Journal of Human Movement Science (2024)
Clausius Scientific Press, Canada

DOI: 10.23977/jhms.2024.050208
ISSN 2523-5850 Vol. 5 Num. 2

Pedestrian Evacuation Dynamics: A Literature Review

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Keywords: Pedestrian Evacuation, virtual reality, simulation

Abstract: This literature review deeply studies the dynamics of pedestrian evacuation in emergency situations, such as fire, earthquake or terrorist attacks, focusing on understanding the modes and principles of controlling human behavior in this situation. In view of the key role of effective evacuation in minimizing casualties and reducing the overall impact of disasters, this study aims to provide a comprehensive synthesis of current research in this field. By reviewing the extensive research spanning six years, we try to emphasize the key findings, theoretical framework and empirical evidence, which have formed our understanding of pedestrian behavior and movement in evacuation environment. The methods used in this review include systematic classification and analysis of relevant literature. We formulate research questions, determine the most relevant work, evaluate the quality of research, and summarize evidence to provide a comprehensive overview of the current state of knowledge. This paper paid special attention to the analysis of pedestrians' behavior, including their decision-making process, social interaction and reaction to stress and panic. In addition, we evaluate the effectiveness of various models in predicting evacuation results and determine their advantages and limitations. This review includes empirical research and modeling and simulation methods. The former examines real-world evacuation events and experiments, while the latter aims to replicate and predict pedestrian behavior in emergency situations. We discussed the challenges in accurately simulating the real-world evacuation process and put forward the potential direction of future research. Generally speaking, this literature review is a valuable resource for researchers, practitioners and decision makers, who are interested in improving pedestrian evacuation strategies and improving public safety. By synthesizing the current understanding of pedestrian evacuation dynamics, it lays a foundation for the further development of this multidisciplinary field.

1. Introduction

The efficient evacuation of pedestrians during emergencies, such as fires, earthquakes, or terrorist attacks, is a critical aspect of public safety management. Ensuring orderly and rapid evacuation can significantly minimize casualties and reduce the overall impact of disasters. In recent years, the study of pedestrian evacuation dynamics has garnered substantial attention from multidisciplinary fields, including physics, engineering, psychology, and urban planning, due to its complex nature that intertwines human behavior, infrastructure design, and emergency response strategies.

This literature review aims to provide a comprehensive synthesis of the current understanding of

pedestrian evacuation patterns and the underlying principles guiding these dynamics. By examining a broad spectrum of studies conducted over six years, this work seeks to illuminate the key findings, theoretical frameworks, and empirical evidence that have shaped our comprehension of how people behave and move in evacuation scenarios. Particular emphasis will be placed on analyzing the behavioral aspects of pedestrians, the efficacy of various models in predicting evacuation outcomes, and the challenges that persist in accurately simulating real-world evacuation processes.

In this review, we adopt a systematic literature classification and analysis method, aiming at comprehensively and deeply summarizing the research progress of pedestrian evacuation behavior. Firstly, according to the core differences in research methods, we divide the literature into two categories: empirical studies and computational simulations. Empirical research focuses on verifying theories or hypotheses through observation, measurement and data analysis, while computer simulation uses mathematical models and algorithms to reproduce and predict phenomena in a virtual environment. On this basis, we further refine the research under each category and classify it according to the specific problems discussed and the methodology adopted. This hierarchical analysis strategy can not only reveal the core issues and development trends of various research, but also promote a deep understanding of the advantages, limitations and complementarities of different research methods. Through this review, readers will have a comprehensive insight into the current situation, trends and possible future research directions of pedestrian evacuation behavior research.

The structure of this review commences with an overview of an in-depth exploration of empirical studies that have contributed to our practical knowledge. A detailed analysis of pedestrian behavior, a pivotal factor influencing evacuation efficiency, will then be presented. Subsequently, the review delves into the realm of modeling and simulation techniques, highlighting their advancements and limitations. Lastly, the discussion will identify the existing gaps in knowledge and propose potential avenues for future inquiry, emphasizing the need for continued interdisciplinary collaboration in addressing the complexities inherent in pedestrian evacuation dynamics.

Through this systematic examination, it is anticipated that this review will serve as a valuable resource for researchers, policymakers, and practitioners involved in enhancing public safety protocols and infrastructure design, ultimately contributing to the development of more effective evacuation strategies and policies.

2. Methodology

The methodology adopted for this literature review was meticulously designed to ensure a comprehensive and systematic exploration of the vast body of research surrounding pedestrian evacuation dynamics. This section outlines the process undertaken to identify, select, and analyze relevant literature, thereby providing transparency and reproducibility of the review's findings.

Literature Search Strategy

A systematic search strategy was employed to retrieve published works from electronic databases, including but not limited to, Scopus, Web of Science, PubMed, and Google Scholar. The search was conducted using a combination of keywords and phrases relevant to the topic, such as "pedestrian evacuation," "evacuation dynamics," "crowd behavior," "emergency egress," and "evacuation modeling." To capture the most recent developments, the search was limited to publications from the last six years (2019 to present), although seminal works preceding this period were also included where they significantly contributed to the field.

Inclusion and Exclusion Criteria

To maintain focus and ensure the quality of the selected literature, predefined inclusion and

exclusion criteria were applied. Studies were included if they:

1) Focused explicitly on pedestrian evacuation dynamics in various contexts (e.g., buildings, transportation hubs, open spaces).

2) Provided empirical data, theoretical frameworks, or modeling approaches related to pedestrian evacuation.

3) Were published in peer-reviewed journals, conference proceedings, or reputable technical reports.

4) Were written in English, due to the international scope of the research and to facilitate accessibility.

Exclusion criteria involved excluding studies that were not directly related to pedestrian evacuation, were duplicates or did not meet the standards of scientific rigor.

Data Extraction and Synthesis

Relevant information from each selected article was extracted systematically, including study objectives, methodologies, key findings, and conclusions. A qualitative synthesis approach was utilized to analyze and categorize this information thematically. This process involved identifying common themes and trends across studies, comparing and contrasting findings, and critically evaluating the strengths and weaknesses of the methodologies employed.

Quality Assessment

The quality of the selected literature was assessed based on established criteria adapted from similar review studies. These criteria encompassed the study design, sample size, clarity of methodology, and the validity and reliability of results. While recognizing the diverse nature of studies in this field, this assessment aimed to ensure a balanced and unbiased evaluation of the literature.

By adhering to this rigorous methodology, this literature review endeavors to offer a thorough and reliable synthesis of the current state of knowledge on pedestrian evacuation dynamics, providing a solid foundation for identifying research gaps and guiding future studies in the field.

3. Common experimental methods

3.1. Questionnaire survey

Questionnaire survey is a commonly used data collection method, which collects information about emergency evacuation from respondents in written or electronic form by designing a series of questions. The advantages of the questionnaire survey method are: 1) It has high experimental control. The experimenter can flexibly set the questions of the questionnaire according to the purpose of the experiment. 2) It can help researchers to collect comprehensive data samples and cover large and different participating groups conveniently. 3) Convenient and flexible, the questionnaire survey method is carried out in paper or electronic form, which is less limited by time and place. Disadvantages of questionnaire survey method: 1) Low data validity. The questionnaire method only obtains the opinions and attitudes of the participants, which may be different from their behaviors in critical situations.

3.2. Field observation

Field observation is a way for observers to use their sensory organs purposefully and systematically or use scientific observation tools to actively understand social phenomena in a natural state. The observation object of field observation method is in a natural state to reflect the real emergency evacuation process and phenomenon[1]. Field observation has many applications. 1) Field observation can be used to observe evacuation routes and facilities: researchers can learn

about the setting, marking and lighting of evacuation routes, as well as the number, location and layout of evacuation facilities through field observation. This information helps to evaluate the rationality and effectiveness of evacuation routes and facilities, and provides a basis for optimizing evacuation design. 2) Observation of evacuation behavior: Researchers can understand people's behaviors and reactions through field observation. This includes people's moving speed, direction choice, crowding degree and so on. 3) Observation of evacuation effect and influencing factors: Researchers can evaluate the effect and influencing factors of emergency evacuation through field observation. This includes evacuation time, evacuation distance, safety accidents during evacuation, etc. By observing and analyzing these data, researchers can understand the effect and existing problems of emergency evacuation, and provide basis for improving evacuation strategies and emergency plans. Advantages of field observation: 1) Intuitiveness and authenticity: Field observation can directly observe the actual situation in the process of emergency evacuation, including evacuation routes, facilities use, crowd behavior, etc., so the obtained data and information are more intuitive and true. 2) The collected pedestrian behavior data contains abundant information[2]. 3) Data validity, because this method has little interference, participants are more likely to act in a more natural and practical way. Disadvantages of field observation method: 1) The experimental control power is low. 2) The representativeness of the data is poor. 3) The cost is high.

3.3. Control experiment method

The control experiment method aims to explore the causal relationship between independent variables and dependent variables by artificially controlling the experimental conditions and excluding other interfering factors. In the field of emergency evacuation, this method can be used to test the influence of different emergency evacuation strategies, facilities layout, information transmission methods and other factors on the evacuation effect. Advantages of controlled experiment method: 1) Strong controllability: By artificially controlling the experimental conditions, other interference factors can be eliminated, making the experimental results more accurate and reliable[3]. 2) Strong repeatability: The experimental conditions can be strictly controlled, which makes the experimental results highly repeatable. This is helpful to verify and popularize the experimental results. Disadvantages: Limited sample size: Due to the limitation of experimental conditions, the sample size of the control experiment method is usually small. This may limit the universality of the experimental results. With the development of virtual reality technology, more and more scholars now apply virtual reality technology to control experiments.

Virtual Reality (VR) is a brand-new practical technology developed in the 20th century. It provides users with a realistic virtual world with three-dimensional visual, tactile, olfactory and other sensory experiences, mainly through computer technology, combined with the latest development achievements of three-dimensional graphics technology, multimedia technology, simulation technology, display technology and servo technology. Cave automatic virtual environment (CAVE) and Head-Mounted Display (HMD) are two main types of virtual reality (VR) technology, which have their own unique characteristics and application scenarios. CAVE is an immersive virtual reality display system based on projection, which usually consists of a cubic immersive stereoscopic display environment surrounded by three (or four to six) square screens. Head Mounted Display (HMD) is a 3DVR graphics display and observation device in virtual reality applications. It can be connected to the host computer independently to receive 3DVR graphics signals from the host computer. The use mode is head-mounted, and the spatial tracking locator with three degrees of freedom can be used to observe the VR output effect. At the same time, the observer can move freely in space, such as walking and rotating freely, and get a strong sense of immersion. Studies have shown that the experimental results obtained by these two technologies are

consistent, so people are more inclined to use low-cost head-mounted displays. In contrast, using virtual reality technology to carry out experiments has many advantages. 1) The evacuation of dangerous scenes that cannot or is difficult to carry out in reality can be well solved by using virtual reality technology. The biggest advantage of virtual reality technology is that participants are not harmed[4]. 2) Compared with the information transmission media such as words or pictures, the use of virtual reality technology can bring realistic immersive experience to participants, thus naturally showing a more realistic response, so the collected data is more feasible[5]. Head-mounted display is convenient to move. Compared with field observation, virtual reality technology can expand a wider group of subjects, and the data collected in this way will be more representative and expandable[6]. 3) Virtual reality is built by technicians, which can be quickly modified and improved, so experiments using virtual reality technology have higher experimental control[7]. It is convenient for researchers to control variables, create an ideal experimental environment and pay attention to interesting issues.

4. Empirical Studies

Many scholars have used empirical methods to study pedestrian evacuation behavior, among which questionnaire survey method is the most used in empirical articles. Shiwakoti et al. (2020) found that passengers have low trust in emergency pathfinding tools and procedures by questionnaire survey[8]. Shoji (2020) and others affirmed the positive influence of disaster education projects on students by questionnaire survey [9]. J Wu et al. (2022) also studied the influence of education, and found that disaster knowledge will be more beneficial to residents' behaviour [10]. Chang et al.(2021) studied the route choice behavior of residents under hurricane disaster[11]. Gabriele Bernardini and Enrico Quagliarini(2021) found that obstacles and walls can attract the movement of pedestrians because they can protect pedestrians from weapons attacks[12]. Wang et al. (2020) found that older passengers are more likely to actively confirm the authenticity of evacuation events. Different from the findings of Shiwakoti et al. (2020), passengers on ships are more likely to choose to follow evacuation instructions or guidance[13]. Golshani et al. (2019) studied the pedestrian evacuation behavior in the non-notification disaster environment, and found that demographic characteristics, crowd density and event characteristics would significantly affect the evacuation behaviour [14].

However, the declarative choice experiment has also been questioned by scholars, because the data is not from the real environment, and the questionnaire only investigates the participants' thoughts, which may be deviated from their real behaviour [8, 15]. Many scholars have adopted on-the-spot observation method to study evacuation behavior. Nguyen et al. (2023) studied the effect of electrical stimulation on the evacuation behavior of mice[16]. R Larrieu et al. (2023) studied the evacuation behavior of fish schools at narrow exits[17]. However, many scholars have found that the evacuation behavior of animals and insects is different from that of humans[16, 18].

Scholars focus more on crowd evacuation drills gradually. Haghani and Sarvi(2019)observed the movement of evacuated people through cameras and found that human beings tend to avoid the choices of most people[18]. The difference is that Chen et al. (2020) found that people showed grazing tendency when they decided to evacuate through evacuation drills[19]. Similarly, Haghani et al. (2020) found that evacuees showed an obvious tendency to follow their neighbors[20]. Shi et al. (2022) found that evacuees are more inclined to evacuate according to the instructions of evacuation signs[21]. Lu et al. (2021) conducted pedestrian evacuation experiments on staircases to uncover behavior characteristics[22]. The data collected by field observation method is more accurate and convincing. However, this method usually consumes physical strength and brings personal safety risks to participants such as trampling and squeezing during evacuation[21]. And it

lack the ability to set variables flexibly[23]. In contrast, virtual experiments can help to improve the control of experiments and flexibly set and modify variables to facilitate researchers to pay attention to the variables of interest. The development of virtual reality technology has brought technical support to the field of evacuation, and many scholars have confirmed the effectiveness of virtual reality technology through research[24]. Fu et al. (2021) found that people with high risk tolerance are more likely to choose a shortcut filled with smoke by virtual reality technology[25]. The author also found that individuals will comprehensively consider various types of environmental information [26]. Feng et al. (2021) used virtual reality technology to study and found that although good visibility of exit signs can help participants identify the exit, it has little effect on the exit choice of participants. On the contrary, participants are more likely to choose the exit that others have already chosen[27].

5. Modeling and Simulation

Although a large number of empirical studies provide us with data support, how to build accurate models in theory and predict and verify these models through computer simulation is still a hot and difficult point in current research. Therefore, this chapter will focus on the model construction and computer simulation of pedestrian evacuation behavior.

Sun et al. (2020) simulated the evacuation efficiency of different group sizes through BIM software, and explored the key factors affecting human evacuation behavior[28]. Chen et al. (2022) established a route selection model and simulated it[29]. Wang Guanning et al. (2022) found that the more familiar pedestrians are with the environment, the less time they spend fleeing the room and the less sensitive they are to danger [30]. Liu et al. (2019) found that pedestrians tend to choose the nearest exit and consider other factors by simulating the evacuation action in outdoor public places[31]. Şahin et al. (2019) suggested that the exit width should be determined according to the evacuation crowd density by simulating indoor fire evacuation [32]. Shirvani et al. (2020) coupled fluid dynamics with pedestrian model, and built a pedestrian simulator for flood to simulate the two-way interaction between flood and individuals. [33]. In the second year, the pedestrian response to the stadium flood disaster was simulated by using this model[34]. Rendón Rozo et al. (2019) simulated the emergency evacuation plan in the building based on agent simulation technology[35]. Zhang et al. (2023) proposed a simulation model based on cellular automata [36]. Xie and others implemented a new social group model based on the framework of social forces to study the evacuation dynamics of pedestrians. The simulation results show that the group effect promotes the overall evacuation, especially in the case of wide exits [37]. Haghani and others suggest that individuals should be discouraged from imitating or following others' choices when choosing the escape direction in the evacuation scene of crowded space through the research on evacuation behavior[38]. Zou et al. modified the cellular automata model by introducing local density field and hesitation time cost to study the influence of pedestrians' judgment on the environment on evacuation[39]. Barnes et al. (2021) have created an agent-based modeling (ABM) framework tool, which contains a powerful human behavior model, which can help management professionals to formulate and test their emergency plans in an emergency [40].

6. Conclusion

This literature review deeply discusses the research status of pedestrian evacuation law. Through extensive literature analysis and systematic classification, we can fully understand the pedestrian evacuation behavior and dynamic principles in emergency situations (such as fire, earthquake or terrorist attacks). This review not only emphasizes the importance of pedestrian evacuation research in public safety management, but also highlights the key role of interdisciplinary research in solving

this complex problem.

In the process of literature review, this paper finds that there are still some contradictions in the research results in the field of pedestrian emergency evacuation. For example, some scholars think that personal characteristics have little influence on pedestrian evacuation behavior[41], while some scholars think that personal characteristics can significantly affect evacuation behavior. At the same time, in the process of literature review, this paper found that many scholars did not determine the specific disaster types in their research, and different disaster types often lead to different evacuation behaviors[8]. For example, in the process of terrorist attacks, pedestrians tend to be close to obstacles or walls to avoid being attacked by weapons, but in earthquake disasters, pedestrians tend to evacuate to open areas to avoid falling rocks and other objects hitting themselves. Therefore, we call on scholars to further refine the determination of the research environment.

In the aspect of behavior analysis, we realize that pedestrian evacuation behavior is not a simple linear process, but is influenced by many psychological and social factors. This requires future research to adopt more complex and sophisticated models to capture these behavioral characteristics.

To sum up, the study of pedestrian evacuation law is a complex and important field, which needs interdisciplinary research and continuous innovation. By deeply exploring the dynamic characteristics and influencing factors of pedestrian evacuation behavior, we can provide more scientific and effective support for public safety management and emergency response strategy formulation. We look forward to more breakthroughs and progress in this field in the future.

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