planning to enhance evacuation effectiveness and safety.

Environmental visibility refers to the degree to which individuals perceive their surroundings. Reduced visibility, often caused by factors, such as smoke or poor lighting, impedes an individual's ability to locate exits and navigate effectively, potentially increasing the risk of collision.[132] For instance, under indoor lighting conditions, changes in the field of view impact the movement speed of evacuees on level ground. However, in the presence of adverse factors, such as smoke, alterations in the field of view significantly affect the distance traveled and evacuation speed. Berard *et al.*[49] demonstrated that lighting conditions influence the strategies of individuals for adapting their avoidance behavior; for example, children tend to slow down, shorten their step length, and widen their steps in low-light environments, indicating a more cautious approach based on environmental conditions. Galea *et al.*[99] used simulation tools, such as air EXODUS, and have underscored the critical role of environmental visibility in ensuring conflict-free evacuation, accurate navigation, and efficient egress, particularly in structurally complex environments, such as passenger cabins. Furthermore, extreme temperatures and exposure to toxic gases can significantly impact the effectiveness of evacuation. Psychologically, discomfort caused by temperatures beyond the comfort range can impair mobility and induce negative emotions, such as irritability and anxiety.[133] Behaviorally, elevated concentrations of toxic gases can lead to physiological distress, including shortness of breath and dizziness, hampering mobility and increasing the risk of injury.[134] These factors may complicate and delay evacuation decisions, thereby increasing the risk of collision. In addition, experimental studies have shown that under invisible conditions, pedestrians tend to walk along walls and form clustered distributions because of the cautious strategies that individuals adopt when searching for environmental information.[135] Under no visibility, it was observed that pedestrians are more inclined to choose the left movement and exhibit the following behavior, whereas conflict resolution strategies become more complex. Compared with everyday visibility, the speed of blind evacuation significantly decreases, the evacuation time is significantly prolonged, and the distribution of time intervals between individuals shows a power-law relationship.[124] Therefore, considering these factors in evacuation planning is crucial for promoting efficient and safe evacuation in emergencies, ensuring that crowds can effectively pass through, and minimizing collision risks.

Crowd density refers to the concentration of individu-

als within a specific area relative to its spatial capacity.[136] When the number of people exceeds the standard capacity of the area, it increases the likelihood of crowding and collisions during evacuation. Several researchers have investigated this phenomenon through simulations and empirical research methods. Niu *et al.*[17] observed the dynamics of cooperation and conflict strategies during evacuations. They noted variations influenced by psychological stress levels, initial cooperative proportions, and pedestrian flow density within a dynamic network of game relationships. Do *et al.*[14] found that average walking speeds increase in crowds with densities ranging from 0.4 p/m^2 to 0.8 p/m^2, whereas collision probabilities rise with higher crowd densities. Similarly, Zhang *et al.*[137] observed that in low-density crowds where pedestrians have

Table 3. Studies of collision related to environmental factors.

Factors	Contents	Related work	Method	Scenario	Findings
channel condition	channel size	[22]	field experiments	walking channel	Appropriate bottleneck width and obstacles can help pedestrians form a stable dynamic layer and improve evacuation efficiency. The collision avoidance behavior and competitive behavior at bottlenecks have different impacts on evacuation time. More collision avoidance behavior prolongs evacuation time, while competitive behavior slightly shortens evacuation time.
		[94]	field experiments	walking channel	
		[128]	field experiments,	corridor	
		[21]	simulation (CA model)	classroom	
	bottleneck, geometric features	[20]	field experiments	corridor	
		[49]	survey, field experiments	corridor	
exit condition	exit layout	[123]	simulation (CA model)	rectangular room	The location, quantity, and pedestrian flow density of exits not only affect pedestrians′ subjective judgments of exit choices but also affect the "competition" and "cooperation" relationships between pedestrians and others.
		[130]	field experiments	walking channel	
		[21]	simulation (CA model)	classroom	
	number of exits	[52]	questionnaire survey, Simulation	cafeteria of a university	
		[99]	field experiments, simulation	BWB cabin	
		[134]	simulation	cabin	
		[137]	simulation	rectangular room	
environment condition	environmental visibility	[99]	field experiments, simulation	BWB cabin	Decreased environmental visibility weakens an individual′s position recognition ability, leading to movement speed and gait changes. Still, when visibility deteriorates beyond the tolerance threshold, an individual′s decision-making and action abilities decrease, psychological pressure increases, and collision risk is further exacerbated.
		[135]	field experiments	rectangular room	
		[124]	simulation	square	
		[49]	survey, field experiments	corridor	
	toxic and harmful gases and their concentrations	[133]	questionnaire survey, simulation	a chemical park	
		[134]	simulation	cabin	

Table 3. Continued.

Factors	Contents	Related work	Method	Scenario	Findings
crowd density	–	[94]	data survey	–	The density of pedestrian flow within the evacuation area significantly affects the collision behavior during the evacuation process and further affects the "cooperation" and "game" strategies. Appropriate pedestrian flow density can help pedestrians maintain a certain order and improve evacuation efficiency.
		[17]	simulation	rectangular room	
		[14]	data survey	train stations	
		[94]	field experiments	walking channel	
		[123]	simulation (CA model)	rectangular room	
		[137]	simulation	rectangular room	

sufficient space, individuals in uniform flows tend to avoid those in the front while maintaining a certain distance. From these studies, it is evident that crowd distribution should be carefully managed, particularly in potential evacuation corridors, to minimize collision risk. When crafting emergency evacuation plans, attention must be given to crowd psychology and corridor capacities to ensure efficient evacuation, even in high-density scenarios. A comprehensive understanding of crowd density and distribution is a valuable reference for decision-makers, aiding in effectively managing crowd flow during emergencies, reducing collision risks, and safeguarding an individual's safety.

Table 3 presents a synthesis of the studies conducted by researchers exploring the impact of various environmental factors on evacuation collisions. These findings underscore the significance of factors, such as exit width, environmental visibility, exit layout, number of aisles, bottleneck width, and crowd density, in shaping the evacuation efficiency and safety. Typically, narrower exit widths and environments with limited visibility are associated with reduced evacuation safety, whereas moderately improved evacuation efficiency can be achieved through more efficient utilization of exits. Imbalances in exit layouts and inadequate passage numbers may prolong evacuation times and increase collision risk. Furthermore, reduced bottleneck widths often coincide with heightened collision probabilities. These insights offer crucial references and guidance for optimizing building designs, refining evacuation plans, and enhancing emergency management strategies. By considering these environmental factors, decision-makers can better anticipate and mitigate collision risks during evacuations, ultimately ensuring the safety and well-being of individuals in emergency scenarios.

3.3. Guiding factors

Signage and appropriate guidance methods can effectively reduce confusion during evacuation and minimize the risk of collision. Proper signage, including its placement, quantity, and status (static or dynamic), plays a crucial role in enhancing the efficiency and safety of individual evacuations during emergencies. They offer unambiguous directions to individuals by marking safe exits, emergency routes, and escape paths, thus reducing psychological stress and helping evacuees swiftly navigate toward safety. In other words, clear signage helps prevent disorientation, which steers individuals away from incorrect routes and reduces the likelihood of collisions. Furthermore, physical guidance, such as signs and broadcasts, is instrumental in providing clear instructions, whereas human guidance offers added flexibility. Human guides can communicate directly with evacuees through speech and gestures, offering immediate and detailed information and helping to alleviate psychological stress. Table 4 summarizes the studies into various guidance methods for crowd evacuation. These studies shed light on the efficacy of different approaches, aiding in the development of more effective evacuation strategies.

Studies on the characteristics and placement of guidance signs for evacuation have highlighted their critical role in improving the efficiency and safety of emergency evacuations.[138] Ramírez *et al.*[139] developed various evacuation icons tailored to different emergency contexts, emphasizing the importance of clear signage. Shi *et al.*[32] conducted an experimental validation demonstrating that guidance signs significantly enhance building evacuation efficiency. On this basis, they also investigated the impact of sign color, pattern, and status on route selection. Ding *et al.*[6] expanded this inquiry to include sign placement considerations alongside color, pattern, and status, reaffirming the pivotal role of evacuation signage in reducing psychological stress, confusion, and collisions during evacuations. Zhang *et al.*[7] found that disorientation can exacerbate confusion during simulations, underscoring the critical role of signs in guiding individuals, particularly those who may be lost, toward emergency exits. Yuan *et al.*[140] classified emergency signs into wall signs (WS) and ground signs (GS) using a social force model to analyze their impact on evacuation dynamics. Their findings emphasized

Table 4. Studies related to guiding factors.

Factors	Contents	Related work	Method	Scenario	Findings
guidance status and location	color of signs status of signs position of signs graphic of signs	[32]	field experiments	university building	Appropriate guidance instructions can provide clear guidance for pedestrians, help them quickly find exits, and reduce the probability of pedestrians getting confused and causing collisions in psychological stress.
		[141]	field experiments, questionnaire survey	university building	
		[6]	field experiments	university building	
number of guides	–	[7]	simulation	public space	When setting the distribution of guidance signals, the influence range of guidance information should be fully considered, and the number and density of guidance should be balanced when determining the number of guidance to provide clear guidance. Reasonable guidance quantity can help individuals make wise decisions in emergencies, reduce congestion and collision risks, and avoid secondary accidents such as crowd crush.
		[144]	simulation	rectangular room	
		[141]	field experiments, questionnaire survey	university building	
		[142]	simulation	rectangular room	
		[140]	simulation	rectangular room	
guidance method	leading signal	[148]	Field experiments	subway train	The static guidance method is mainly used to transmit information, while the dynamic guidance method can adjust strategies in real time according to emergencies. In emergencies, the selection of guidance methods should consider the characteristics of the emergency, as well as the perception and behavioral characteristics of pedestrians, to provide more specific guidance.
	the effect of different modes of voice guidance on evacuation efficiency	[149]	field experiments	university building	
	strategy of guides	[147]	simulation	recta ngular room	
	different sound signals	[150]	field experiments	rectangular room	

that correctly positioned wayfinding signage is essential for directing individuals and reducing the risk of collisions. Song *et al.* found that high-level markers positively impact the path selection of individuals, especially in cases where they tend to have longer decision-making times when they do not rely on markers. Therefore, high-level markers can help improve pop-

ulation mobility and effectively reduce procrastination behavior caused by social influence in group decision making.[141] This study further verified the impact of markers at different positions on individual psychological stress and behavior.

Optimizing the quantity of guidance elements is paramount in building design and safety planning, particularly concerning the deployment of guide signs and individuals along evacuation routes. A reasonable number of guides can significantly reduce collision risk by offering clear directions and aiding individuals in making informed decisions during emergencies. In a study by Tang *et al.*,[142] the distribution of the number of guides influenced the overall evacuation efficiency. The researchers observed behaviors, such as crowding and blocking, during evacuations by conducting comparison experiments involving double-exit and triple-exit scenarios, with and without guides. Zhao *et al.*[143] investigated the impact of the number of guides and their range of influence on successful evacuations at each exit. They concluded that a reasonable arrangement of guides can help evacuees swiftly identify evacuation goals, reduce wandering behaviors, and regulate evacuation density, thus enhancing the overall efficiency. Building on this research, Tang *et al.*[142] conducted a study using the AnyLogic simulation platform, comparing guided and unguided evacuation scenarios. They found that the absence of guidance often resulted in secondary accidents, such as a crowd crush, leading to prolonged evacuation times and decreased efficiency. When determining the appropriate number of guides, balancing effectiveness and minimal disruption is crucial. For instance, areas with high population densities may require more guides to efficiently manage increased flows. In addition, Ma *et al.* demonstrated through experiments that even under limited visibility conditions, a few evacuation leaders can effectively guide large-scale crowds,[144] indicating that the proportion of evacuation leaders should be adjusted according to environmental visibility, crowd distribution, and building size under different evacuation conditions. For complex buildings and large-scale evacuation crowds, the proportion of leaders should be appropriately increased to ensure the smooth progress of the evacuation process. Further research is needed on the distribution and guidance methods of evacuation leaders to optimize evacuation routes and reduce collision risks caused by misleading information. In addition, according to Fu *et al.*'s study on group behavior, social relationships can affect an individual's detection and acceptance of markers under group conditions. Their experimental results showed that the detection and acceptance probabilities of markers under individual conditions are higher than those under group conditions.[141,145,146] This finding emphasizes the necessity of considering group behavior in evacuation design, especially when designing the number and location of signs, considering possible social interactions and information transmission effects.

A previous study has identified two primary types of guidance strategy: static and dynamic.[147] Static guidance involves the use of fixed signs or markers, such as directional and exit signs, that do not move with the crowd. Dynamic guidance relies on real-time communication methods, such as announcements, audible alarms, and variable message signs, to convey information. Numerous experimental studies have explored the effectiveness of these guidance strategies. Li *et al.*[148] investigated the impact of fire alarms on the initial evacuation stages in a carriage, highlighting the importance of effective communication methods, such as hazard signals (smoke), alarm bells, and standard audible alarms, in preventing confusion and guiding evacuees. Plocher, Tronstad, *et al.*[149,150] explored different sound signal modes and concluded that monophonic and sequential loop modes were more effective for guiding and alerting individuals. Cao *et al.*[147] investigated the impact of guide movement strategies on evacuation outcomes and found that optimal guiding efficiency occurred when the guide speed was approximately 75% of the crowd movement speed. These studies underscore the importance of effective communication in static guidance, emphasizing the role of clear signage and markers in guiding individuals during evacuations.

In contrast, dynamic guidance strategies offer the advantages of real-time updates, adaptability to changes during emergencies, and the capability to provide more precise guidance. The selection of guidance strategies should be based on the characteristics of the building and emergency management strategy used. In summary, devising an appropriate evacuation guidance strategy and organization requires a thorough consideration of the structural attributes of the building and specific emergency response requirements.[144] Additionally, human perception and behavioral factors must be carefully considered to ensure the timely and effective conveyance of information.

After a comprehensive examination of the intricate influences of individual, environmental, and guidance factors on evacuation collision behavior, this section offers a clearer understanding of the multifaceted aspects of individual behavior during emergencies. It highlights how an individual's cognitive and physical capabilities, environmental conditions, and availability of guidance facilities collectively shape their responses during a collision. However, a deeper exploration of the specific behavioral characteristics of individuals following a collision remains necessary, which includes delving into the dynamic behavioral and psychological changes that manifest in emergencies. In subsequent sections, this paper will focus on analyzing the nuanced features of individual behavior post-collision, such as alterations in gait and psychological shifts in decision making. By closely examining these behavioral char-

acteristics, we aimed to provide insights for establishing more effective emergency response mechanisms and psychological support systems.

4. Behavioral characteristics of individuals after a collision

4.1. Relationship between individual collisions and decision making

When navigating through crowded environments, such as public spaces, sports arenas, and shopping centers, individuals often adjust their original movement directions because of interactions with others. During emergencies, individuals must swiftly decide whether to avoid collisions or locate exit points to ensure safety. During post-collision evacuations, the subjective behavior of individuals regarding the direction of evacuation is influenced by various factors, including human perception, emotional responses, and environmental cues. Among these factors, perceptual influences play a significant role because individuals are more inclined to alter their direction to evade collisions when they perceive the risk of a collision or observe the movements of others.[151] This shift in perception relies on sensory inputs, such as visual or auditory cues, which individuals use to determine the direction of evacuation. Consequently, enhanced sensory capabilities can decrease the likelihood of collisions.[152] Emotional responses, including stress, anxiety, and fear, can render individuals more susceptible to collisions or prompt them to change direction hastily without adequate rational thought.[64,153–156] Although such emotionally driven responses are natural mechanisms for coping with emergencies, their impact becomes particularly pronounced when navigating through crowds. Moreover, pedestrian flow density and crowding fluctuations significantly influence strategy evolution.[16,17,157] In environments with a high proportion of initial cooperators, pedestrians tend to move cooperatively because individuals are more likely to mimic and be drawn toward cooperative behavior.[17,83,158] Conversely, in evacuation settings characterized by heightened psychological stress levels[48,159] and dense pedestrian populations, individuals may lean toward self-protective decisions, gravitating toward betrayal because of increased confusion and tension.

An intricate relationship exists between individual evacuation behavior and decision making, which has been extensively studied using various approaches across various evacuation scenarios, focusing mainly on individual and social factors and simulated the decision-making behavior of pedestrians during emergency evacuations through individual agent-based behavioral rules. For instance, Hassanpour[160] and Ha *et al.*[161] used social force-based, emotional, perceptual, and other factors to simulate the behavioral decision making of pedestrians in crowded indoor and outdoor evacuation scenarios, respectively. Lovreglio *et al.*[162] used a discrete event system model to depict the evacuation process, simulating the decision-making behaviors of individuals, such as state transitions and actions during emergencies. Hughes *et al.*[163] used continuous mathematical equations rooted in hydrodynamics principles to model crowd flow and the evacuation process, considering factors like density and velocity to simulate the behaviors and decision making of individuals during emergencies. Lo *et al.*[164] explored individual behavioral decision making during emergencies using game theory, focusing on rational decision making and interactions to maximize individual benefits during evacuation. These studies have yielded valuable insights into the factors that influence the decision making of individuals during emergencies. Hassanpour *et al.*[160] found that environmental action ability significantly affects individual decision making. In contrast, low action ability, such as crowded conflicts, increases psychological stress, damages perception, and reduces decision-making ability. Ha *et al.*[161] identified conflict between individuals as a primary cause of crowding and blockages during evacuation, observing that individuals tend to accelerate rapidly toward the target direction during emergencies, often irrespective of obstacles. Lovreglio *et al.*[162] observed that the decisions of individuals are influenced by distance from the exit, group behavior, and cooperative or competitive tendencies, noting that individuals typically opt for the closest exit but may be swayed by the behavior of others in competitive scenarios. Hughes *et al.*[163] pointed out that crowd density influences individuals' dispersal patterns around barriers, with denser crowds dispersing more autonomously. At the same time, less crowded situations often see individuals concentrating on one side of the obstacles for evacuation. Lo *et al.*[164] highlighted crowding, collisions, conflicts, and competition as factors influencing exit choice behavior, noting that competition and conflict arise when multiple individuals vie for passage through narrow exits, prompting individuals to seek relatively empty exits to avoid resource competition.

In addition to these factors, individuals can be influenced by psychological states, such as anxiety, fear, and nervousness, which directly impact their actions during collision scenarios. Moreover, their cognitive abilities and information-processing styles can affect emergency perception and decision making. For instance, Lindel *et al.*[165] revised the protective action decision-making model and identified core perceptions (threat, protective action, and benefit stakeholder perceptions) as components of a decision-making system for emergency response. Environmental factors, such as crowd density, access flow, and incident type, also directly affect individual evacuation decision-making behavior. Perceptual differences across various environments can lead to divergent behavioral judgments.

Cinelli *et al.*[166] demonstrated that participants perceive situations differently in distinct environments, resulting in varied action judgments. Guidance factors, including emergency management measures or external guidance mechanisms, are crucial in guiding and intervening in individual evacuation decisions. Paris *et al.*[167] explored autonomous navigation for crowd evacuation based on the predictability of pedestrian actions. Each pedestrian sensed the surrounding crowd, deduced their movement trajectory, reacted to potential collisions, and facilitated collision avoidance among the pedestrians. This underscores how decision making during actual evacuation scenarios directly influences the behavior selection and path planning of individuals during evacuation. To investigate the role of emotional contagion in individual decision making during emergencies, Fu *et al.* proposed a CA sIRS model by modifying the epidemiological SIR model to simulate the dynamics of emotional contagion between populations. Research results indicate that individual exercise accelerates the speed of emotional transmission and increases the stable proportion of emotional contagion in infected populations, which may lead to normal or abnormal merged group behavior, thereby affecting evacuation decisions and group dynamics.[168]

Table 5. Research on evacuation collision decision behavior.

Factors	Contents	Related work	Method	Scenario	Findings
route selection	nearest path to exit	[160]	simulation	train station	Reasonable path selection and dynamic adjustment can effectively reduce collision risks during evacuation. Pedestrians can avoid conflicts by changing their direction and predicting others′ trajectories
	pedestrian paths vary with foot traffic	[163]	simulation	the Jamarat Bridge in Mina	
	change of original direction of motion before approaching the point of contact	[166]	field experiments	9.5-meter-long passageway	
	predict the trajectory of others and calculate the range of movement direction to avoid collision	[167]	field experiments, simulation	square areas, intersections, corridors, etc.	
exit options	nearest path to exit	[160]	simulation	train station	Pedestrians′ reasonable choices of exits influence the collision decision during evacuation. Pedestrians tend to choose farther or smoother exits based on the level of congestion near the exit and the distribution of people around.
	increase in the number of people in the vicinity, with a preference for more distant exits	[162]	questionnaire survey, simulation	closed scenario	
	selection of suitable exits according to the degree of congestion at the exit	[164]	simulation	2 rooms	
motion state	faster in a state of psychological stress	[161]	simulation	building	The psychological pressure of walking, the movement state, and the trajectory of surrounding pedestrians determine the movement speed. In contrast, emotional state and tactical behavior affect individual selection and group evacuation efficiency.
	overtaking decision and proportion	[169]	simulation	corridor	
	emotional transmission state	[168]	simulation	–	
	predicting the trajectory of others, calculating the speed range and avoiding collisions	[167]	field experiments, simulation	square areas, intersections, corridors, etc.	

Environmental and guiding factors play essential roles in influencing individual evacuation decisions. Under group evacuation conditions, due to social influence, individuals have a lower probability of detecting and accepting signs than under individual evacuation conditions. The positive impact of high-level signs on route selection is particularly evident, especially in individual evacuation situations. However, decision times that rely on markers are sometimes shorter than

those that do not, indicating that group effects may prolong the decision-making process.[141] In addition, the physical state of individuals during evacuation may also change with path selection, such as reduced mobility and decision-making ability due to overtaking fatigue or injury. In Fu *et al.*'s multi-speed ground field cellular automaton model, pedestrian overtaking behavior was simulated, and the effects of conflict density and successful overtaking rate on evacuation efficiency were analyzed.[169] The study showed that pedestrians evaluate the environmental (crowd density and movement speed) and obstacle (distance and speed difference) conditions of a route when making overtaking decisions to optimize tactical choices. At the same time, psychological and situational factors deeply influence the decision-making behavior of individuals during emergency evacuation. Gao *et al.* studied the exit selection behavior of individuals during evacuation using virtual reality (VR) technology.[170] They found that individuals exhibit systematic preferences and pattern tendencies in uncertain risk scenarios. In addition, the study revealed the critical role of background preference reversal effects, such as compromise, similarity, and attraction effects, in export selection.

Research on the relationship between individual collisions and decision making reveals the primary characteristics of individual decision making in emergencies. Previous studies indicate that decision making could be easily affected by psychological state, cognitive ability, and information processing influence.[3,4,51,52,165] In other words, the decisions of pedestrians are grounded in their interests and goals and are influenced by environmental conditions, social interactions, individual characteristics, and motivations. The aforementioned studies on evacuation decision behavior and their essential characteristics are presented in Table 5. These studies have primarily emphasized the intricate interplay among individual collision behavior, evacuation decision making, and individual, environmental, and guidance factors. These interactions form an integrated decision network encompassing an individual's mental state, cognitive ability, perceptual radius, environmental cues, and guidance mechanisms. These findings deepen our understanding of the factors shaping individual collision behavior and provide a foundation for further refining and validating existing theories.

4.2. Relationship between individual collisions and gait changes

Usually, post-collision gait adjustment of evacuated individuals is a multifaceted process influenced by a combination of factors, wherein individual and environmental elements interact to shape the locomotor response following a collision. The intensity and angle of the collision directly affect an individual's dynamic adjustment.[171] A higher collision intensity can disrupt the balance and alter the step length and frequency. Additionally, the speed and direction of movement before the collision are crucial factors that affect gait changes. For instance, individuals moving at higher speeds may need to adjust their step length quickly to avoid a collision, whereas inertial thinking can hinder swift adaptation.[172,173] If an individual's movement direction aligns with the colliding objects before impact, significant adjustments may be required to avoid further conflict; conversely, opposing directions may facilitate easier pace adjustments. Individual characteristics also influence gait adjustments; factors such as age and physical condition can increase the susceptibility to collisions.[49,113,114] Environmental conditions, such as terrain, crowding, and obstacle layout, further shape an individual's gait adaptation capabilities.[21,22,128] Psychological states, including psychological stress and calmness, elicit varied post-collision gait responses. Perceptual and cognitive abilities dictate how rapidly an individual perceives a collision and influence timely gait adjustments. Moreover, an individual's motor goals, intentions, and interactions with others contribute to gait changes.[111,151,152] Finally, an individual's awareness of emergency and situational understanding further affects post-collision gait adjustments. These intricate interactions result in diverse gait changes during emergencies, underscoring the need to consider multiple factors for flexible and safe motor responses during evacuation. For a more intuitive understanding of the factors that influence individual behavioral collisions, these factors are explained in detail below.

(i) Individual characteristics: Athletic ability and reaction speed are directly related to an individual's post-collision adaptation. Individuals with better physical ability and faster reaction speed may be more able to make rapid gait adjustments to adapt to the external shock of a collision.[49,50,114]

(ii) Interaction and cooperation (competition): During the transfer phase, individuals may begin to cooperate (compete) to assist (interfere with) others in passing through narrow passages or obstacles to ensure safety.[174]

(iii) Collision intensity: Severe collisions can cause individuals to lose balance and require additional swaying to remain standing. They usually manifest as a change in gait to swaying, stumbling, or even falling, especially in the moments following a collision.

(iv) Emotional changes: As the evacuation phase changes, an individual's mood and anxiety levels may also change. During the recognition phase, an individual's mood is usually calmer, whereas during the reaction phase, the mood may become tense.[175]

(v) Layout of obstacles: The layout of obstacles may block evacuation paths, forcing individuals to change their original paths and leading individuals to quickly turn or choose a new path after a collision, resulting in gait changes related to

the shape and distribution of obstacles.[128,171]

(vi) Emergency behavior and contingency actions: Individuals perform different contingency actions at different stages, such as avoiding collisions, moving quickly, and avoiding obstacles.[176]

(vii) Movement speed: Different movement speeds can lead individuals to show various gait adjustments and behavioral responses after a collision.[177,178] For example, individuals moving at high speeds may need to adjust their step frequency and step length more quickly to adapt to the post-collision environment, and higher movement speeds may cause the individual to lose balance after a collision, resulting in additional swaying or wobbling.

An extensive literature review indicated that individuals adjust to environmental changes after collisions, and studies have shown that these adjustments involve parameters, such as speed, reaction time, step length, step frequency, and center of gravity shift (see Table 6). Researchers have investigated the impact of collisions on an individual's gait across these dimensions, revealing that individuals make nuanced adjustments based on individual and environmental conditions. For instance, Cinelli *et al.*[28] investigated the collision avoidance behavior of individuals approaching an object by dividing their movement into pre- and post-collision. They observed changes in the movement speed of individuals, perception time of the object during movement, and trajectories before and after collision. Their findings suggested that individuals tended to move laterally faster when approaching quickly moving objects and slower when the objects moved slowly. In addition, Cinelli *et al.*[166] explored the gait adjustments of individuals during locomotion when they were aware of obstacle locations and movements beforehand. They found that individuals tended to alter their direction of movement first upon encountering an obstacle, followed by adjusting their walking speed. When the minimum distance between individuals and obstacles reached a critical level, changes in movement trajectory occurred. Gérin *et al.*[105] investigated the effects of various environmental factors on individual space and discovered that individuals exhibit flexible movement strategies when confronted with moving obstacles. Typically, they decelerate and shorten their steps to adapt to uncertain situations. However, when individuals are aware of the position and movement of a moving obstacle in advance, they adjust their movement to minimize the distance from the obstacle and change the speed more rapidly, effectively avoiding collisions. When navigating obstacles, individuals maintain a certain amount of space by adjusting its size based on attention allocation and environmental factors. Olivie *et al.*[179] reported that when the distance between two individuals is less than 1 m, they adapt their motion to avoid collisions. However, minimal motion adjustments were made when the distance ranged from 1 m to 1.5 m. The interaction process typically involves observation, reaction, and adjustment phases, each of which requires specific time durations. Furthermore, Fajen *et al.*[171] examined the steering dynamics and obstacle avoidance in individuals. They found that individuals may increase speed if they perceive an evacuation target, but they decrease speed to avoid collisions with perceived obstacles. The strength of the obstacle repulsion force correlates with the shortest distance between an individual and an obstacle, leading to various evacuation paths in different obstacle scenarios. Chen *et al.* also showed that increased pedestrian density in densely populated environments leads to decreased speed and exhibits a transition between free motion and linear constraints.[180] A study of gait parameters further revealed a critical speed value of 1.4 m/s. Beyond this value, the step increment rapidly decreases, and the center of gravity shift increases. These changes indicate the crucial impact of gait adjustment on individual stability and movement efficiency.[181] In addition, environmental and interactive factors affect gait adjustment. For example, when facing moving obstacles, individuals adapt to uncertainty by slowing down and shortening their pace. However, when perceiving impediments in advance, they prioritize adjusting their direction and speed of movement to avoid collisions. Li *et al.*'s flood evacuation scenario confirmed this.[182]

Table 6. Gait changes after collision.

Related work	Gait changes
[28,105,166,183]	velocity changes: changes in the mean velocity, maximum velocity, and velocity distribution of individuals during the two phases before and after the collision
[105,166,183–185]	changes in step length and step frequency: changes in step length and step frequency in individuals before and after collision and gait adjustment
[171]	acceleration change: acceleration of an individual at the moment of impact, including angular acceleration and acceleration of motion
[28,105,171,183–185]	changes in trajectory: trajectories before and after the collision; analysis of the changes in trajectory, degree of curvature, etc.
[105,179,184]	reaction time variation: time interval between pre- and post-collision when individuals adjust their locomotor state
[105,166,171,179,186,187]	minimum distance change: minimum distance at which individuals begin to adjust their locomotion before a collision

To deepen our understanding of the relationship between collisions and gait alterations, the experiments and studies on gait changes are listed in Table 7. Analyzing and summarizing previous studies revealed common trends and laws governing the gait adjustments of evacuated individuals in response to collisions. These studies show that individuals tend to uphold

Table 7. Studies on gait changes.

Contents	Related work	Method	Scenario	Findings
changes in the mean velocity, maximum velocity, and velocity distribution of individuals during the two phases before and after the collision	[166]	field experiments	channel length: 12 m	The average speed, maximum speed, and speed distribution of individuals will adjust with environmental changes. Knowing about environmental changes, individuals will adjust their speed more quickly.
	[28]	field experiments	channel length: 12 m	
	[105]	field experiments	public place	
changes in step length and step frequency in individuals before and after the collision, gait adjustment	[166]	field experiments	channel length: 12 m	When facing moving obstacles, individuals will slow down and shorten their steps to achieve gait adjustment. When the minimum distance between an individual and an obstacle reaches a certain level, the direction of travel (trajectory) will be changed to avoid collision.
	[105]	field experiments	public place	
the acceleration of an individual at the moment of impact, including angular acceleration and acceleration of motion	[171]	field experiments	room: 12 m × 12 m	When individuals perceive evacuation targets or obstacles, they will accelerate or decelerate accordingly. Individuals experience changes in angular acceleration and motion acceleration when changing their direction of motion, especially during acceleration.
trajectories before and after the collision, analyze the changes in trajectory, degree of curvature, etc.	[171]	field experiments	room: 12 m × 12 m	In the context of obstacles, an individual′s trajectory may change significantly. The movement state of obstacles can affect the trajectory changes of individuals (gentle or intense).
	[28]	field experiments	channel length: 12 m	
	[105]	field experiments	public place	
the time interval between pre- and post-collision when individuals adjust their locomotor state.	[105]	field experiments	public place	Individuals will have a specific time interval to adjust their motion before a collision occurs. Knowing the movement trajectory of obstacles in advance allows individuals to adjust more quickly.
	[179]	field experiments	room: 15 m × 15 m	
the minimum distance at which individuals begin to adjust their locomotion prior to a collision	[166]	field experiments	channel length: 12 m	Individuals will adjust their motion based on the minimum distance when approaching obstacles or other pedestrians. When the minimum distance reaches a particular critical value, individuals will change their direction or speed of travel to avoid obstacles or others.
	[171]	field experiments	room: 12 m × 12 m	
	[105]	field experiments	public place	
	[179]	field experiments	room: 15 m × 15 m	

certain safety boundaries and distances during movement, aiding effective collision avoidance. When confronted with collision threats, individuals exhibit sequential behavioral changes, prioritizing heading adjustments as a common coping strategy. Subsequently, they adjust their speed based on collision environmental conditions and prior knowledge, adapting to evolving evacuation environments and individual mobility changes. Angular adjustment emerged as a crucial aspect of collision avoidance, with angular acceleration positively correlated with the target angle, particularly evident when facing a more direct target direction. Moreover, previous knowledge of an individual's motion may prompt earlier path deviation, and individ-

uals may also adjust their steps based on their understanding of obstacle motion, thereby enhancing collision avoidance efficiency. These studies provide scenarios and representations of collision-induced gait changes and offer a robust reference base for future research and practical applications.

5. Research methods for individual collision behavior

In recent decades, there have been many studies related to the collision behavior of evacuating individuals through various methods, encompassing both macro- and micro-levels of analysis. Initially, researchers relied heavily on questionnaires and field observations using statistical analysis and relevant theoretical frameworks.[188–191] Afterward, researchers conducted evacuation behavior experiments by setting up simple field sites.[115,192] This method mainly involved observing, recording, and analyzing the outcomes of these experiments, yielding more intuitive and practical data for understanding evacuation behavior and revealing individual behavior patterns and characteristics during emergencies. Over time, researchers have gradually adopted more sophisticated approaches, namely, developing a series of models, such as flow-based, force-based, and multi-agent-based models based on onsite observation experimental data to simulate the collective movement of pedestrians.[84,163,164,193–195] These evolving research methods have laid a valuable foundation for comprehending the evacuation collision behavior in this study.

In recent years, with the continuous development of science and technology, relevant research methods have been gradually upgraded. Researchers can now not only analyze surveillance camera footage to study pedestrian movement patterns and characteristics comprehensively but also alleviate some constraints associated with field experiments, enhancing research feasibility and applicability. With continuous advancements in virtual technology,[113,196–199] researchers can further simulate real accident scenarios to study the collision behavior of evacuated individuals with greater realism and accuracy. This approach yields more experimental data and allows for the exploration of changes and responses in individual behavior under various conditions.

Research methodology for studying evacuation behavior has evolved from traditional questionnaire surveys and field observations to field experiments and surveillance video analysis. Each method has its own unique advantages and limitations. However, these different stages of the research method complement each other, fostering a deeper understanding of the collision behavior of an evacuated individual. Figure 5 illustrates the evolution of this research methodology.

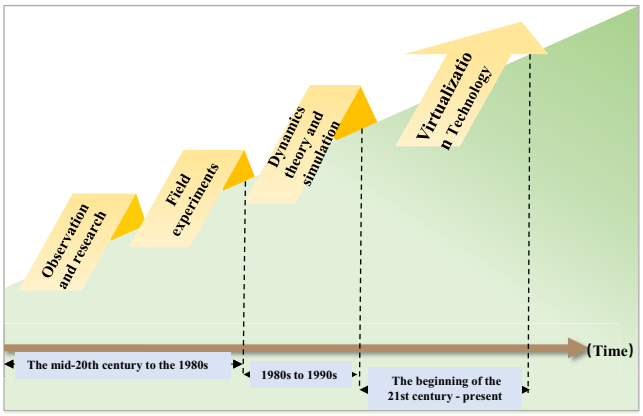


Fig. 5. Evolution of methods for studying individual collision behavior.

5.1. Questionnaire survey

Questionnaires serve as a standard data collection method for investigating the collision behavior of evacuating individuals, focusing on gathering the opinions, experiences, and perceptions of participants to comprehend pedestrian behavior and decision making during evacuations. These surveys typically inquire about the perceptions, understanding, and feedback of individuals or groups regarding evacuation plans and procedures. They are commonly used to assess people's preparedness for emergency evacuation situations, their knowledge of evacuation plans, and the challenges they may encounter in real-world scenarios. Philpot *et al.*[200] studied the effect of fire warnings on the initial phase of carriage evacuation by observing the behavior of evacuating pedestrians during the emergency response phase using questionnaires. Johnson *et al.*[201] studied the levels of psychological stress and competitive behavior of pedestrians during the evacuation process following the 1977 Cincinnati fire in Ohio. Their findings indicate that pedestrian behavior is noncompetitive during the initial stages of escape but becomes competitive as the escape process becomes more urgent. Koshiba *et al.*[202] interviewed 109 faculty, staff, and students to comprehend the behavioral factors influencing the emergency evacuation process following an earthquake, exploring the likelihood of returning to evacuate the building based on the emergency. Li *et al.*[203] used a questionnaire survey to analyze the effects of individual factors, such as social roles, types, and training, on evacuation behavior in a commercial building. Questionnaires serve as a valuable tool for understanding individual or group perspectives; they possess unique advantages and disadvantages. Thus, it is essential to thoroughly analyze the role of questionnaires in research to explore their primary strengths and limitations.

One of the primary advantages of questionnaires is their ability to gather large amounts of data swiftly and efficiently. Through large-scale questionnaires, researchers can collect information from numerous individuals and obtain a comprehen-

sive sample of data. For instance, Ding *et al.*[29] evaluated individual leadership skills using participant questionnaires and devised scientific planning and exercises for the emergency evacuation process based on the questionnaire results. Questionnaires can also aid in modifying evacuation simulation models and facilitating the development of evacuation plans. Furthermore, they enable the exploration of various aspects of evacuation behavior, including decision-making factors, perception, and action, which allows researchers to gain insight into the participants' thought processes and behavioral patterns, synthesizing results from multiple questionnaires. Disaster management agencies can use questionnaire data to predict the behavior of individuals in catastrophic accidents.[95]

However, questionnaires have several limitations. First, they are susceptible to bias, and participants may not always provide truthful or accurate responses because of memory errors or other factors. Additionally, questionnaires typically yield subjective perceptions rather than objective behavioral data, potentially resulting in descriptions of evacuation behavior that do not align with actual behavior, thus reducing the credibility of behavioral data.[204] Moreover, because it is challenging for participants to engage in surveys during emergencies, the availability of actual behavioral data for study is often limited. Therefore, incorporating other methods, such as experiments, observations, and simulations, is often necessary to gain a more comprehensive understanding of evacuation behavior.

6. Controlled experiments

A controlled experiment is a traditional method for studying pedestrian behavior that involves conducting experiments under normal or evacuation conditions and observing the impact of manipulating specific variables on evacuation behavior. Usually, this method studies pedestrian motion patterns and characteristics by analyzing video recordings from camera equipment under laboratory conditions.[205] Controlled experiments are a supplement to pedestrian behavior datasets collected onsite, allowing researchers to design conditions based on research needs and to control other variables to analyze their impact on participant behavior.

The primary advantage of controlled experiments is their ability to provide causal information. By controlling and manipulating variables, researchers can determine how specific factors influence the evacuation behavior of individuals, identify key characteristics and interactions between factors, and enhance the understanding of collision behavior. Moreover, the experimental conditions of controlled experiments are repeatable. Through careful experimental design, researchers can replicate experiments in different contexts to verify the consistency and reliability of the results and ensure the scientific validity of the findings. For example, Parisi[206] and Huber[1] *et al.* investigated changes in walking direction and speed during pedestrian avoidance, whereas Dias *et al.*[207] studied walking characteristics on sidewalks in inclined corridors to understand the behavior in specific architectural environments. Hoogendoorn.[22] and Kretz *et al.* explored the impact of bottleneck structures on pedestrian flow.

However, controlled experiments have some limitations. Simulating real-world emergencies may be challenging, and laboratory conditions may need more stress and chaos than in actual emergencies. Consequently, the experimental results may not fully reflect real-world evacuation scenarios. Additionally, certain factors, such as people's emotions and psychological states, may not be entirely controllable in experiments but play a crucial role in evacuations. These factors are difficult to manipulate, necessitating other methods, such as questionnaires or observations, to obtain more comprehensive data for better modeling of evacuation situations.

6.1. Computer simulation

Pedestrian dynamic models, including macro and micro-models, are critical for studying pedestrian behavior. Over the last century, researchers have proposed a series of macroscopic models based on observed data to simulate the motion of pedestrians as a moving group. Henderson *et al.*[208] proposed a method for analyzing crowd motion based on gas and flow dynamics. Hughes *et al.*[209] assumed the pedestrian population to be a continuous flow medium. Macroscopic models are more suitable for simulating high-density pedestrian flows, especially during emergency evacuation.

Unlike macro-models, there are two micro-models (i.e., social force and CA models), which describe the movement state of pedestrians on an individual basis. Lewin[210] first proposed the social force model in 1951. The development of the modern social forces model came from the outstanding contribution of Helbing *et al.*,[2] who introduced the psychological stress factor and simulated some familiar crowd self-organization phenomena, such as the oscillating walking direction in narrow passages and the self-organization phenomenon in emergencies. Although the model is a sound reproduction of the interaction between pedestrians and the environment, it lacks some pedestrian behavioral characteristics. It has many parameters that need to be calibrated; therefore, in a later study, Lakoba *et al.*[211] added the density of the surrounding crowds and memory of the exits into the social force model. In the last few years, Han *et al.*[212] added information transfer between pedestrians during emergencies. The cellular automata (CA) model divides space into many discrete identical cells that move according to the formulated rules. This model was first proposed by Von Neuman[195] and is widely used in computers, mathematics, and physics. Gipps *et al.*[193] used CA to simulate pedestrian behavior. In 1985, they used

color images to demonstrate the interaction between pedestrians, indicating that repulsion, friction, and attraction between pedestrians were the main causes of complex phenomena during evacuation, providing model validation for subsequent research on predicting pedestrian walking changes.

Using computers to simulate the crowd evacuation process allows researchers to reproduce evacuation behavior in different situations. This approach will enable researchers to conduct numerous experiments in controlled environments that do not involve real-world risks. It also allows precise control over various variables in the evacuation process to observe how they affect evacuation behavior, which can help researchers gain insight into the patterns of collision behavior and can be used to test the effectiveness of different evacuation strategies.

However, this method also has several limitations. For example, the accuracy of the model depends on the accuracy of input data and parameters; if the input data are inaccurate or the parameters are inappropriate, the predictions may be wrong. In addition, the model may ignore some complexities of the natural world, such as complex emotional factors and interpersonal interactions, which can lead to an oversimplified simulation of the actual situation, and an improperly chosen model can lead to unrealistic results. Therefore, computer simulations are often used with other methods (experimentation and observation) to ensure the integrity and validity of the data and results.

6.2. Virtual reality (VR) experiments

Virtual technology has undergone continuous evolution and progress. Figure 6 depicts the history of virtual technology in studying evacuation collisions, indicating its roots in the late 20th century, when computer graphics and simulation began to gain traction. Researchers developed computer simulations during this period to comprehend people's emergency evacuation behavior,[213,214] focusing on modeling simple roadways, buildings, and other structures. The work in this period focused on building evacuation and fire simulation, simulating how people make decisions in these situations. The study of evacuation behavior during collisions has entered a new phase with the advent of virtual reality (VR) technology. VR enables participants to simulate emergencies in controlled environments for more accurate observation and recording of crowd behaviors and provides visual and auditory feedback to simulate real-world scenarios. This enhanced realism offers more profound insights into how individuals cope with collisions and crowding during evacuations,[213,215] facilitating a better understanding of behavior and decision making while providing valuable insights into evacuation strategies. At the turn of the 21st century, significant advancements in virtual reality technology have emerged, including lighter head-mounted displays, higher-resolution graphics, and more advanced tracking technologies.[216] These innovations have rendered virtual environments more realistic and user friendly for research purposes. Consequently, researchers have begun using virtual reality to simulate various types of emergencies, such as fires, earthquakes, and crowd crushes, to understand behavioral decisions in such situations.

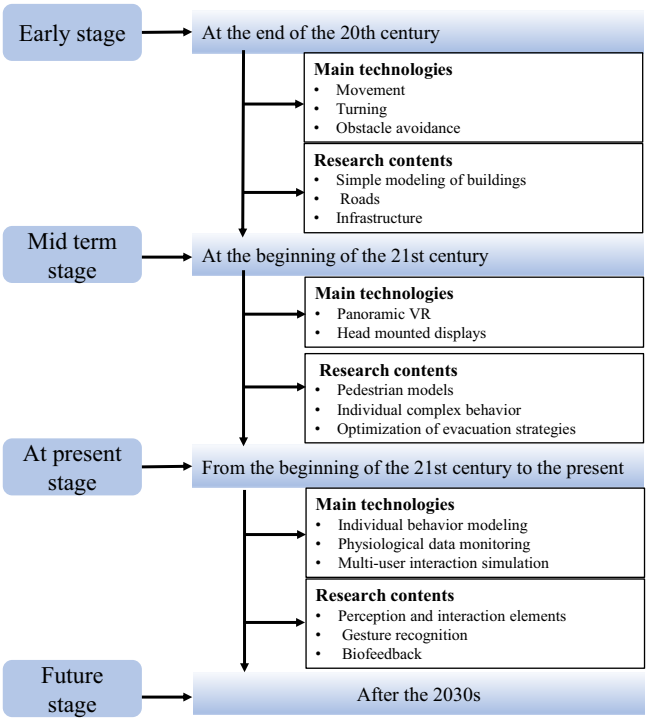


Fig. 6. History of the application of virtual technology in the field of evacuation collision.

Some researchers have used VR technology to collect and quantitatively analyze pedestrian dynamic data in VR environments and have made significant progress in evacuation research. Li *et al.*[217] used VR technology to study pedestrian avoidance and turning behavior in virtual environments and obtained behavior data results that were consistent with real environments. Kinateder *et al.*[218] studied the interaction between social influence and exit environment by setting the proportion of exit choice for virtual characters, which is influenced by both the size and promotion of the emerging crown. Lu *et al.*[219] analyzed the path selection behavior of experimental participants by setting up virtual scenes of fires in residential buildings. Although virtual reality technology is expected to be widely applied in evacuation research, there are still some technical challenges.

First, wearing VR headphones will limit mobility because the current VR technology cannot provide a fully immersive walking and running experience. In addition, immersive VR experiences may lead to motion sickness, which arises from the conflict between the physiological motion signals received by the user's vestibular system and the virtual motion signals generated by VR devices. This discomfort is characterized

by dizziness, fatigue, and nausea,[220] which can affect pedestrian behavior to some extent. To alleviate these problems, researchers often conduct control experiments in virtual reality environments to study the simple decision choices or attention distribution of pedestrians. However, the data collected in these experiments, such as pedestrian speed and motion path, may differ from the behavior observed in the natural environment. This difference may depend on the quality of the VR devices and accuracy of the modeling scenarios. Therefore, continuous technological progress and research are necessary to address these challenges and limitations. Improving the capabilities of virtual reality devices and modeling techniques can enhance the authenticity and accuracy of virtual reality simulations, ultimately helping to better understand pedestrian behavior in evacuation scenarios.

6.3. Mixed reality (MR) experiments

Mixed reality (MR) integrates virtual elements with the real world, allowing users to interact with virtual objects while simultaneously perceiving the natural world.[188] MR technology, facilitated by head-mounted devices, such as Microsoft HoloLens, overlays virtual objects onto the user's field of view, enabling interaction with these virtual elements within the real-world environment. Early applications of MR focused on training and navigation, such as visualizing fires, smoke, and structural damage in buildings and earthquake disasters, to enhance the environmental perception of participants.[198,221,222] MR has also been used to develop navigation functions in low-visibility environments to provide evacuation information during emergencies.[215,223,224] As MR spatial perception and interaction techniques have advanced, researchers have identified their potential for formal applications in evacuation research.[199,225] Recent studies have implemented systems that allow interaction with avatars via voice commands, linked evacuation simulations to naturally built environments for visualization on mobile devices, and used Microsoft HoloLens and eye-tracking components to study the effect of evacuation signs on evacuating pedestrians' attention.[216,226,227]

MR represents the convergence of technologies that drive innovation by offering new viewing and interaction methods. Although MR technology is still emerging and less widely applied owing to its immaturity, it enables users to seamlessly navigate both the virtual and real worlds, providing a more realistic and immersive experience. This integration allows researchers to accurately observe individual behavior and reactions during evacuations, yielding valuable data for studying evacuation dynamics and enhancing evacuation strategies.[196,228] However, several challenges have hindered the widespread adoption of MR technology in research:

(i) The high cost and complexity of MR devices limit their accessibility and scalability, particularly in studies with constrained budgets.

(ii) Prolonged use of MR devices may induce user fatigue, compromise user experience, and potentially reduce experimental reliability.

(iii) The reliability and stability of MR technology are crucial factors affecting the accuracy of experimental results, necessitating careful consideration during experimental design.

Despite these challenges, MR technology holds promise in revolutionizing evacuation research and improving emergency response strategies.

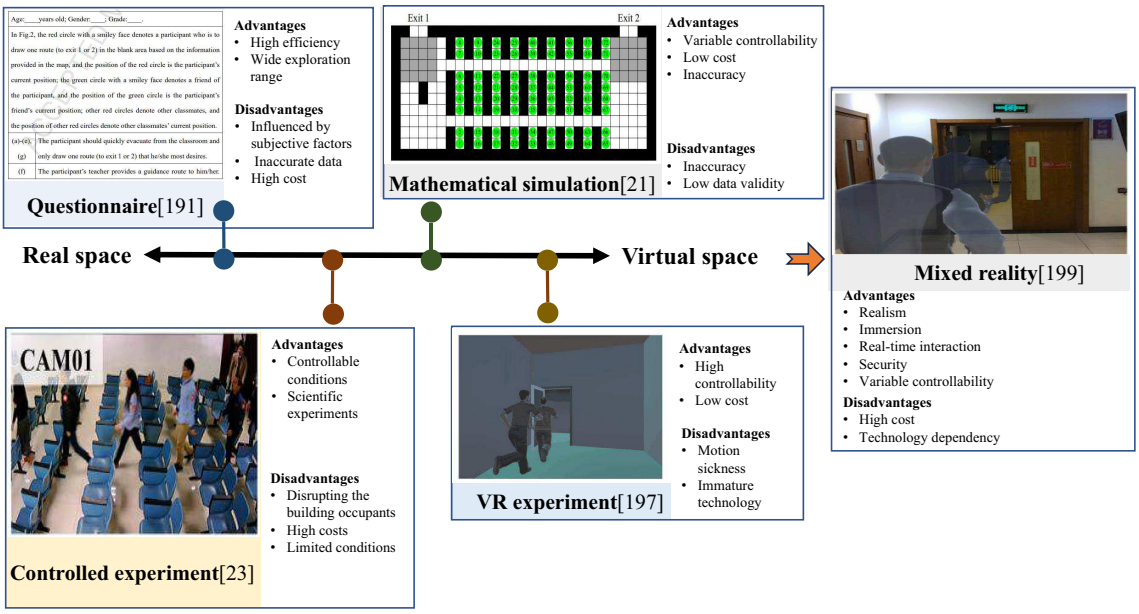


Fig. 7. Advantages and disadvantages of research methods in the field of evacuation collision (reprinted from Refs. [21,23,191,197,199] with permission of Elsevier).

After comprehensively analyzing the respective advantages and disadvantages of questionnaires, controlled experiments, computer simulations, VR experiments, and MR technology, as well as previous applications, this paper summarizes the strengths and weaknesses of each method in the study,[21,23,191,197,199] as shown in Fig. 7. By acknowledging the strengths and weaknesses of each method and using appropriate strategies to overcome these limitations, researchers can leverage a diverse array of methodologies to gain deeper insights into evacuation behavior and enhance emergency response strategies.

7. Conclusions and future work

The evacuation of individual collision behavior is an important interdisciplinary research field that involves various factors, such as psychology, physiology, and sociology, which directly or indirectly affect the overall evacuation efficiency. This paper provides a systematic review of 1127 literature records using CiteSpace visualization software, summarizing and organizing the current research status on individual collisions during evacuation, including research content, results, and methods.

Existing research indicates that environmental conditions (such as evacuation route width and lighting conditions) and emergency guidance measures (such as clarity of emergency signs and timeliness of evacuation instructions) have a crucial impact on collision risk. These factors directly affect the behavior of individuals during evacuation and significantly impact their emotions and psychological states. In addition to the influence of the external environment and strategies, the role of personal psychological activities in evacuation cannot be ignored. Emotional fluctuations, anxiety levels, and psychological adjustments during the decision-making process are important factors that affect evacuation efficiency and collision risk. Future research can use functional near-infrared spectroscopy (fNIRS) and eye-tracking devices to monitor individual psychological and decision-making states in real time to obtain more accurate data and provide a scientific basis for further exploration of individual evacuation behavior.

The individual behavioral characteristics after a collision are mainly reflected in the gait adjustment and decision changes. Studying individual reactions in chaotic environments provides essential references for developing more realistic evacuation plans and improving overall efficiency. Future research should investigate the behavioral characteristics and psychological states of individuals after collisions during evacuation to better manage this critical step and reduce potential risks.

In terms of research methods, previous studies have used various traditional methods to study the collision behavior of evacuees, including controlled experiments, field observations, and computer simulations. Controlled experiments can strictly control variables and provide high-precision data but may lack the complexity of real-world scenarios. Onsite observation provides behavioral data in real situations but is limited by the environment and time. Computer simulations, such as those based on cellular automata and multi-agent models, can simulate large-scale crowd evacuation, but the selection and validation of model parameters are key challenges. With the development of technology, virtual reality (VR) and augmented reality (AR) technologies have been introduced into pedestrian research. In particular, these technologies demonstrate enormous potential in the study of evacuation behavior. Virtual reality technology can create realistic evacuation scenarios, allowing researchers to test different evacuation strategies and designs in a controlled environment. Mixed reality (MR) technology is a new tool that combines the advantages of virtual and real worlds, providing researchers with more flexible and intuitive research methods. For example, through MR technology, researchers can simulate different evacuation scenarios and environmental conditions, observe individual behavioral responses and psychological changes, and optimize evacuation plans and emergency response strategies.

Future research should focus on the collision behavior and psychological characteristics of individuals during the evacuation process to efficiently manage this critical link and reduce potential risks. Although mixed reality technology has been able to reconstruct natural scenes and reveal the collision avoidance strategies of pedestrians in dynamic environments, further exploration is still needed on how information diffusion affects the psychological states, behavioral evolution, and obstacle avoidance coping strategies of pedestrians. In addition, exploring the impact of individual differences (such as age, gender, and physical condition) on collision behavior will help develop precise evacuation plans adaptable to different scenarios. Considering the interaction of various factors, such as environment, psychology, and society, can help construct a more comprehensive collision behavior model. In the future, artificial intelligence technology can become a new paradigm for modeling and simulation using big data analysis to explore potential behavioral patterns and rules, thereby enhancing the predictive ability of models. In-depth research in these directions will provide a scientific basis and technical support for improving evacuation efficiency and safety.

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