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Experimental Study on Pedestrian Behaviors during Fire Emergency Conditions with Minecraft: Case Studies in a Classroom

Zhichao Zhang [1], Wenke Zhang [1], Yueyao Ma [1], Eric Wai Ming Lee [2] and Meng Shi [1,*]

[1] School of Computer Science, South-Central Minzu University, 182 Minyuan Road, Hongshan District, Wuhan 430074, China; zhic.zhang@mail.scuec.edu.cn (Z.Z.); wenkez@scuec.edu.cn (W.Z.); myy2022@scuec.edu.cn (Y.M.)

[2] Department of Architecture and Civil Engineering, City University of Hong Kong, Tat Chee Avenue, Kowloon 852, Hong Kong; ericlee@cityu.edu.hk

* Correspondence: mengshi@mail.scuec.edu.cn

Abstract: The comprehension of the fire evacuation process is crucial for developing effective evacuation management strategies to enhance pedestrian safety. In this study, we construct a classroom with internal obstacles forming intersecting pathways in Minecraft, and conduct a series of virtual evacuation experiments involving multiple pedestrians to investigate the pedestrian behaviors. Case studies in a single-exit classroom demonstrated that normal obstacles and fire in the main evacuation path prompt pedestrians to detour, and pedestrians exhibit fire-avoidance behavior in advance during fire emergency. In the two-exit classroom experiments, normal obstacles have a limited effect on the exit choices of pedestrians, as they primarily choose the nearest exit. Pedestrians positioned in the center of classroom are influenced by their initial orientations, and some pedestrians opt for exits in their initial facing directions. The presence of fire has a greater influence on pedestrians' exit choices, with most opting for exits away from the fire. Furthermore, during fire emergencies, some pedestrians engage in risk-taking behavior by choosing higher-risk paths in pursuit of a faster evacuation. These adventurous pedestrians proactively plan routes that maximize their distance from the fire and exhibit orderly queuing behavior. These findings are helpful to reveal pedestrian behaviors during fire emergencies.

Keywords: evacuation dynamics; fire emergency; virtual environment; Minecraft; experimental study; choice behavior

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1. Introduction

Classrooms, gymnasiums, and supermarkets represent archetypal indoor environments characterized primarily by high population density and the presence of numerous obstructions. In the event of a fire or other emergency incident, the absence of efficient evacuation management strategies may engender unforeseeable human and property losses [1]. Consequently, the precise and high-fidelity comprehension of pedestrian evacuation behavior during emergency situations assumes paramount significance for the formulation of effective evacuation management strategies, ensuring the safeguarding of human lives and the design of evacuation support systems, exemplified by evacuation signage [2], intelligent evacuation guidance systems [3], and secure egress pathways [4].

Over the past few decades, researchers have conducted comprehensive investigations into indoor pedestrian evacuation, employing numerical simulation and experimental research methods. In the domain of numerical simulation, researchers have primarily relied on empirically observed pedestrian behaviors, such as queuing behavior [5], competitive behavior [6], and herding behavior [7], as the basis for developing mathematical and physical models. These models serve to analyze pedestrian evacuation trajectories and motion patterns. Subsequently, these models are subjected to validation and further refinement through real-world experiments, with the overarching aim of achieving precise prognostications of pedestrian behavior during evacuation processes. Presently, a multitude of models have been established, encompassing social force models [8,9] and cellular automaton models [10,11], which find extensive applications in elucidating the dynamics of pedestrian evacuation processes within indoor environments. Yu et al. [12], drawing upon the social force model, have introduced interactive rules between ordinary pedestrians and those displaying aggressive behavior to scrutinize the mechanisms underpinning exit selection by pedestrians in multi-exit rooms. Zhang et al. [13], utilizing controlled pedestrian experiments and an improved multi-grid model, have conducted an in-depth examination of pedestrian behavioral characteristics during classroom evacuations, inclusive of variable velocity, dislocatable queuing, and monopolizing exit behaviors. In a similar vein, Wang et al. [14], grounded in an enhanced cellular automaton model, have delved into the influence of various pedestrian behaviors when encountering obstacles within classrooms, namely, traversing over obstacles and pushing obstacles. Furthermore, Chen et al. [15], through evacuation exercises, have analyzed the collective evacuation behavior of children within a classroom and subsequently incorporated these insights into the cellular automaton model. Though numerical simulation methods have demonstrated the capacity to replicate pedestrian behaviors during evacuation processes, the inherent challenge remains that, due to the absence of empirical data support for emergency situations, particularly fire-related scenarios, the veracious and precise anticipation of pedestrian behavior and the elucidation of evacuation dynamics within indoor emergency conditions remain elusive. Consequently, numerous researchers are fervently dedicated to advancing the field through the exploration of evacuation experiments.

Experimental research encompasses a variety of methodologies, primarily including field observations [16], evacuation drills [17], controlled human experiments [18], animal experiments [19], and virtual experiments [20]. To date, researchers have extensively investigated evacuation processes within certain typical geometric layouts, such as corners [21], T-junctions [22], and corridors [23]. These distinctive geometric configurations have given rise to unique phenomena of self-organized pedestrian behaviors, including phenomena like pedestrian queuing, merging, and corridor diversion [24]. Additionally, the presence of obstacles can potentially augment the complexity of pedestrian evacuation processes [25]. However, it is important to note that, driven by concerns related to safety and ethics, there are inherent limitations in conducting emergency evacuation experiments involving humans or animals in the real world. In recent years, virtual pedestrian experiments have gained widespread adoption for the collection of pedestrian behavior data due to their high safety, strong controllability, and flexibility. Researchers have extensively studied pedestrian behaviors in emergency situations, such as exit selection [26] and route choice [27]. Bode and Codling [28] employed interactive virtual environments to investigate pedestrian exit choices under different densities and pressure levels, revealing that pedestrians may make irrational choices under high-pressure conditions. Kinateder et al. [29] used virtual environments to study the impact of exit familiarity and others' exit choices on pedestrian exit selection, finding that exit familiarity and the behavior of nearby individuals influence evacuation behavior, with their influence expanding as the number of nearby individuals increases. Zhang et al. [30] designed fire scenarios within buildings and studied pedestrian turning behavior, demonstrating that pedestrian information perception is influenced by their turning angles. Fu et al. [31] developed a controlled virtual environment to examine pedestrian route decisions in hazardous scenarios, showing that pedestrians do not blindly follow the paths of surrounding pedestrians, and some pedestrians may engage in adventurous behavior. Furthermore, many researchers have evaluated the reliability of virtual experiments. Li et al. [32] compared the impact of obstacles on path selection behavior in controlled pedestrian experiments and virtual experiments under the same settings, concluding that using virtual experiments to study path selection behavior is reliable. de Schot et al. [33] conducted straight-line pedestrian movement experiments in both virtual and real-world physical environments, finding no significant differences in pedestrian "pushing" or "following" behavior between the two experimental settings and affirming the potential of utilizing virtual experiments to obtain individual motion data. Nevertheless, most current virtual experiment studies are limited to individual participants conducted one at a time, lacking social interactions among pedestrians. Recently, we introduced a novel approach for evacuation experiment research based on Minecraft [34], conducting a series of virtual evacuation experiments involving multiple pedestrians simultaneously in non-fire and fire scenarios on the Minecraft platform. We compared the experimental results with commercial evacuation simulation software, Pathfinder, and Anylogic. The results indicate the feasibility of Minecraft in reflecting real pedestrian behavior and evacuation processes. Despite the extensive research conducted using virtual experiments on pedestrian exit and route selection, it should be noted that there is still a relative scarcity of experiments involving multiple real-time participants in fire evacuation scenarios within indoor environments.

To delve deeper into the movement patterns and evacuation characteristics of pedestrians during fire incidents indoors, and to gather essential data on pedestrian behavior data during emergency situations, we construct a classroom within Minecraft. We introduce internal obstacles forming intersecting pathways and conduct a series of virtual evacuation experiments involving multiple pedestrians simultaneously. First, we conduct single-exit evacuation experiments within the classroom by introducing normal obstacles and fire in the main evacuation pathways to study differences in pedestrian evacuation behavior. Subsequently, we carry out a series of two-exit evacuation experiments to investigate the effects of obstacles and fire on pedestrian choices when faced with multiple exit options.

The remainder of this section is structured as follows. Section 2 introduces the details of the experimental scenario and the utilization of Minecraft. Section 3 describes the experimental procedure and methods for extracting experimental data. Section 4 presents the experimental results and discussion. Section 5 summarizes the conclusions and future works.

2. Experiment Design

2.1. Experiment Setup

Figure 1 depicts a schematic illustration of the typical indoor environmental configuration to be investigated in this study. The depicted environment corresponds to a classroom with dimensions of 12×8 m^2. Within the classroom, a lectern with an area of 3×2 m^2 is situated, along with 18 desks and a 1×1 m^2 obstruction denoting the air conditioning system (AC) (located in the lower-right corner of Figure 1). Each desk measures 0.5×0.75 m^2, with a spacing of 1.5 m between them, providing ample maneuvering space for participants and ensuring minimal interference from adjacent participants during the preparatory phase of the real experiment. The desks divide the entire classroom into three passable aisles (i.e., Aisle 1, Aisle 2, and Aisle 3). Two exits are positioned, respectively, in the upper-left and upper-right corners, representing typical exit locations in indoor environments. Furthermore, a 1×1 m^2 blue region is demarcated along the central axis of the classroom (indicated by the dashed line in Figure 1) for the placement of fire (marked in red) or a normal obstacle (marked in black). Taking into account the spatial carrying capacity of the indoor environment, a total of 34 participants are included in the experimental cohort, with each individual's initial position being fixed. In order to mitigate the potential impact of gender disparities in participant numbers, we recruit 17 male and 17 female participants, with an average age of 21.4 years and an average height of 1.68 m. Specifically, the ellipses in the figure represent participants, with numerical labels denoting their identification numbers (i.e., ID). Different colors are employed to signify their initial orientations: red indicates participants facing Exit 1, green indicates those facing Exit 2, and gray signifies those facing Aisle 2. Furthermore, to represent the initial positions of participants, Row and Column values are assigned to all initial positions.

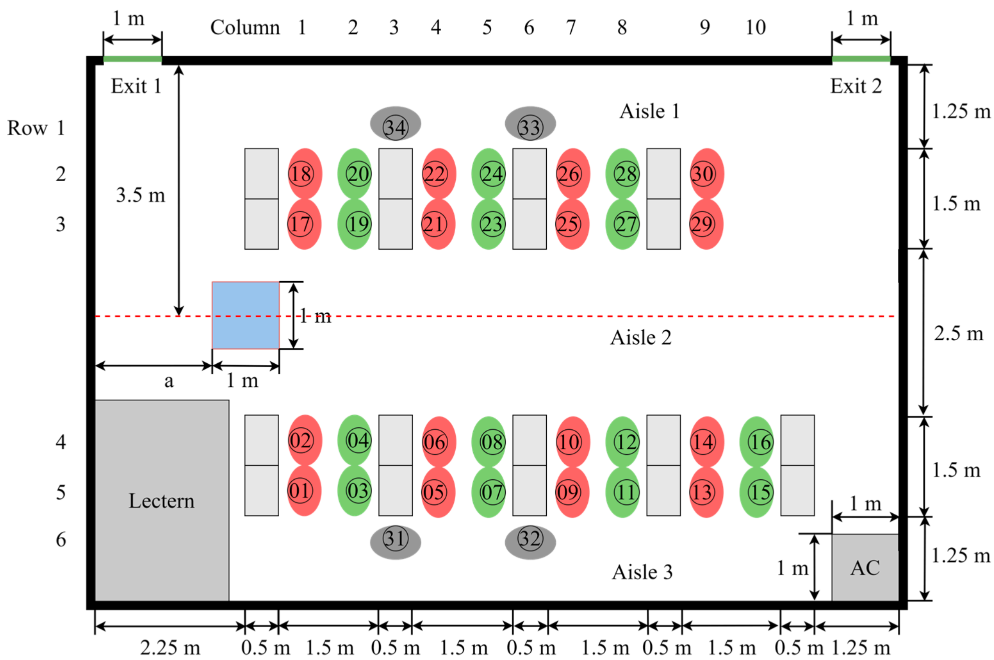
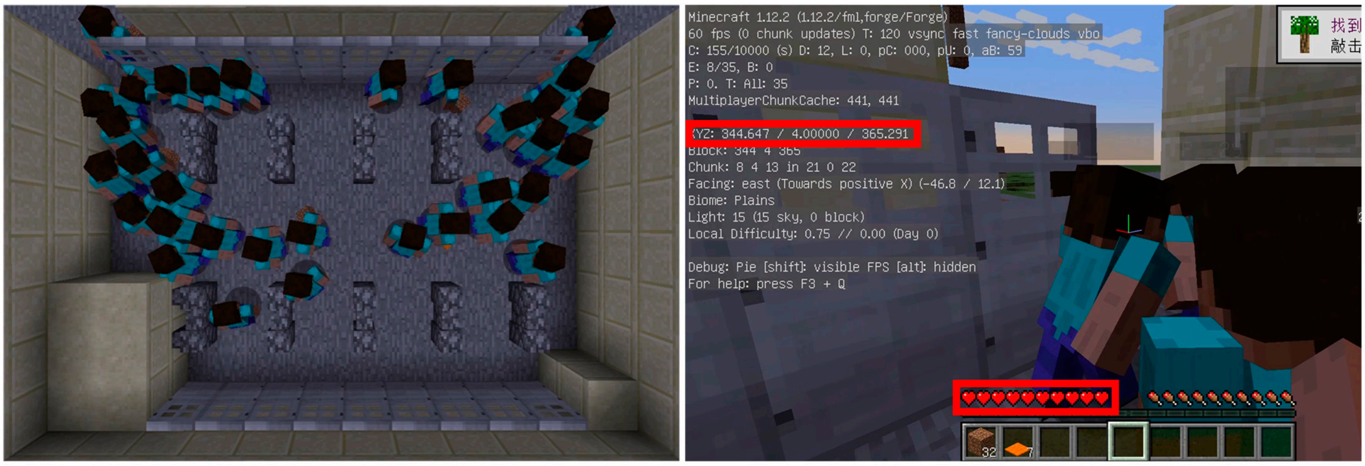


Figure 1. Schematic illustration of the classroom and the initial distribution of pedestrians. Different colors denote the initial orientation of the pedestrians: red indicates participants facing Exit 1, green indicates those facing Exit 2, and gray signifies those facing Aisle 2.

2.2. Introduction of Minecraft

For the virtual experiments, we select Minecraft as a platform for experiments with high efficiency. As this game has been detailed in previous literature [34], a brief review of the platform and the corresponding settings in the context of our virtual experiment is presented here. Minecraft stands as one of the preeminent sandbox video games on a global scale. We have deliberately selected the version of Minecraft distributed by NetEase and have procured a dedicated server infrastructure to facilitate the establishment of our controlled experimental milieu. Within the Minecraft platform, participants exercise their creative faculties by manipulating an array of three-dimensional blocks, each constructed from an assortment of materials, including, but not limited to, dirt, stone, and coal. The intricate orchestration of character movements is achieved through a synthesis of mouse and keyboard inputs, affording a nuanced level of control over in-game actions. Moreover, the salient feature of Minecraft resides in its ability to seamlessly accommodate the synchronous participation of multiple players, each interacting with the virtual world from their distinct computational terminals. This collective engagement unfolds within the immersive realm of a first-person perspective, conferring upon participants the prerogative to scrutinize the spatial coordinates and vectorial trajectories of co-players.

Within the expansive gamut of Minecraft, two predominant modes reign supreme, namely, the Creative Mode and the Survival Mode. In the former, participants are emancipated from the shackles of mortality, endowed with limitless reservoirs of resources requisite for the fabrication of complex virtual environments, and vested with the faculty of aerial mobility within the digital confines. Consequently, this mode serves as an invaluable instrument for the meticulous observation and systematic documentation of the entire egress process, as lucidly exemplified in Figure 2a. In stark contrast, Survival Mode imposes a finite number of lives upon participants, as conspicuously illustrated in Figure 2b. In this exigent milieu, players grapple with the imperative to safeguard their virtual existence by evading perilous encounters, thereby instigating a fervent quest for self-preservation. This latter mode inherently lends itself to the rigorous scrutiny of real-time fire evacuation experiments, featuring the dynamic interaction of multiple virtual pedestrians navigating hazardous terrain. Thus, it is incumbent upon our research to harness the intrinsic capabilities of both modes, thereby affording a holistic vantage point from which to investigate and elucidate the nuances of the evacuation phenomena under examination.



(a) (b)

Figure 2. Screenshots of the experiment in Minecraft: (**a**) screenshot of the researcher in Creative mode and (**b**) screenshot of a player in Survival mode.

3. Methodology

This study is based on the scenario described in Section 2.1 and it involves the design of seven experimental groups by varying the types of obstacles (i.e., normal obstacle and fire) and the positions of obstacles. Across these seven experimental groups, we systematically manipulate the number of exits to investigate distinct cases involving varying exit quantities, thereby categorizing the seven experimental configurations into two distinct case categories. In Case 1, only Exit 1 is accessible, whereas in Case 2, both Exit 1 and Exit 2 remain open. The details of the seven experimental configurations are comprehensively summarized in Table 1.

Table 1. The details of the seven experimental configurations.

Case	Experiment No.	a (m)	Obstacle Type	Exit 1	Exit 2
1	1-1	/	Without obstacle	Open	Closed
	1-2	3	Normal obstacle		
	1-3	3	Fire		
2	2-1	/	Without obstacle	Open	Open
	2-2	0	Normal obstacle		
	2-3	0	Fire		
	2-4	11	Fire		

In the week preceding the formal experiment, evacuation experiment manuals were given to participants, as well as access to the Minecraft environment, in order to cultivate familiarity with the requisite operational procedures inherent to the Minecraft platform. Note that additional training courses have also been arranged for better usage of the customized platform. Prior to the initiation of the experiment, all participants were furnished with comprehensive elucidations pertaining to the study's objectives and methodologies, and informed consent was procured through the execution of consent forms. Diverging from conventional experimental paradigms, the Minecraft-based experiments facilitated the precise retrieval of participant coordinates via the platform's debug mode, subsequently visualized on screen, as exemplified in Figure 2b. Optical Character Recognition (OCR) technology was harnessed to exactingly extract real-time pedestrian coordinates. In this study, all participants navigated within the Survival Mode, thereby controlling pedestrian avatars characterized by a stature of 1.5 m, dimensions of 0.6×0.6 m^2, a maximum movement velocity of 1.295 m/s, and a field of view spanning 70°. They were explicitly informed that their avatars possessed a limited number of lives and any contact with the fire could lead to injuries or even the loss of their avatars' lives. At the experiment's inception, all participants engaged in the game from a first-person perspective, activating debug mode to access on-screen pedestrian coordinates, and maintained stationary positions during the preparatory phase. Upon receipt of the commencement signal, participants deftly manipulated pedestrian avatars through the utilization of keyboard and mouse inputs, guiding them towards predetermined exit points. Simultaneously, they recorded the entirety of their evacuation endeavors from their unique individual views at a frame rate of 30 Hz/s through video recording software. Furthermore, throughout the course of the experiment, a designated researcher assumed the role of an observer within the Creative Mode, levitating above the virtual landscape to facilitate aerial observations and the documentation of the motion trajectories of all 34 participants. Following the culmination of the evacuation process, all recorded evacuation videos authored by the participants were systematically amassed. The access to the Minecraft server, detailed video recording process, and the evacuation videos can be seen in Supplementary Materials.

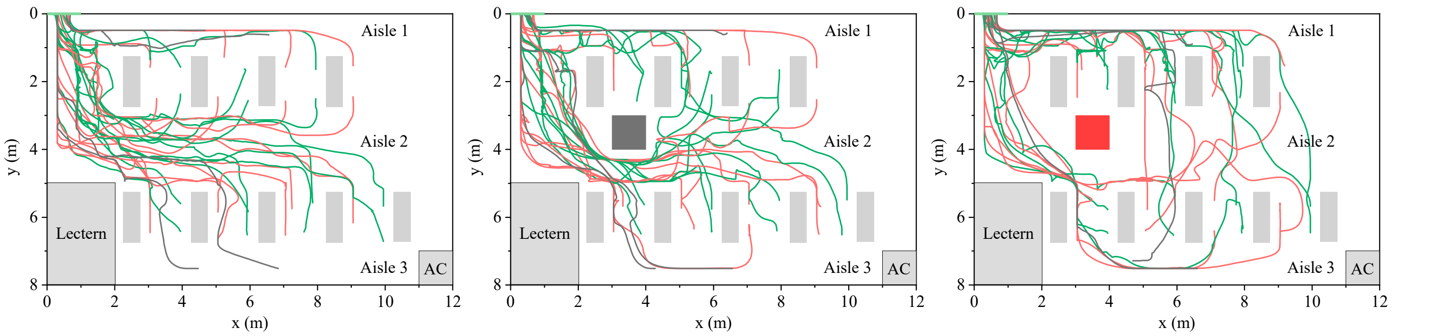
Videos acquired from the researcher's vantage point served as the basis for the observation and analytical evaluation of the evacuation dynamics exhibited by the collective cohort of pedestrians. Simultaneously, videos captured from the participants' individual perspectives were subjected to post-processing using the MCTrack software [34], thereby enabling the extraction of spatial coordinates and the subsequent generation of motion trajectories for each individual pedestrian.

4. Results and Discussion

4.1. The Result of the Experiments in a Single-Exit Classroom

Figure 3 presents the evacuation process of pedestrians in a single-exit classroom in normal and fire conditions. In the unobstructed scenario (see Figure 3a), pedestrians primarily move towards the exit through Aisle 2, and the dense trajectories near the exit indicate congestion. Additionally, some pedestrians are initially positioned near Aisle 1, leading them to opt for the path through Aisle 1 to the exit. Despite the lower pedestrian density in Aisle 1 at this point and pedestrians within Aisle 2 do not exhibit a shift in their evacuation route by traversing the gaps between desks to access Aisle 1. In the scenario with a normal obstacle (see Figure 3b), the majority of pedestrians still favor Aisle 2. However, when encountering the normal obstacle (represented by black cube), discrepancies in the evacuation paths begin to emerge. Certain pedestrians choose to move closely alongside the normal obstacle and circumvent it from below, whereas others opt to retreat and enter Aisle 1 through the gaps between desks. Furthermore, owing to the presence of the normal obstacle, all pedestrians located in $x < 5.5$ m and $y < 2.75$ m decide to enter Aisle 1. This phenomenon is attributed to the obstruction of the primary evacuation route by the normal obstacle, compelling pedestrians to alter their trajectories.

In the event of a fire scenario (shown in Figure 3c), we observe fire-avoidance behavior in advance among pedestrians. Trajectories of pedestrians near the fire (represented by red cube) are notably sparse, as the majority of pedestrians proactively shift from Aisle 2 to the more distant Aisle 1 to mitigate potential harm. This underscores pedestrians' paramount concern for their safety during fire emergencies. However, intriguingly, the minority of pedestrians persist in using Aisle 2. This behavior confirms the existence of risk-taking behavior among pedestrians during fire evacuation, wherein some individuals select a higher-risk path in pursuit of a faster evacuation, aligning with the findings of the research by Fu et al. [31]. Furthermore, these adventurous pedestrians proactively plan routes that maximize their distance from the fire.



(**a**) Experiment 1-1 (**b**) Experiment 1-2 (**c**) Experiment 1-3

Figure 3. The trajectories of pedestrians in the single-exit classroom. (**a**) Experiment 1-1, (**b**) Experiment 1-2, and (**c**) Experiment 1-3. Different colors denote the initial orientation of the pedestrians: red indicates participants facing Exit 1, green indicates those facing Exit 2, and gray signifies those facing Aisle 2.

Figure 4 presents experimental screenshots from three trials conducted within a single-exit classroom, each representing distinct scenarios: no obstacle, normal obstacle, and a fire incident. These screenshots offer a lucid depiction of variations in pedestrian behavior across different contexts. During the initial phase of the evacuation process (t = 3 s), in the absence of obstacles (refer to Figure 4a), pedestrians rapidly vacate their initial positions and proceed towards the nearest aisle. In scenarios involving the normal obstacle (as illustrated in Figure 4e), pedestrians tend to closely follow the contours of the normal obstacle to minimize the evacuation distance. Furthermore, the presence of normal obstacles induces congestion in close proximity to them, compelling a portion of pedestrians to switch from Aisle 2 to Aisle 1. In the context of a fire scenario (depicted in Figure 4i), the majority of pedestrians demonstrate a determined effort to distance themselves as far as possible from the fire. They transition from Aisle 2 to Aisle 1 to circumvent the area affected by the fire. Between t = 10 s and 24 s, during Experiment 1-1 (no obstacle) and Experiment 1-2 (normal obstacle), pedestrians gradually progress towards the exit, resulting in the emergence of congestion. In the fire scenario, the pedestrian population gradually segregates into two queues. Those opting for Aisle 1 form a straight-line queue with minimal spacing between individuals, whereas pedestrians exhibiting adventurous behavior near the fire assemble in a loosely organized yet orderly queue.

Figure 5 shows bar charts delineating the evacuation time of pedestrians in the single-exit classroom experiments. In Experiment 1-1 (shown in Figure 5a), it is observed that pedestrians within the same Row experience longer evacuation times as their respective Column increases. Similarly, for pedestrians located on the same Column, when the Column is less than 6, an increase in the Row results in a progressively greater distance from the exit, consequently prolonging the evacuation time. However, when Column exceeds 6, pedestrians positioned in Row 1 exhibit longer evacuation times. This phenomenon can be attributed to the fact that these pedestrians initially enter Aisle 1, which is relatively narrow, leading to pedestrians typically forming an ordered queue. Under the conditions of exit congestion, pedestrians within Aisle 1 encounter difficulties being confined for long periods of time away from the exit, as depicted in Figure 4b–d.

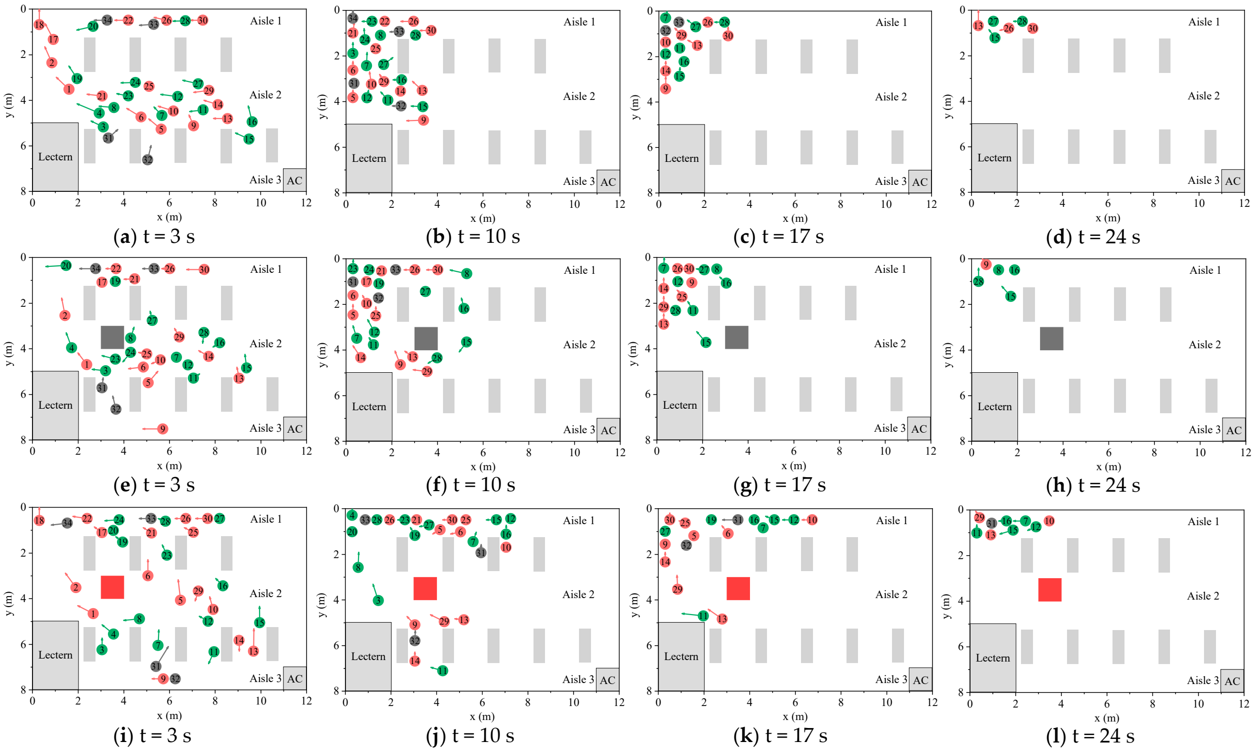


Figure 4. Screenshots of pedestrian evacuation from the single-exit classroom: (**a**–**d**) Experiment 1-1, (**e**–**h**) Experiment 1-2, and (**i**–**l**) Experiment 1-3. Different colors denote the initial orientation of the pedestrians: red indicates participants facing Exit 1, green indicates those facing Exit 2, and gray signifies those facing Aisle 2.

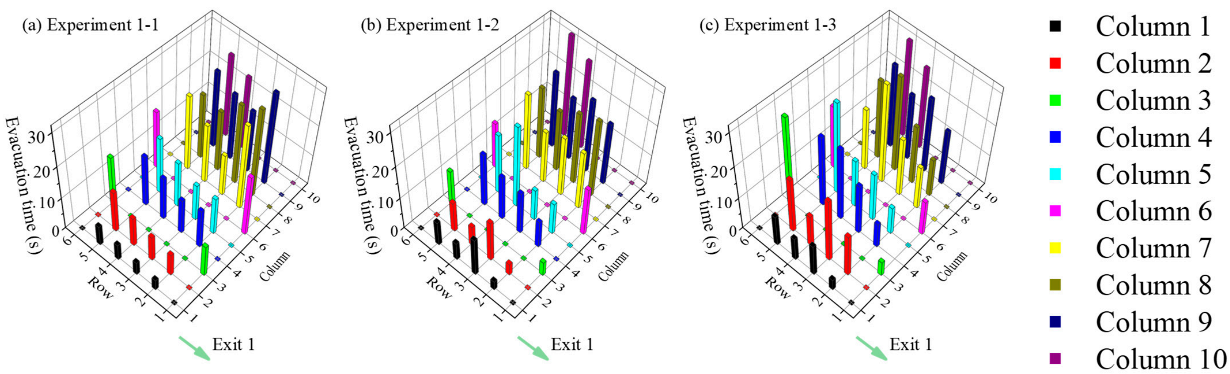


Figure 5. Bar charts delineating the evacuation time of pedestrians in the single-exit classroom experiments. (**a**) Experiment 1-1, (**b**) Experiment 1-2, and (**c**) Experiment 1-3.

In Experiment 1-2 (shown in Figure 5b), the overall distribution of evacuation times closely resemble that of Experiment 1-1. Pedestrians within the same Row experience prolonged evacuation times as their Column increases, indicating an increasing distance from the exit. However, Row 3 presents an exception due to the presence of the normal obstacle within Aisle 2. This condition necessitates some pedestrians in Row 3 (Column ≤ 4) to redirect their path towards Aisle 1. Yet, pedestrians in Row 2 are able to enter Aisle 1 first and form an organized queue, making it challenging for the pedestrians in Row 3 to access Aisle 1. For Columns greater than 6, pedestrians in Row 3 choose to enter Aisle 2 to bypass the normal obstacle, resulting in evacuation times similar to those in Row 4. Nevertheless, the pedestrian numbered 8 (i.e., Row 4 and Column 5) opted to retreat and enter Aisle 1 through the gaps between desks from Aisle 2, contributing to an increase in the evacuation time.

In Experiment 1-3 (shown in Figure 5c), the pedestrians within the same Row experience longer evacuation times as their Column increases, indicating an increase in evacuation distance. Compared to pedestrians on the left side of the classroom in Experiment 1-2 (Column $\leq$ 5), pedestrians in Experiment 1-3 (Column $\leq$ 5) exhibit longer evacuation times. This is attributed to certain individuals in Experiment 1-3 opting to slow down their evacuation speed and pass through the area affected by the fire, whereas others choose to circumvent the fire. Furthermore, it is observed that the pedestrian (ID: 31) located at Row 6 and Column 3 experiences longer evacuation times relative to surrounding pedestrians, which is attributed to retreating behavior yielding a longer detour route. Therefore, obstacles obstructing critical pathways during evacuation have a significant impact on the pedestrians' evacuation process, resulting in prolonged evacuation times. In the event that obstacles at these pathways have triggered a fire, evacuation times would further increase.

4.2. The Result of the Experiments in a Two-Exit Classroom

Figure 6 depicts pedestrian trajectories in a two-exit classroom under various types and locations of obstacles. In the absence of obstacles (shown in Figure 6a), pedestrians exit their positions and move towards the nearest aisle, proceeding towards the exits. Notably, pedestrians directed towards Exit 1 (highlighted in red) and those directed towards Exit 2 (highlighted in green) both primarily move towards their nearest exits. This indicates that in an obstacle-free scenario, exit choice is primarily influenced by the proximity of the exits. Similar to single-exit classroom scenarios, there is no observed tendency for pedestrians in Aisle 2 to enter Aisle 1, even when Aisle 1 is less populated. In the case of normal obstacles (shown in Figure 6b), pedestrians directed towards Exit 1 (highlighted in red) and those directed towards Exit 2 (highlighted in green) also mainly move towards their nearest exits after leaving their initial positions. Table 2 summarizes the exit choice results for all pedestrians and the ratio of choosing two exits in the two-exit classroom experiments. The results show that pedestrians' exit choices are identical in the scenarios without and with a normal obstacle. The presence of a normal obstacle does not significantly alter pedestrians' exit choices. However, congestion forms near the normal obstacles due to pedestrian crowding, resulting in chaotic trajectories and, in some cases, pedestrians entering Aisle 1 from Aisle 2. Additionally, in Figure 6a,b, pedestrians positioned in the center of the classroom (5.5 m $< x <$ 7.5 m) exhibit exit choices influenced by their initial orientations; some pedestrians opt for exits in their initial facing directions. In the event of a fire scenario (shown in Figure 6c,d), most pedestrians choose to move towards the exit furthest from the fire, with only those near that exit selecting the one close to the fire. When the fire is closer to Exit 1, there are relatively fewer pedestrians choosing Exit 1 over Exit 2, and vice versa when the fire is closer to Exit 2. This underscores the impact of fire on pedestrians' exit choices. Moreover, in comparison with the scenario with a normal obstacle (shown in Figure 6b), in the fire scenario (shown in Figure 6c), more pedestrians enter Aisle 1 from Aisle 2. This suggests that the presence of fire influences pedestrians' evacuation routes.

Figure 7 presents snapshots of four experiments conducted in the two-exit classroom (no obstacle, normal obstacle, fire near Exit 1, and fire near Exit 2). In this study, we primarily focus on the exit selection behavior during the initial evacuation phase, capturing moments at 3 s, 5 s, and 7 s. In the absence of obstacles, as shown in Figure 7a–c, the majority of pedestrians initially leave their positions to enter the nearest aisle and opt for the exit closest to them. Pedestrians located in the central region of the classroom are influenced by their initial orientations, with some individuals (ID: 8, 10, 23, 24) selecting the exit facing their initial positions. In the presence of a normal obstacle, as seen in Figure 7d–f, pedestrians exhibit behavior similar to that in Experiment 2-1. Pedestrians heading towards Exit 1 enter Aisle 2 and move closer to the normal obstacle. It is worth noting that in Figure 7d,e, one pedestrian (ID: 9) changes the exit choice during the evacuation process. This change is likely due to congestion near the normal obstacle, which can influence pedestrians' exit choices based on the evacuation speed around the exits.

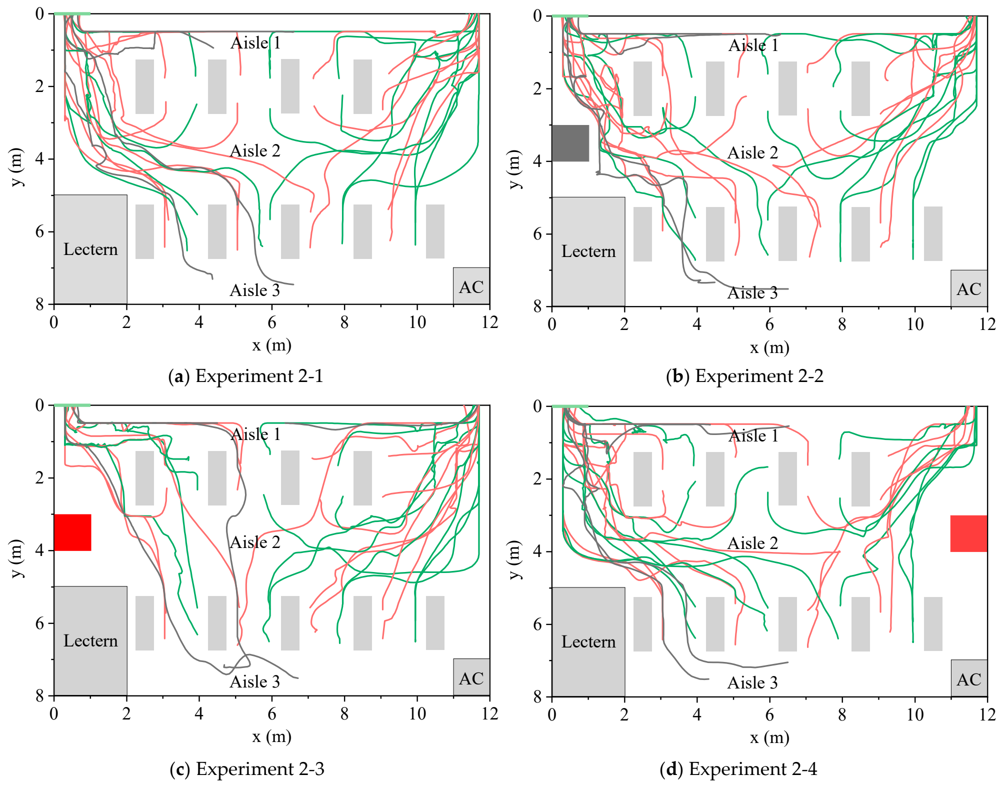


Figure 6. The trajectories of pedestrians in the two-exit classroom. (**a**) Experiment 2-1, (**b**) Experiment 2-2, (**c**) Experiment 2-3, and (**d**) Experiment 2-4. Different colors denote the initial orientation of the pedestrians: red indicates participants facing Exit 1, green indicates those facing Exit 2, and gray signifies those facing Aisle 2.

Table 2. The exit choice of pedestrians in the two-exit classroom.

ID	Experiment 2-1	Experiment 2-2	Experiment 2-3	Experiment 2-4
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4	1	1	1	1
5	1	1	2	1
6	1	1	1	1
7	1	1	2	1
8	2	2	2	1
9	2	2	2	2
10	1	1	2	1
11	2	2	2	1
12	2	2	2	2
13	2	2	2	2
14	2	2	2	2
15	2	2	2	2
16	2	2	2	2
17	1	1	1	1
18	1	1	1	1
19	1	1	1	1
20	1	1	1	1
21	1	1	1	1
22	1	1	1	1
23	2	2	2	2
24	2	2	2	1

Table 2. *Cont.*

ID	Experiment 2-1	Experiment 2-2	Experiment 2-3	Experiment 2-4
25	2	2	2	2
26	2	2	2	1
27	2	2	2	2
28	2	2	2	2
29	2	2	2	2
30	2	2	2	2
31	1	1	1	1
32	1	1	1	1
33	1	1	2	1
34	1	1	1	1
Total	Exit 1:Exit 2 = 18: 6	Exit 1:Exit 2 = 18:16	Exit 1:Exit 2 = 14:20	Exit 1:Exit 2 = 22:12

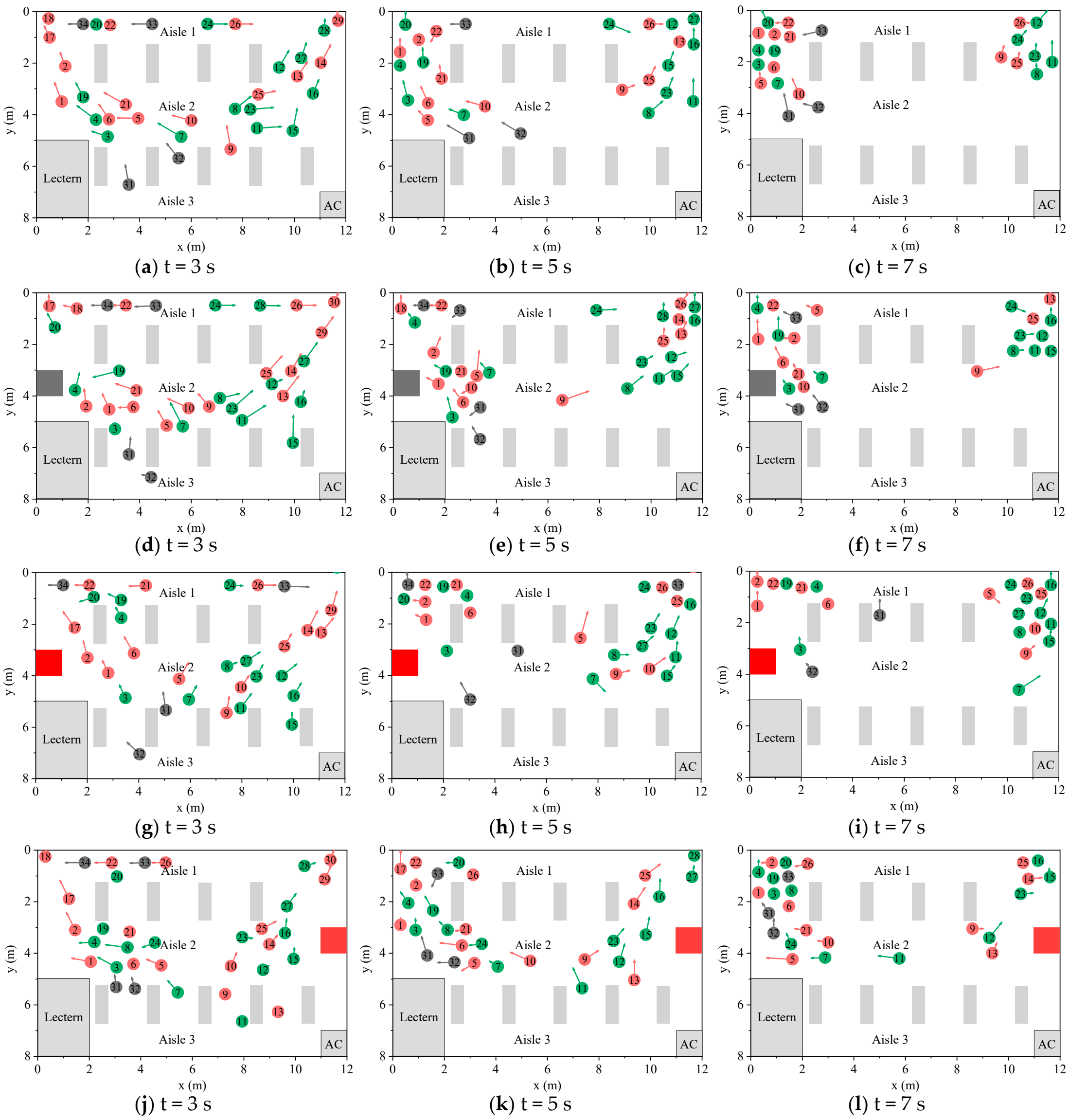


Figure 7. Screenshots of pedestrian evacuation from the two-exit classroom: (**a**–**c**) Experiment 2-1, (**d**–**f**) Experiment 2-2, (**g**–**i**) Experiment 2-3, and (**j**–**l**) Experiment 2-4. Different colors denote the initial orientation of the pedestrians: red indicates participants facing Exit 1, green indicates those facing Exit 2, and gray signifies those facing Aisle 2.

In Experiment 2-3, when the fire is located near Exit 1 (shown in Figure 7g–i), the fire alters pedestrians' exit choices. More pedestrians choose to move towards Exit 2, whereas some exhibit adventurous behavior. Compared to Experiment 2-2, pedestrians congest around the normal obstacle, and in the fire scenario, pedestrians near the fire form queues, driven by their intent to maximize distance from the fire. In Experiment 2-4, when the fire is near Exit 2 (shown in Figure 7j–l), more pedestrians opt to move towards Exit 1. Furthermore, the presence of fire results in changes in exit choices among pedestrians (ID: 10) during the evacuation process.

Figure 8 displays the bar charts delineating the evacuation time of pedestrians in the two-exit classroom experiments. In Experiment 2-1 (shown in Figure 8a), it is observed that pedestrians in the center of the classroom have longer evacuation times as they are farther from the exits, whereas pedestrians on both sides of the classroom are relatively close to the exits and have shorter evacuation times. Additionally, pedestrians located on the same Column experience longer evacuation times as their respective Row increased, indicating a gradual distancing from the exit. It is worth noting that the pedestrian on Row 2 and Column 5 (ID: 24) has a longer evacuation time due to the fact that the pedestrian is influenced by the initial orientation and chooses to move to Exit 2 through Aisle 1, thus meeting the pedestrians on Aisle 1. Experiment 2-2 (see Figure 8b) shows a similar overall distribution of pedestrian evacuation times to Experiment 2-1, as the presence of the obstacle has a limited effect on the pedestrian's movement pattern and exit choices. Notably, the pedestrians numbered 15 and 16 exhibit longer evacuation times compared to their immediate neighbors. This discrepancy in evacuation times may be attributed to some fluctuation due to the longer distance between the exits and pedestrians in Row 4 and Row 5.

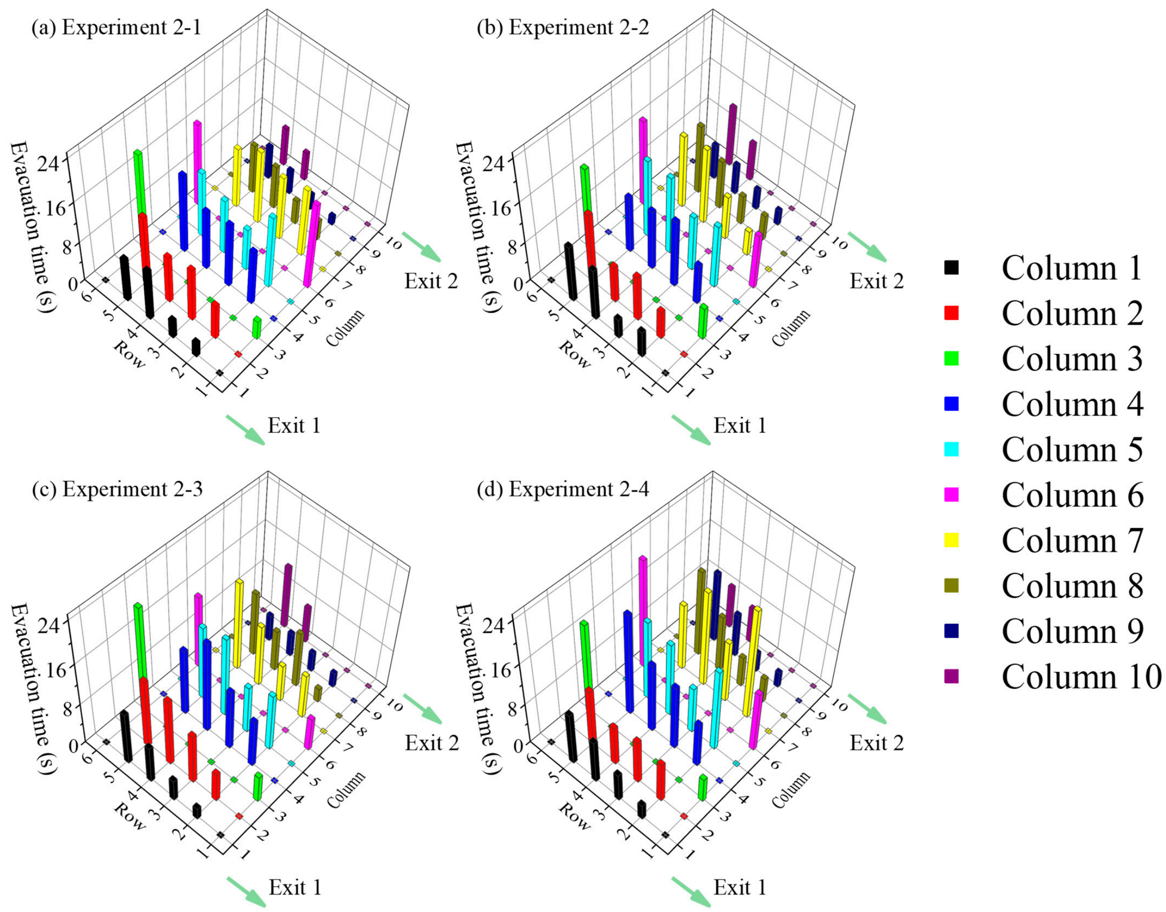


Figure 8. Bar charts delineating the evacuation time of pedestrians in the two-exit classroom experiments. (**a**) Experiment 2-1, (**b**) Experiment 2-2, (**c**) Experiment 2-3, and (**d**) Experiment 2-4.

As shown in Figure 8c, in Experiment 2-3, when the fire is located near Exit 1, only some pedestrians at Column $\leq$ 4 choose to evacuate from Exit 1, whereas all pedestrians at Column $\leq$ 2 select Exit 1. This results in a typical distribution of evacuation times, that is, a tendency to increase with the distance from the exit. It is worth mentioning that there is an outlier in the evacuation time for pedestrians in Column 4, attributable to one pedestrian's choice to evacuate from Exit 1, blocked by the queue in Aisle 1 (ID: 6). Moreover, the evacuation time for pedestrians who choose Exit 2 increases as the distance from Exit 2 increases. For Experiment 2-4 (shown in Figure 8d), with the fire near Exit 2, all pedestrians with Column $\leq$ 4 choose to exit the classroom through Exit 1, and the evacuation time increases with distance from Exit 1. Pedestrians occupying Columns 5 to 7 experience fluctuations in evacuation times due to variations in their exit choices. Additionally, for Column > 8, all pedestrians choose Exit 2, and the evacuation times for these pedestrians conformed to the expected norm. Comparing Experiment 2-3 and Experiment 2-4, it is observed that the fire in various locations primarily affects pedestrians' exit choice and evacuation efficiency in the center area of the classroom, with minimal impact on pedestrians near the exit.

5. Conclusions and Future Work

5.1. Limitations and Future Work

In this study, Minecraft was adopted to investigate fire emergency evacuation in a classroom. This study provides novel insights into pedestrian behavior and exit choices. However, this study still has some limitations. Firstly, it is important to note that all participants in this experiment are students, which may limit the generalizability of the results, as some notable phenomena may only be found in the young population. For future research, it is imperative to extend the investigation to encompass other demographic groups, thereby broadening the applicability of the results. Secondly, the study primarily focuses on the examination of exit choice and evacuation behaviors among pedestrians during fire emergencies. However, it should be acknowledged that the psychological factors, specifically the dynamics of peer pressure, group interaction, and social norms, have not been examined, and the mechanisms governing individual decision-making for fire evacuation have not been fully investigated. To address these related deficiencies, future research efforts will involve incorporating questionnaires and other methodologies to delve into the intricate psychological underpinnings that influence pedestrian behaviors. Thirdly, the virtual environment constructed in Minecraft is still relatively basic compared to other immersive virtual reality technologies and fire spread is not considered in this study. For future studies, we will attempt to develop additional modules and resource packs for Minecraft to enhance the realism of virtual environments. Finally, with the increase of complex in scenarios, we will involve exploring more flexible pedestrian movement speed schemes to simulate intricate evacuation processes, and meticulously design more comparative experiments and employ statistical analysis to mitigate the influence of the sequence virtual environment and individual differences, such as the familiarity with playing Minecraft, on the experiment results.

5.2. Conclusions

The investigation of evacuation behavior during fires in indoor buildings with high population density and multiple obstacles, such as classrooms, is essential for the development of effective evacuation management strategies to ensure pedestrian safety. In this study, we construct a classroom with internal obstacles forming intersecting pathways in Minecraft, and conduct a series of virtual evacuation experiments involving multiple pedestrians with a single exit and two exits. By analyzing pedestrian behaviors and movement patterns in normal and fire scenarios, we observed the following:

(1) In the single-exit classroom experiments, a normal obstacle and fire in the main evacuation path prompt pedestrians to detour, resulting in prolonged evacuation times. In normal obstacle scenarios, pedestrians move close to the obstacle and part

of them opt to retreat in front of the obstacle. During fire emergencies, pedestrians exhibit fire-avoidance behavior in advance, detouring at a greater distance from the fire to ensure their safety.

(2) In the two-exit classroom experiments, normal obstacle has a limited effect on exit choices of pedestrians, and all pedestrians choose the same exit as in the no-obstacle scenario. The exit choices of pedestrians are principally influenced by their initial position and they primarily choose the nearest exit. Pedestrians positioned in the center of the classroom are influenced by their initial orientations; some of them opt for exits in their initial facing directions. In addition, normal obstacles can cause congestion, which may cause some pedestrians to change their initial exit choice.

(3) During a fire emergency in the two-exit classroom, the presence of fire had a greater influence on pedestrians' exit choices, with most opting for exits away from the fire. The pedestrians who select the exit in proximity to the fire experience an increase in evacuation time.

(4) In both single-exit and two-exit classroom experiments, some pedestrians engage in risk-taking behavior by choosing a higher-risk path in pursuit of a faster evacuation during fire emergencies. In addition, these adventurous pedestrians proactively plan routes that maximize their distance from the fire, and exhibit orderly queuing behavior.

This study delves into the utility of Minecraft as a tool for simulating complex built environments, and its potential application in the study of pedestrian evacuation during fire emergencies. The results reveal noteworthy phenomena that provide valuable insights into pedestrian behaviors during fire emergency scenarios.

Supplementary Materials: The access to the Minecraft server, detailed video recording process, and the evacuation videos can be found at https://github.com/magicalsky/Evacuation_in_classroom (accessed on 26 October 2023).

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