Route Choice and Flow Rate in Theatre Evacuation Drills: Analysis of Walking Trajectory Data-Set

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Abstract. This study analysed evacuees' movements in three sequentially announced evacuation drills in a theatre to clarify evacuees' route choice mechanism in an auditorium and to obtain a data-set for the validation of evacuation simulations and egress time calculations. The drills were conducted in a multi-purpose theatre in Japan over consecutive years, involving approximately 400–540 occupants aged 6–90. The coordinates of every occupant in the auditorium during the drills were accurately obtained every 0.5 s using the authors' original software programmes, so that evacuees' trajectories and walking speeds at each point could be obtained. Thereby, we obtained more than 100,000 data points in total to analyse. The drills were also compared from the point of view of the flow control of the facility's staff during the evacuation. The results revealed that, while the evacuees in the centre blocks chose the closest aisle from their seats, most of the evacuees in the side blocks chose the wall side aisles. The occupants did not create queues in aisles between seat blocks. They tended to walk along seatways, the narrow spaces between seat rows to get closer to their target exit, rather than stacking in the aisles. In addition, the specific flow at exit doors from the auditorium in a congested situation was ca. 0.96 pers./m/s.

Keywords: Evacuation, Human behaviour, Theatre, Route choice, Walking trajectory, Data-set

1. Introduction

Theatres are one of the places where a large number of people can be packed tightly in a large room. The evacuation of theatres has been much discussed because of their characteristics: the room is filled with rows of seats, which restrict evacuees' movements; the audience sits close together; multiple exits exist to process hundreds or even thousands of audience members simultaneously; and the audience is usually not familiar with the venue.

To make an audience evacuate from such a room in a short time, it is important to know the characteristics of evacuees' behaviour and to plan the audito-

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rium taking the needs of an evacuation into consideration. A theatre that is well planned for evacuation should have accessible exit doors so that there is a balanced distribution of the number of people using each exit. If evacuees converge on a single exit, the total evacuation time becomes longer. Therefore, each exit should receive an equal share of evacuees. It is required that the doors are located evenly from audience seats. In addition to this, the route to the exit doors is also an issue. Even if the exits are distributed evenly, evacuation takes longer time when the evacuees cannot easily reach the nearest exit.

However, it has not yet been proven whether occupants can actually evacuate well even if the theatre is well planned. Furthermore, the guidance to the audience by facility staff may also be a factor that affects the efficiency of the evacuation. This study clarified the evacuation behaviours of occupants in a well-planned theatre with multiple levels of facility staff intervention.

1.1. Understanding Theatre Evacuation in Existing Evacuation Planning Guidelines

This section briefly introduces guidelines regarding theatre evacuation in each country.

US: In the latest *SFPE Handbook* [1], a description of the evacuation from a room with seats and aisles can be found in the ‘Exit Components’ section. The evacuation is divided into three parts: ‘exit access’, ‘exit’ and ‘exit discharge’. The phase involving seats to exit doors, is categorised in the ‘exit access’ part. Whether multiple exits are required for a space depends on the number of occupants. A specific model about evacuees’ behaviours in this type of room, such as route choice or flow rates is not mentioned in the handbook. The layout requirements inside theatre auditoriums for fire safety are specified in detail in the Life Safety Code 101 [2] issued by the National Fire Protection Association.

UK: The *British Standard 9999* [3] covers recommendations of fire safety design for theatre, especially quantitative codes such as required widths of walkways or maximal numbers of seats in a row. Additionally, the UK government issued fire safety guidelines, the *Fire safety risk assessment: large places of assembly* [4], for people who are responsible for large assembly facilities, including theatres. Unlike the British standards, these guidelines devote more pages to human behaviours behind evacuation safety regulations. They describe that occupants evacuate first from their seat through a seatway to the end of the row to an aisle, then use those aisles to reach an exit. Moreover, the *Guide to Safety at Sports Grounds* [5], also known as the *Green Guide*, regulates plans for stadiums, which are similar to theatres. In the guide, the emergency evacuation time is determined separately from the normal egress time. The guide also suggests having more than one emergency evacuation route from a viewing area.

Japan: In Japan, the evacuation time calculation of auditoriums is specified in *The New Guidelines for Building Fire Safety* [6]. In these guidelines, auditoriums are categorised as rooms that contain bottlenecks. The guidelines suggest considering the evacuation of large auditoriums carefully because they may have bottlenecks along the way. Figure 1 is the instruction figure from these guidelines,

Figure 1. Example figure in the Japanese guidelines for the evacuation time calculation, captioned 'A plan with bottlenecks in a room'. Adopted from The New Guidelines for Building Fire Safety (1996) [6]. Text was translated by the author.

explaining the available safe egress time, calculated from audience seats to the exit doors in a cinema. As the figure indicates, the room is zoned for each exit, assuming that the evacuees go to the nearest exit through the nearest aisle from their seat. More specific theatre planning for fire safety is regulated at the city level. For instance in Tokyo, the Tokyo Fire Department regulates the seat arrangements in theatre auditoriums such as the required widths of aisles, walkways and seatways, and the maximal numbers of rows and seats in a seat block, in the fire prevention ordinance [7]. In the ordinance, required widths are designed based on the number of people who may use each aisle or walkway. Furthermore, the Bureau of Urban Development Tokyo Metropolitan Government regulates the structural framework of theatres in their building safety ordinance [8] such as the required number and width of exits for theatres.

1.2. Studies About Theatre Evacuation

There are several studies regarding the evacuation of theatres and cinemas. Nilsson and Johansson [9] noted social influence factors during the pre-movement phase through an unannounced evacuation experiment. Lovreglio et al. [10] proposed a new decision-making model for the pre-movement phase using Nilsson's evacuation experiment data-set. Another unannounced evacuation experiment was held by Galea et al. [11] during a live performance in a theatre. They carried out a very realistic fire evacuation situation and analysed the occupants' behaviours in

the response phase. These studies all focused on the phenomena in the pre-movement phase and clarified that occupants require extra time for decision-making before physically evacuating their seats. There are several other simulation models and case studies about theatre evacuations [12, 13].

Orazio et al. [14] carried out experiments including an evacuation drill in a theatre to determine the effects of photoluminescent signage on evacuees' wayfinding strategies. They recorded participants' paths from their seats to building exits observing videos from cameras installed along the evacuation route. As route selection in the auditorium was not the aim of their study, it is not clearly mentioned in the paper how the paths corresponded to the plan. The collected paths are enough to analyse the occupants' wayfinding strategies in the building; however, they are not detailed enough to study occupants behaviours within an auditorium spatially and temporally.

Regarding methodological trials to collect trajectories of occupants in theatre-like rooms, computer image recognition or other modern technologies were attempted in the latest studies. Yamashita et al. [15–17] investigated developing a measurement method for pedestrian flows on evacuation drills in a theatre. They evaluated several methods, including modern computer image recognition programmes, a RFID tag system, and LIDAR scanners to accurately measure evacuees' flow rates at doorways or corridors. In an empirical investigation by Boltes et al. [18] on pedestrian dynamics in a non-emergency situation of a spectator stand through a single exit at a stadium (highly congested state), stereo cameras were utilised to automatically extract the markers that participants equipped on their heads. These studies succeeded in obtaining microscopic pedestrian trajectories; however, they focused more on the physical pedestrian dynamics in a specific area of an entire room, such as bottlenecks.

As there remain many technical issues to track large numbers of occupants in crowded, large non-laboratory rooms, such as a theatre, neither evacuees' movement trajectories nor detailed evacuees' behaviours in the evacuation movement phase for an entire auditorium have yet been obtained.

1.3. Goals

The aim of this study is to obtain data for the validation of evacuation simulations and egress time calculations by analysing the evacuees' behaviours in a theatre during the evacuation movement phase. This was achieved through fire evacuation drills, utilising an approach of extracting detailed evacuees' trajectories from videos. This paper focuses on the route choice of evacuees inside an auditorium and the flow rate at the exit doors.

2. Methods

We surveyed annual fire evacuation drills in a theatre (Fig. 2) from 2015 to 2017. The drills were carried out during a so-called 'evacuation drill concert' in Japan, which is a free-of-charge concert that includes an evacuation drill as a requirement for participation. Recently, this type of event has been held in several Japa-

Figure 2. Camera view of the second evacuation drill in which a camera was used for occupants' trajectory extraction.

nese theatres to exercise an emergency situation for both concert audience and facility staff. Thus, the audience knew that there was to be an evacuation drill during the concert, but did not know exactly when or have any specific details.

Table 1 shows a summary of the condition differences amongst the three drills.

2.1. Subject Theatre Specification

The subject theatre is a multi-purpose municipal theatre (Fig. 3) located on the fourth floor of a high-rise building in Tokyo, Japan. It has a typical theatre layout with a capacity of 925 folding seats and eight wheelchair seats on the main floor and an additional 721 seats in the upper-level balconies. However, in these evacuation drills, only the main floor of the theatre was open to the audience. Figure 4 shows the plan of the main-level auditorium. The width of each seatway, the distance from the edge of an armrest to the seat back of the front row, is 600 mm and the narrowest widths of the aisles are 950 mm for the middle aisles and 750 mm for the side aisles. There are eight doors in total to the auditorium and all also serve as emergency exits. The inner width of all doors is the same: 1650 mm (Fig. 5). In front of the doors of exits 1A and 1F, there are stairs with six steps, while exits 1B, 1C, 1D and 1E connect directly to the auditorium. Concerning emergency evacuations, this theatre auditorium was well planned. It has a symmetric plan, with enough aisles to provide various exit routes and to enable rerouting if necessary, it has a balanced distribution of exits, and all emergency doors easily visible from every seat location. The dot-dash lines in Fig. 4 represent the border of the blocks in which occupants would evacuate using the same exit in a typical evacuation plan in Japan, based on the distance to the exit from the seat.

Table 1
Drill Conditions

	1st drill	2nd drill	3rd drill
Date	Aug, 2015	Aug, 2016	Aug, 2017
Number of occupants			
Able-bodied	349	449	456
Wheelchair users	2	2	0
From disability care centres	47	89	20
Total	398	540	476
Facility staff control	Control actively	Just giving information	None
Number of flow control staff			
On-stage	1	1	1
Exit door	5	6	1
Aisle	7	0	0
Timing to evacuate wheelchair users	Same as others	After all others evacuated	–
Other spatial differences	Stage ladders, 1D exit closed	–	Outer doors of 1C/1D closed
Number of trajectory data points	30,330	41,305	29,549

Owing to facility activities, there were minor spatial differences amongst the drills. In the first drill, two small ladders to the stage were present, blocking the walking space between the stage and the seats in the first row. These ladders were removed in the subsequent drills. Also in the first drill, both doors of exit 1D were closed. Then, in the third drill, the outer side doors of exits 1C and 1D were closed.

2.2. Occupant Characteristics

Occupants were all volunteers who were invited from the general public. In each drill, 398 (first drill), 540 (second drill) and 476 (third drill) people participated. As drill concerts occur once a year, the occupants in each drill were not identical. According to questionnaires, the age and gender distribution of occupants are shown in Fig. 6. The average age was 59.4 years in the first drill, 58.6 years in the second drill, and 60.8 years in the third drill. All occupants were required to evacuate during the drills.

Two wheelchair users were involved in the first and second drills, but there were none in the third drill. They evacuated with help from their attendants. In all three drills, people from several disability care centres participated; consisting of approximately 20 to 90 people, including the care centre staff (Table 1). On evacuation, they allowed other occupants to go first and then evacuated, assisted by their own care centre staff.

Figure 3. Plan view of the main floor of the subject theatre with evacuation routes to outside the auditorium.

2.3. Occupants' Seating

Occupants entered the theatre through the ticket gate on the floor below the main floor, then moved to the main floor via either the stairs or the escalator in the foyer (Fig. 3). The door to enter the auditorium was not controlled by the facility staff, although the majority of the occupants used exit 1C or 1D. The seat locations of all occupants were specified in advance by facility staff. Wheelchair users

Figure 4. Plan view of the subject auditorium.

were seated with their attendants in a wheelchair area, which was located in the middle of the auditorium, and the people from the disability care centres were seated together in the front part of the rear side blocks, as these were close to an exit. As with a normal performance in the theatre, seats were filled starting from the front rows. Hence, the rear seats were relatively vacant, as the concerts were not fully booked (60% occupied).

Therefore, in this paper, we focus mainly on the front section of the auditorium, where seats were mostly occupied.

2.4. Drill Scenario

The evacuation drills were conducted on the assumption that an earthquake had occurred during a brass-band concert, which then triggered a fire at the right-hand side of the stage. After the first announcement about the earthquake, the audience were instructed to protect their heads and to wait at their seats for the next

Figure 5. Photos and floor plans near exits 1A–1C. Exits 1F–1D are symmetric. a Exit 1A, b Exit 1B, c Exit 1C.

Figure 6. Distribution of occupants' age and gender.

instruction, because the building was deemed safe regarding the earthquake. Then, after the fire broke out, all occupants were ordered to evacuate the theatre, on the fourth floor of the building, using emergency staircases leading to the outside of the ground floor. To make the situation realistic, a smoke effect and a red-orange light imitating a fire were provided on the right stage wing. During the evacuation, the use of elevators and escalators was prohibited. Announcements were provided through the PA system installed in the theatre. The announcement script and siren were the same as those used in the Japanese Fire Service Act for a real fire, supplementing that it was a drill. A staff member on the stage provided some additional information, including the evacuation cue, using a megaphone. It took approximately five minutes between the first announcement of the earthquake and the evacuation cue.

2.5. Flow Control by Facility Staff

The method to control the flow of people by facility staff was changed in each of the three drills to evaluate any differences in evacuees' behaviour.

In the drills, several facility staff members were distributed in the auditorium to guide occupants to exit doors. There were three types of staff who controlled evacuation flow in the auditorium. The first type, named 'on-stage staff', was always a single person who made announcements about the evacuation, including the evacuation cue, from the stage using a megaphone. The second type, named 'exit door staff', were people who stood by an exit door and called out the location of the available exit. Each exit door had an exit door staff member. As shown in Fig. 7a, those staff waved an LED traffic wand and also called to occupants in a natural voice, repeating: 'Here is an exit.' The third type, named 'aisle staff', were people who were distributed in the aisles and controlled evacuees' movements to ensure evacuees used the nearest exit door. They could change their position around their 'beat' by their own decision. Figure 7b shows such an aisle staff member, restraining evacuees from moving ahead. In addition, there were also one or two staff walking around in the centre horizontal walkway, but this was only for safety reasons; therefore, they did not manage evacuee flow actively.

The strategy of flow control directed by the staff was purposely changed for every drill to clarify the effect of the facility's flow control on the evacuees' route selection. Table 2 shows the instructions by the on-stage staff to occupants. The on-stage staff judged uncrowded exits by observing the auditorium area from the centre of the stage. The first drill controlled the flow the most strictly and had the greatest number of facility staff, including all three types mentioned previously. Because of the aisle staff, occupants had almost no chance to head to other exits across their territory. In the second drill, aisle staff were removed, but the exit door staff as well as on-stage staff were present; therefore, occupants were able to use their own judgement to select an exit. Occupants could obtain information about uncrowded exits by the on-stage staff and exit door staff, but did not have to follow their instructions. In the third drill, there was no control of evacuees in the auditorium, except for an exit door staff member beside exit 1F. The on-stage staff member was present; however, this time, he only cued the evacuation and gave no follow-up information about uncrowded exits. Occupants therefore needed to select a route individually. The exit door staff member at 1F was included to compare with the other doors having no staff. She swung a traffic wand but said nothing to occupants.

The timing of the evacuation of wheelchair users was also different between the first and second drills. The wheelchair users in the first drill began evacuating at the same time as other occupants. However, in the second drill those users were evacuated once others exited the auditorium. No wheelchair users were in the auditorium for the third drill.

While the evacuation route inside the auditorium was left up to evacuees, the evacuation route outside the auditorium was always fixed, as shown in Fig. 3. Approximately 12 facility staff guided evacuees along those evacuation routes to the emergency staircases.

Figure 7. Photos showing a member of the staff who controlled occupants’ flow during the evacuation drill.

Table 2
Instruction Phrases by the On-Stage Staff

	Basic repeating phrase	Other frequent phrase
1st drill	‘Please evacuate leisurely and calmly’	‘Please use the left-side (which is uncrowded)’
2nd drill	‘Please evacuate calmly by following staff’s instructions’	‘The rear exits are relatively uncrowded’
3rd drill	‘Please evacuate leisurely and calmly’	–

2.6. Data Collection and Processing

The evacuation was recorded mainly utilising a 4K-quality video camera, which was hung on a lighting baton over the stage at a height of 12.2 m from the stage floor (Fig. 2). In addition, several supplemental video cameras were also installed in the auditorium to record the edge areas where the stage-mounted main camera could not observe.

Evacuees’ trajectories were extracted from the video recorded by the stage-mounted main camera using our original software. First, the movie was sliced into 0.5-s intervals and the coordinates of every occupant in the still frames were extracted by clicking on the heads of the occupants manually utilising our GUI application named Mogura, written in Swift on the Cocoa framework. Then, the coordinates of occupants in the still frames were translated to the real-world with another programme [19] using coordinates based on 32 reference points that were shot in the same video before the concert started. Reference points were installed at 1700 mm above the floor assuming body height of all occupants to be 1700 mm so that the translation of the occupants’ coordinates could be calculated at occupants head height level by Mogura. In this translation process, any camera lens distortion was also removed based on the reference points utilising the Camera

Calibration APIs of OpenCV, an open source library for image processing [20]. Finally, the coordinates of every occupant during the drills were recorded accurately every 0.5 s so that pedestrians' movements, trajectories and walking speeds at each moment could be obtained. These trajectory data were also translated into animation to observe detailed behaviours while evacuating. However, as described in Fig. 4, occupant trajectories at the rear corners could not be taken, due to obstruction by the upper-level balconies.

After the evacuation, all occupants were asked to answer a questionnaire regarding their general characteristics and other topics, such as impression and opinions about the drill. The recovery rates of those questionnaires were 67.6% in the first drill, 67.3% in the second drill, and 63.4% in the third drill.

2.7. Accuracy of Trajectory Data

As regards the data uncertainty, the trajectory data contains the following errors. First, because all occupants were assumed to be 1700 mm in height in the coordinates translation, each trajectory is possibly shifted, especially in the Y-axis, from the actual walking route due to body height difference or the occupant's posture. Second, errors could occur on the coordinate projection by assuming the surface was precisely flat in the height direction due to the irregularly increasing floor level caused by steps in the auditorium. In addition, there can also be errors caused by an occupant's head swing motion, the reference point location, or in the process of the manual plot. Consequently, spatial error margins can be considered to be 500 mm (maximal).

The trajectories are, however, accurate enough to analyse the routes occupants selected or the time transition of stacked areas, on which this study focuses, but not for microscopic pedestrian dynamics, such as individual distances or avoidance behaviours. The nature of the errors leads to errors that are either entirely shifted in a specific direction or skewed gradually, and there are no unexpected jumps. Therefore, instantaneous walking speed and direction analysis were also applicable.

Meanwhile, the temporal resolution is accurate (0.5-s) without errors, as time-frames were directly taken from the video and no manipulation or estimation was performed. Thus, flow rates at exit doors where the walkable width is physically restricted could be calculated.

3. Results

Analysing the occupants' trajectory data, as well as their behaviours in the videos, we determined the occupants' route choice characteristics, walking speed distribution and the flow rates at exits during evacuation from the theatre auditorium.

3.1. Evacuation Ratio and Pre-movement Time

As one of the requirements of attending these concerts was to participate in the evacuation drill, all the audience evacuated without doubt, excepting several occu-

Figure 8. Walking trajectories of all occupants.

pants in the second drill. Those non-evacuees were: seven from a disability care centre, and exempted from evacuation because it was difficult for them, but also two able-bodied people, who unexpectedly refused to move from their seats after hearing the evacuation cue. Likewise, no pre-movement time was observed in these drills. The occupants started evacuation immediately after the evacuation cue.

3.2. Occupants' Trajectories

The occupants in all three drills had a similar tendency when selecting their routes and exits. Figure 8 shows the trajectories of all the occupants. The diagrams depict that a large number of occupants who were seated in the front centre block did not use the middle aisles until the centre horizontal walkway or the stage, but walked through a side block to reach the side wall first. In addition, the centre part of the horizontal walkways was not used at all. Occupants did not go to the

Figure 9. Sequence of occupants' movements at 10-s intervals in the second drill. The bar indicates walking direction and speed in seconds.

exits on the other side of their seats, excepting exit 1C in the first drill, where the rear door on the other side was closed.

Figure 9 shows the sequence of occupants' movements at 10-s intervals in the second drill. According to Fig. 9, occupants moved away from the centre of the auditorium after the evacuation cue, then walked towards an exit. While occupants in the rear blocks headed for an exit through the aisles and the centre horizontal walkway, occupants in the front blocks walked firstly towards to the wall side then to an exit door. It can also be observed, at exits 1B and 1E, that occupants did not cluster around the door in a semicircle shape but along the side aisles.

3.3. Walking Speed

In evacuation or pedestrian behaviour studies, the density of occupants is often used to evaluate congested points. However, in these diagrams, it was difficult to distinguish a location where occupants flowed freely from an actually congested location. So detailed trajectory data was evaluated to develop average walking speed contour diagrams to evaluate the congestion, to solve this issue.

The average walking speed contour diagrams are created in the following procedure. First, classify every occupant's data point in every slice into two-dimensional meshes by their coordinates, but the data points whose occupant was still seated are omitted. Then, calculate the average walking speed of each mesh by adding all occupants' speeds and divide by the number of data points in the mesh, where the walking speed at each moment was defined as the distance between the current position and the position one sec later. Finally, draw a contour map using a graph plotter from the average walking speed mesh data with a contour interval of 0.2 m/s. Because this diagram aimed to discover areas where speed reduction occurred, meshes where average walking speed is over 1.0 m/s are ignored.

With these diagrams, locations of congested points can be evaluated, as the darker colour represents a lower speed without the need for a density diagram, as the frequency of occupants' arrivals at each point does not affect the values. From the viewpoint of the degree of congestion, the diagram evaluates an area, for instance, where all the occupants walked slowly and an area where half of the data points fully stacked but others walked at a normal speed as the same congestion level.

Figure 10 shows contour diagrams of the average walking speed of all the occupants in 400 mm meshes. According to the diagrams, congested points were not present in the middle aisles but were present in the side aisles. Hence, queues for exits did not stretch to the middle aisles through the horizontal walkway but in the side aisles. Considering this together with Fig. 8, occupants were not stuck in the aisles but kept walking in a seatway in the side blocks until reaching a side aisle, then queued up in a side aisle for an exit.

○ occupant (seating) —○ occupant (walking) ● occupant (speed < 0.2 m/s)

Figure 10. Distribution of average walking speed reduction with 400-mm meshed contour.

The diagrams also demonstrate that the occupants’ walking speed in seatways was lower than it was in the aisles.

3.4. Aisle and Exit Choice

Figure 11 illustrates the route choice of occupants. The symbols show the initial seating position of occupants, and the symbol colours and shapes represent the exit where they finally escaped from the auditorium. The dashed lines, on the other hand, represent a division line, showing in which direction occupants went from their initial position.

As indicated in the diagrams, occupants in a centre block chose the closest aisle from their seats, as the aisle selection was divided vertically in the middle of the blocks. However, by the side blocks, most of the occupants did not choose the closest aisle but chose the side aisles. In all drills, occupants strictly avoided pass-

Figure 11. Occupants' aisle and exit choice based on initial seating position. The occupant symbol types indicate the final exit they chose, and the dashed lines indicate a division line, showing in which direction occupants went from their initial position (Colour figure online).

ing each other in seatways, although this action was sometimes observed in aisles, which were wider. Thus, all occupants inside of a division line went to the same side aisle excepting one case. Likewise, overtaking in the same direction was also not observed. Moreover, this tendency can also explain an observed phenomenon that when somebody came from the centre blocks into the side blocks, the occupants still in the side block reversed their walking direction to the wall side. As a result, occupants in the side blocks could have a chance to access a middle aisle only up until the first person from another block came into their seatway, as long as the persons in the centre blocks (who were assumed to use the closest aisle but not side blocks) went through the side blocks. From viewing the raw movie foo-

Table 3
Queuing Time of Occupants' Who Abandoned Queuing Halfway

	Number of persons	Queuing time (s)			
		Average	S.D.	Min.	Max.
1st drill	0	—	—	—	—
2nd drill	20	14.9	12.9	0.4	41.0
3rd drill	14	18.1	8.3	5.5	35.1

tage, it was also observed that groups containing people who knew each other chose the same route. They moved tacitly together but sometimes also talked to each other to convey information about a reasonable route. Here, those groups were identified from the video as they talked to each other closely, were obviously a family group with parents and children, shared their belongings, or touched another group member's body.

Regarding exit choice, occupants generally chose the closest exit. This tendency seems especially strong in the first drill, because the facility staff controlled their movements in this trial. In the other drills, some of the occupants even changed the target exit during evacuation because of congestion at the closest exit in which they had initially queued. Table 3 summarises the queuing time of all those occupants who initially queued up at a congested exit and then changed to another one. The queuing time was defined as the time range between when the occupants first reduced the walking speed substantially by reaching a queue for an exit and when they resumed walking to move toward the new destination. As a tendency, they were people who arrived at the queue lately. Consequently, they needed to wait for a long time; however, at the same time, they had an opportunity to turn back the way because no one queued behind them. Occupants did not move against the flow so far as elbowing other people. In the second drill, Fig. 11 indicates that some occupants in the front blocks went out from exit 1C, which is located at the rear. According to the animation, they initially queued up at exit 1B but changed after realising it was taking too much time. Similarly, during the third drill, two occupants who were seated in the front centre block initially queued up to exit 1E but then changed to exit 1D. Concerning the rear part by comparing with the assumed exit choice, a significant number of occupants belonging to the area of the middle exits, 1B and 1E, actually went to the rear exits, 1C and 1D. It may be because they preferred an obviously uncrowded exit than the nearest but more congested one due to the vacant seats in the rear part of the theatre. This phenomenon would likely not occur if the seats were fully booked, or the seating distribution was even.

3.5. Flow Rate and Evacuation Movement Time

The appropriateness of occupants' exit selections were examined by comparing the usage of the exit doors. The rear exits, 1C and 1D, actually have two doors each;

Table 4
Specific Flows at Exit Doors

	Peak specific flow (pers./m/s)			Total specific flow (pers./m/s)		
	1st drill	2nd drill	3rd drill	1st drill	2nd drill	3rd drill
Exit						
1A	0.82	0.73	0.85	0.61	0.64	0.60
1B	0.94	1.06	1.09	0.63	0.87	0.73
1C	1.12	0.67	0.94	0.37	0.51	0.47
1D	–	0.36	0.48	–	0.32	0.33
1E	1.12	1.03	1.24	0.54	0.58	0.79
1F	0.85	0.88	0.91	0.54	0.70	0.64
Average						
1A/1B/1E/1F	0.93	0.92	1.02	0.58	0.70	0.69
All	0.97	0.79	0.92	0.54	0.60	0.59

however, those two doors were calculated together because the outer doors of 1C/1D were almost not used, even opened.

Table 4 provides a summary of the specific flow at each door at a stable peak moment, named the ‘peak specific flow’, and all the movement, from the start cue until the last person for each exit arrived, is named ‘total specific flow’. The stable peak moment of the first drill was in the range of 30–50 s from the evacuation cue, and those of the second and third drills was 20–50 s, as annotated in Fig. 12. Because the rear exits are not of significant concern, the average specific flow was calculated without exits 1C and 1D. Comparing the three drills, the peak time flow rate exhibits no large difference between drills. The average peak specific flow among all three drills was 0.96 pers./m/s.

Figure 12 shows the time transition of the numbers of occupants who had arrived at an exit, per exit. Each graph line ends when the last occupant arrived. Thus, the efficiency of the exit door usage can be evaluated with these graphs, comparing finishing times amongst the exits. Exits in the rear part, 1C and 1D, are drawn with thinner lines. As mentioned in the methods section, people who had a disability waited for other people, letting them go first before moving from their seats. However, they caught up others queueing for exits, so this time lag did not affect their evacuation time.

Comparing Fig. 12a with b, c, the finishing times of each door in the second and third drills are concentrated, but not in the first drill. In the first drill, the initial seat distribution was asymmetric and exit 1D was blocked, so occupants were restricted from moving to other exits across their territory due to the block by flow control facility staff. Therefore, they needed to queue in their exit in the territory even though there was a nearby uncrowded exit. Thereby, the finishing times in Fig. 12a were scattered. Additionally, the occupants’ arrival to exit 1C can be divided into two phases. Occupants in the first phase headed to exit 1C directly while those in the second phase first headed toward exit 1D and then changed direction to exit 1C after arriving at exit 1D because they realised it was closed. In

Figure 12. Time transition of numbers of arrivals at each exit door of the auditorium and the ranges of the stable peak times used in Table 4. Zero seconds indicate the evacuation cue.

the second and third drills, the finishing times were similar among exits except for exit 1E in the second drill, which wheelchair users used after all other occupants egressed. According to the initial seat distribution and the borderlines of the nearest exits drawn in Fig. 11, exits 1B and 1E would have theoretically received

almost double the number of occupants than 1A and 1F, and consequently took more time to complete. However, because some occupants did not simply go to the nearest exit but to an uncrowded one, as mentioned in the previous section, the two exits' finishing times were autonomously levelled off to other exits.

According to Fig. 12c, there was almost no difference between 1A, where a door staff waited, and 1F, where the spatial condition was the same as 1A but without door staff.

4. Discussion

4.1. Evacuees' Route Choice Strategy

From the results, the route choice strategy of evacuees, from their seat to an exit door in a theatre auditorium, can be modelled as follows.

Firstly, after deciding to evacuate, occupants stand up and look around to find the closest exit. They choose the closest exit from the exits that they can see from their seat or that they know of already, for example, the door through which they entered the auditorium. Then they walk towards the target exit, but only after the person ahead of them starts moving. If they come across a junction, they generally choose the closest branch to their target. However, if that branch is blocked with other people, they choose another way to get closer to the exit that allows them to keep walking, rather than waiting for others to go first or creating a queue. Finally, when they arrive as near as possible to an exit, and there is no other way to get closer but to queue for the target exit, they get into line. However, if the queue appears to be too long and they locate another exit that appears to be uncrowded, they may leave the queue line to go to the uncrowded one, as long as their way to the new exit is not blocked by others.

Overtaking and passing each other is avoided, especially in the space between seat rows. If someone comes from the opposite side of a seat row, the evacuee who is walking away from the wall side reverses walking direction. A quick passing against the mainstream in a wide walkway seems to occur occasionally.

There are also some social influences. If occupants are in a group who know each other, they move together. Evacuees follow staff instructions well and do not go against their guidance, especially if addressed directly. However, unclear instructions by staff can be ignored by evacuees.

4.2. Effects of Flow Control by Facility Staff

As aforementioned, the occupants generally followed facility staff instruction well. Thus, it is important for facility staff to lead evacuees on a reasonable route in an emergency situation. Evacuation routes are often not the same as the routes people would normally use. To find such a hidden emergency route is difficult for audience members to do by themselves, as they are not normally familiar with the venue. Audience members could also hesitate to open an emergency door that is closed without permission from facility staff.

Regarding the results of this paper, the occupants could choose an efficient exit (i.e. one which can be reached in the shortest time) even without facility staff support. It must be deduced from this that the auditorium of the theatre where the drills were held had a well-planned layout for evacuation. The exit doors were distributed evenly and, as a result, the occupants also split evenly to each exit, even when each simply chose the closest exit from their seats. Hence, if there are emergency doors that are not visible from audience seats, facility staff should give information about the location of those exits to evacuees. Or, if the auditorium layout is unbalanced so that occupants may congest some specific exits, facility staff should direct some of the evacuees to other exits. Our results suggest that a well-planned auditorium can also make up for an accidental lack (or lack of) facility staff to control an evacuation.

4.3. Limitations of this Study

As the results of this study were based on three announced evacuation drills in a single theatre, there are some limitations to be taken into consideration when reviewing the results.

- This paper does not deal with the process of the pre-movement phase, but only with evacuees' behaviours in the evacuation movement phase. The occupants were required to participate in the evacuation drill and the announcements about the fire, before the actual evacuation cue, took some minutes, so the occupants were ready to evacuate as soon as a facility staff member gave the cue.
- Because the drill was announced, the occupants must have had less anxiety or confusion than in an actual fire. These psychological factors can affect the behaviour of occupants.
- The theatre where the drills were held had a well-designed plan: namely, a balanced exit layout and enough aisles, both between seating blocks and the side walls.
- Not all seats were occupied during the drills, especially in the rear blocks. The situation in the rear section would change and become more congested if the seats were fully booked.
- Due to methodological limitations, the coordinates of the occupants' trajectories include some error margin. The coordinates were accurate in most cases; however, those error margins can be about 500 mm maximal, especially in the rear part of the theatre.
- As the evacuation drills were held in a single theatre under specific conditions, the average peak specific flow at exits, 0.96 pers./m/s obtained from the survey results depends on those drill conditions. Attention should be paid to this value in other contexts.

5. Conclusions

In this study, three sequential evacuation drills during a concert were conducted in a multi-purpose theatre over consecutive years to clarify the evacuees' route choice in the auditorium, the flow rate at exit doors, and the effects of flow control by facility staff. From the video of the drills, detailed trajectories of all occupants in the auditorium every 0.5 s could be obtained utilising the authors' pedestrian trajectory extracting programmes. Then, a data-set regarding audience evacuation behaviour in theatre auditoriums was developed and discussed in this paper. A model of evacuees' route choice, from their seats to an exit door of the auditorium, was proposed. The results revealed that the actual occupants' route strategy is partly not the same as assumed in existing fire safety guidelines; the occupants in our study preferred walking in seatways rather than in aisles that were wider but more congested or made a detour to reach their target exit.

This study succeeded in obtaining a data-set and route choice strategy on a theatre evacuation, which can be used for the validation of evacuation simulations or egress time estimations. Attention should be paid to the limitations of the data, because the evacuation drills on which the results were based were announced evacuations. This paper, therefore, focused on the occupants' movement, namely route choice and pedestrian flow, rather than human behaviours in the pre-movement phase or a panic situation. In an actual fire, occupants should evacuate as in an evacuation drill to avoid panic. Multiple real fire incidents in the past also indicate that occupants actually behave rationally, just like in a drill, as long as the fire in their evacuation route is not critical. In practical disaster prevention planning, it is desirable that occupants evacuate before the situation becomes critical. An evacuation plan should be based on actual evacuees' behaviour. Even when calculations of required walkway widths based on the number of occupants who may use those walkways are correct, if the assumption of the usage of those walkways were wrong, occupants may not be able to evacuate in the designed time by concentrating on alternate routes. By understanding occupants' behaviours in evacuation drills, a more reliable occupants' movement model can be developed for evacuation planning. A more reliable model could be developed by combining these results with previous studies on response behaviours in the pre-movement phase of theatre evacuations.

Further studies are needed making use of our huge trajectory data of theatre evacuation drills. Moreover, we have a plan for another drill in the next year. Our future prospects are discussing flow rate at other areas such as aisles, the relationship between time lags when movement starts and seat location characteristics, and the evacuation behaviours of people with disabilities.

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