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A STUDY OF RESPONSE BEHAVIOUR IN A THEATRE DURING A LIVE PERFORMANCE

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ABSTRACT

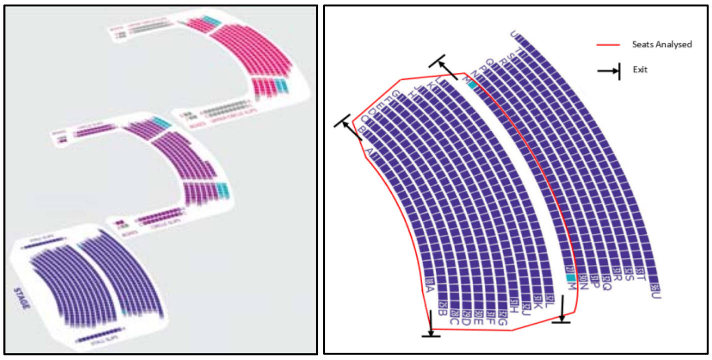
This paper presents the results of an unannounced theatre evacuation involving some 1200 people. The evacuation took place towards the end of a live theatre performance in the Marlowe Theatre in the UK. In particular response phase behaviours are discussed and response time data is presented. A key finding of this work which is different to other reported work is that the occupant response time distribution, while following the typical log-normal distribution is related to the geometrical positioning of the occupants relative to proximity to exit aisles and exit rows. Response time is found to increase relative to distance (seating location) from the exit aisles and exit rows.

INTRODUCTION

Response Phase Behaviour is an important aspect in determining the success of an evacuation that can influence the way in which an evacuation unfolds[1-3]. The way a population reacts to an evacuation alarm is dependent on a number of factors such as population size and distribution, population demographics, interpersonal relationships, prior evacuation experience, training, building familiarity, alarm type, nature of cues received, nature of pre-alarm activities, etc[1,2] . The nature of the building will influence many of these factors, so that a given population exposed to a particular type of alarm may display different Response Phase Behaviours if they are in, for example, an office building, rail station, or shopping mall[1,2]. This in turn will influence the response time (also called pre-movement time) distribution exhibited by the population. Knowledge of the correct response time distribution to use in evacuation analysis for building design and certification is essential, especially when using multi-agent based evacuation simulation models. While much work has been reported in the literature concerning response times in buildings such as office buildings, school buildings, libraries and even rail stations[2-5], theatres have attracted far less attention. This paper reports on a full-scale unannounced evacuation of the 1200 seat Marlowe Theatre in Canterbury Kent[6] on the 6th April 2013 during a full-house live evening performance. In particular the Response Phase Behaviours and the nature of the response time distribution are described. While the derived response time distribution displays the typical log-normal shape found in most evacuations, the distribution of response times amongst the population was found to be highly structured which has significant implications for evacuation modelling applications. Similar experiments have been performed in Sweden in a small cinema with up to 135 participants, the main aim of this study being to explore the impact of the type of alarm system, i.e. a simple bell and a voice alarm had on response time and also the impact of social influence of close neighbours on response time[7].

MARLOWE THEATRE AND THE EVACUATION PROCEDURES

The Marlowe Theatre is a 1200-seat theatre located in Canterbury, England. It consists of two main areas: The Main Auditorium and the Marlowe Studio. The venue is frequently used for shows including plays, musicals, ballet, contemporary dance, opera, as well as other forms of entertainment. The Main Auditorium seating is comprised of three main levels (see Figure 1a), the upper circle (highest level), circle, and stall levels (lowest level). While there are four exits on the lower tier, only the exits located at mid-point, to the right and left of row m, were available for evacuation during this exercise (see Figure 1b). The theatre had two seat widths depending upon seat location: wider seats were 0.525 metres wide, with the smaller seats possessing a width of 0.505 metres. The distance between rows varied between 0.9 metres to 1.0 metres depending upon row location. Video analysis was performed on occupants of the stall level rows A to M (Figure 1b) of the Main Auditorium. Thus people were seated in 13 rows, most of which had 30 seats.



(a) (b)

Figure 1. Seating arrangement in the Marlowe Theatre (a) with the study area highlighted (b)[8]

A total of 30 Sony Handycam camcorders were positioned throughout the auditorium, but video analysis was specifically performed on two cameras positioned in the circle slips at circle level, above the auditorium, to show people entering and evacuating at stall level (Figure 2).

(a) Camera 1 Prior to Evacuation	(b) Camera 1 During Evacuation

Figure 2. Marlowe Theatre Auditorium Level Prior-to and During Evacuation

The evacuation trial took place near the end of an evening performance of ‘Dirty Dancing’ on Saturday 6th of April 2013. The alarm first sounded at 21:53:25. The alarm to evacuate had two phases. In the first phase, fire doors were shut and buzzers, which could not be heard by the audience, were sounded outside the auditorium. In the second phase, all lights went to maximum brightness within the auditorium and, following a period of approximately 30 seconds, a manually activated pre-recorded message was broadcast in the auditorium. The pre-recorded message consisted of a male spoken voice which repeated the following statement: “In the interest of your safety we must stop this performance and must evacuate the building immediately. Please leave the building using only the exits indicated by our staff.” A steel safety curtain, which is part of the stage, also descended during the voice alarm. In addition, a number of fire appliances from Kent Fire and Rescue arrived on the scene with sirens active.

TERMINOLOGY AND METHODOLOGY

The evacuation process is considered to comprise of two broad phases the; Response Phase and Evacuation Movement Phase. In this work we are only concerned with the Response Phase. The Response Phase can be categorised into three stages: Notification, Cognition and Activity; where the

Cognition and Activity Stages run in parallel[1-3]. The Notification stage occurs when initial cues (such as alarms, the appearance of smoke or the behaviour of others) are conveyed to occupants, indicating an event that may require evacuation. This stage ends when occupants begin responding to the cues mentally and/or physically, thus entering the Cognition and Activity stages. During the Cognition stage, occupants interpret the Notification cues and other sources of information and decide on activities. The Activity stage begins when occupants perform a series of tasks which were conceived during the Cognition stage, such as collecting their belongings (an Action Task) or communicating with others (Information Task). The end of the Activity stage denotes the end of the Response Phase and the beginning of the Evacuation Movement Phase. The response time measures the duration of the Response Phase (start of the alarm to the end of the Activity Stage)[1-3].

In this paper, particular attention is paid to the Activity Stage of the Response Phase behaviour, determining at which point a person begins performing an Activity Task and at which point a person enters the Evacuation Movement Phase. It is normally assumed that the start of the Activity Stage marks the end of the Notification Stage, although this may not necessarily be the case. Furthermore, while normally the end of the Activity Stage marks the end of the Response Phase and the start of the Movement Phase, Movement Delays may occur between the completion of the Activity Stage and the start of the Evacuation Movement Phase (see Figure 3). This is usually the result of other factors, such as congestion as in the case of the theatre. In this work the Movement Time is defined as the sum of the Response Time and the Movement Delay and provides an indication of the total time that a person remains at their seat location following the sounding of the alarm.

As part of this analysis the following information was collected from the video footage: gender, row number, seat number, the Activity Start Time, the time at which the person stood up (Standing Time), the time at which the person had completed all Activity Tasks (Activity End Time), the time at which the person began moving (Movement Time), and the time in which they reached the end of the row (End Row Time). Also recorded were observations on a person's chosen direction of exit (left or right), activities performed as part of the preparation process, and any noticeable reasons for differences in a person's Activity End time and Movement Time.

The Activity Start time was identified when a person showed signs of beginning physical Action Tasks, i.e. they had fully acknowledged the alarm and began preparing for evacuation. The Activity End time was identified when a person appeared to have completed all Action Tasks, even if they had not yet entered the Evacuation Movement Phase. In this analysis, due to the nature of the video footage it was not possible to determine if people performed Information Tasks.

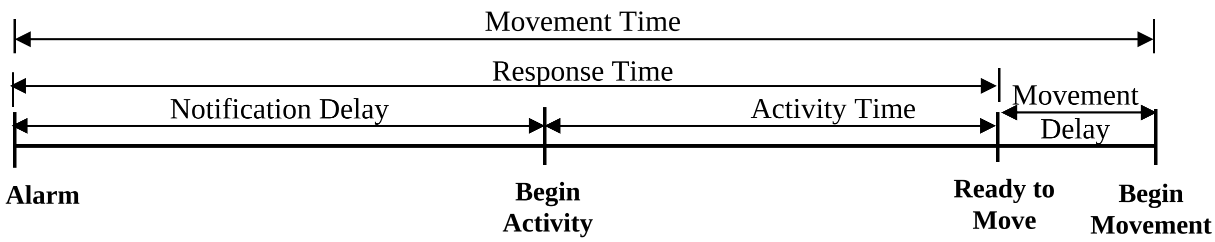


Figure 3. Response Phase

The five key times in this analysis can be summarised as follows:

- **Notification Delay:** the time from the start of the alarm to the time that a person begins activity. Activity begins when a person is seen to perform a physical activity, such as gathering or packing items. The Notification Delay is only considered for those who begin activity while remaining seated, and is therefore not considered for people who stand-up immediately (Note, Information Tasks are not considered in this analysis).
- **Activity Time:** the time required by a person to perform all of their preparation activities. It is the difference between the time when a person is seen to begin an Activity Task, (Activity

Start Time) and the time when a person is seen to complete all Activity Tasks (Activity End Time). The Activity Time can be measured for those who begin or undertake an activity while seated or standing. The Activity Time is only measured for those who are seen to undertake an activity and so there are no zero values for Activity Time.

- **Response Time:** is the time from the start of the alarm to the end of the Activity Time and hence is a measure of the time required to be able to begin movement.
- **Movement Delay:** is the difference between the time people begin purposeful movement towards an exit and the end of the Activity Time (Response Phase). The Movement Delay only considers those who are affected and therefore 0 values are omitted from the analysis.
- **Movement Time:** is the time from the start of the alarm to the time where a person begins purposeful movement towards the exit.

Due to limitations in space, this paper will focus on the analysis of the response time and response phase behaviour.

OBSERVATIONS AND DISCUSSION

Response data was recorded for a total of 321 people, 110 males, 199 females and 12 people of unknown gender. Due to the nature of the performance, the majority of the audience were female adults and this is reflected in our sample. Also, due to the time of year, many people had coats. Where possible, Action Tasks performed as part of the Activity Stage were recorded. The task most frequently observed as part of the Activity Stage (see Figure 4) were gathering or putting on a coat, with 125 people recorded as performing this task. The second most frequently observed task involved picking up a bag or gathering items and placing them in a bag (43 people). 18 people were observed to be putting on a scarf and 4 people were observed assisting others, e.g. helping another person put on a coat.

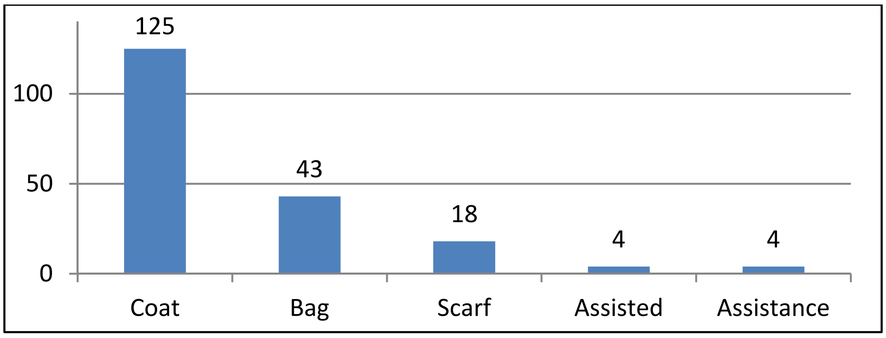


Figure 4. Common activities performed during evacuation

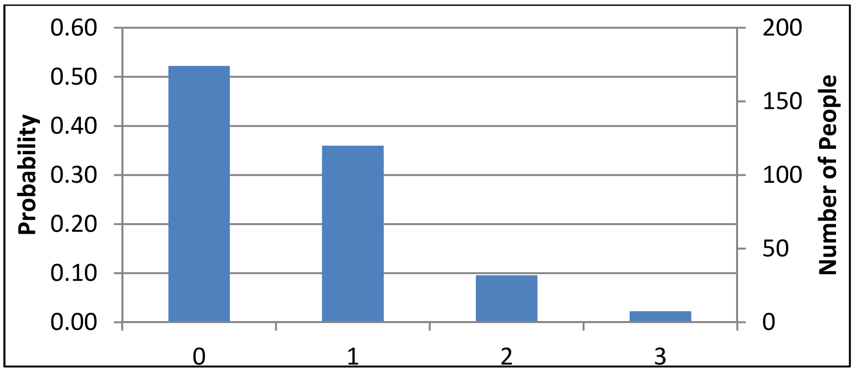


Figure 5. Number of Activities Performed during the Activity Stage

In terms of activities performed during the activity stage for the entire recorded population, it can be seen that the majority of people (55%) did not perform any tasks during the evacuation, followed by 38% of people performing a single task, 10% performing two tasks, and 2% performing three tasks (see Figure 5). The average number of tasks performed by a person was 0.62. The number of tasks performed was also analysed by gender to determine if there was a gender bias to the number of activity tasks undertaken during the response phase. For the male population, 60% performed 0 tasks, while approximately 35% performed 1 task and 5% performed 2 tasks. No males performed 3 tasks during the evacuation while the average number of tasks performed by males was 0.47. For the female population, 49% performed 0 tasks, 35% performed 1 task, 12% performed 2 tasks, and 4% performed 3 tasks. Thus on average females perform 0.70 tasks, 49% more than the males. With this difference it may be expected that males would have a shorter average response time than females, however, the average response time (for the non-disabled population) for the males is 57.8 s while the average response time for the females is 55.3 s (see Table 1). The reason that males have a longer average Response Time (RT) than the females is due to a combination of factors, first the average Notification Time for males (31.1 s) is greater than that for females (28.0 s) and while males undertake fewer tasks than females, they take on average longer to complete a task, 20.2 s for the male population compared to 18.1 s for the female population.

Response Time Frequency Distribution

The overall RT statistics for the population are presented in Table 1. The average RT for the overall population is 64.7 s which includes the RT for two disabled people (in wheelchairs) and their four helpers (545.3 s, 545.3 s, 545.3 s, 545.3 s, 287.6 s and 187.6 s). Excluding the disabled population and their helpers, the average response time for the population was 57.3 s, thus it takes on average about 1 minute for people to respond to the call to evacuate within the theatre.

The RT distribution for the theatre – excluding the disabled occupants and helpers - is depicted in Figure 6 (and equation 1) and follows the typical log-normal distribution with mode between 30 s and 40 s.

$$y = \frac{1}{\sqrt{2\pi}(0.54)x} \exp\left[-\frac{(\ln(x) - 3.99)^2}{2(0.54)^2}\right] \quad (1)$$

Table 1. General RTD statistics for male and female, both with and without disabilities

	Overall pop	Non-disabled pop	Disabled Only	Overall Pop*		No Disabled*	
				Male	Female	Male	Female
Number	314	308	6	106	196	103	194
Max RT (s)	545.3	183.4	545.3	545.3	287.6	133.1	122.0
Average RT (s)	64.7	57.3	442.8	68.1	57.2	57.8	55.3
Min RT (s)	4.12	4.1	187.6	4.1	4.1	4.1	4.1
SD	61.7	24.5	147.9	71.7	28.5	27.0	23.3

*Data excludes a male and female outlier with a response time of 183 s

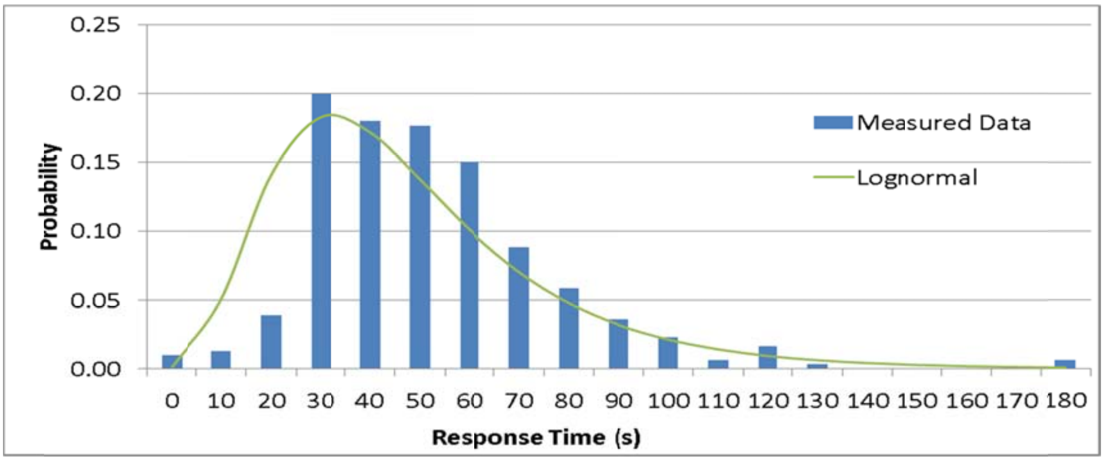
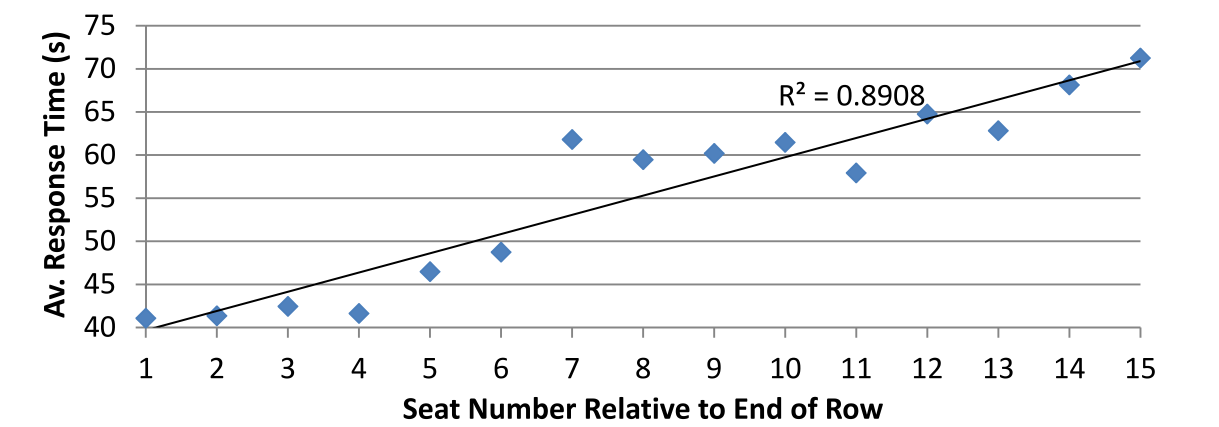


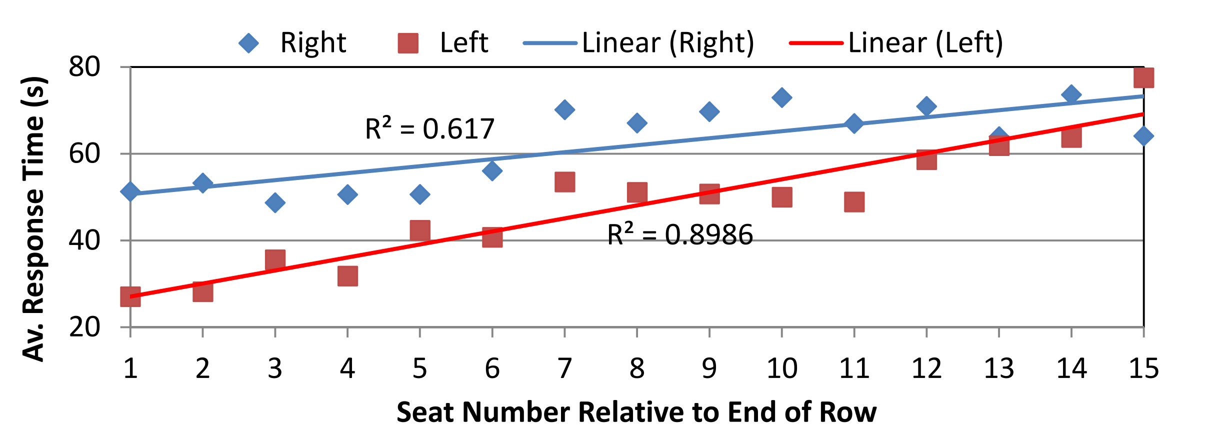
Figure 6. Response time frequency distribution

Response Time Based on Seat Location

The population RT was analysed based on seat location to determine whether there was a geometrical nature to the distribution of response times. Seat location was determined by counting the number of seats from the *nearest exit aisle*, thereby determining the shortest distance to the nearest aisle. From this, the average RT for a seat location across all rows was determined (see Figure 7). Seat 16 was omitted from the analysis due to a limited amount of data, as a minimum of 8 out of the 12 available seats were required to be filled to be considered in this analysis.



(a) Seat number as a function of average response time



(b) Seat number as a function of average response time separated by nearest exit row

Figure 7. Average response time based on seat location

The data suggests that average RT follows an increasing linear relationship (regression coefficient of 0.89) based on seat number, where the larger the seat number (i.e. the further away from an exit aisle), the larger the RT (see Figure 7a). These distances can also be separated based upon the direction of the nearest exit aisle, left or right. When this is done it is found that both the left and right follow a similar linear relationship (see Figure 7b). Thus the RT appears to increase from the exit aisle seat location towards the centre seat location working from both the left and right side. However, seats located on the left of the theatre have slightly lower RT compared to equivalent seat locations on the right and the rate of increase in RT with seat location is slightly greater for seats located on the left. Indeed, the average RT for seats located on the left of the theatre is 47.7 s while the average for those on the right is 61.0 s. The reason for the difference in RT for the left and right part of the theatre is not clear but may be due to the location of the main entrances to the theatre complex and the stalls being located on the right side. Those located on the right are close to the main exits and so do not feel the need to rush their response however, those on the left are far removed from the main entrance (the way the vast majority of them entered) and so may feel a greater need to react quicker than those located closer to the exit. The trend of increasing RT with distance from the exit aisle may be a result of people realising that they are going to have to wait for those ahead of them to begin to move before they can start their evacuation and so they take slightly longer to react.

The population RT was also analysed based on row number (see Figure 8). Rows 1, 2 and 12 were omitted from analysis due to limitations in the data which was collected. In these rows only 15, 15, and 18 people in each respective row was measured whereas in every other row a minimum of 26 data points, was collected with an average of 30 data points for each row. As can be seen in Figure 8, with the exception of row 6, there is a clear pattern in response time behaviour, with rows closer to the front and rear of the auditorium, having the shorter average response times with the response times increasing the further away the row is located from the end row. The reason for this trend is thought to be similar to that for the RT trend with seat number. As the exit points in the auditorium are located near the first and last seat rows, for people in rows further removed from the exit points the more people will be ahead of them and hence the longer they will take to exit and so they need not react so quickly.

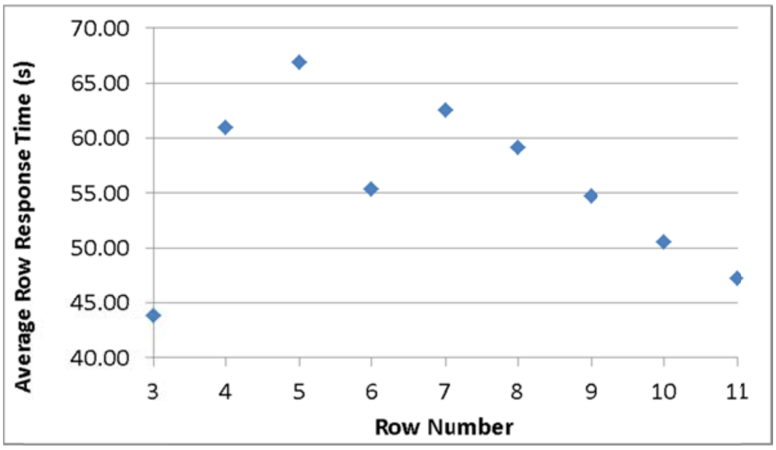


Figure 8. Average Response Time Based on Row Number

This analysis has shown that there is a clear structure to the RT distribution within the theatre, with RT generally increasing linearly the further a seat is removed from an exit aisle and the further the row is removed from an exit row. Thus the seat location relative to exit aisles and exit rows appears to be a good predictor of RT. This is a different behaviour to that observed in the Swedish work[7] which did not observe a strong relationship between seat location and response time. The differences in the results may be due to a number of factors such as; the small size of the sample population observed in the Swedish experiments (which was 40% of the size of the current sample), the small physical size of the cinema in the Swedish trials, the fact that the Swedish cinema was not full or all of the above.

Redistribution Model for Response Times

From the above analysis it is clear that the RT distribution within the theatre is strongly influenced by occupant seating location. Thus if the log-normal distribution given by equation 1 was to be used to generate RTs for the theatre population and they were randomly distributed throughout the theatre, as is typically undertaken in evacuation simulation using software such the buildingEXODUS[3], then the structure in the RT distribution would be lost. Presented in Figure 9 is the measured and predicted RT as a function of seat number (see Figure 9a) and seat row (see Figure 9b). As can be seen, the randomly allocated predicted RTs do not generate the same trends of RT with seat number and seat row as observed in the actual data. As a result, unrealistic results are likely to be produced by the simulation software, with predicted evacuation times likely to be too long or too short and as a result issues relating to the formation of critical congestion may not necessarily be observed.

When allocating RTs to seat locations it is thus necessary to allocate the RTs in a manner that preserves the observed structure of the RT distribution. To achieve this, the general pattern in RT

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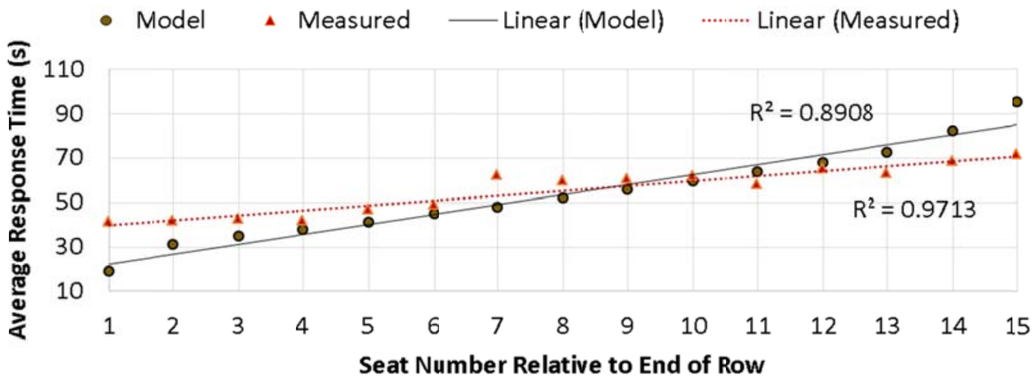
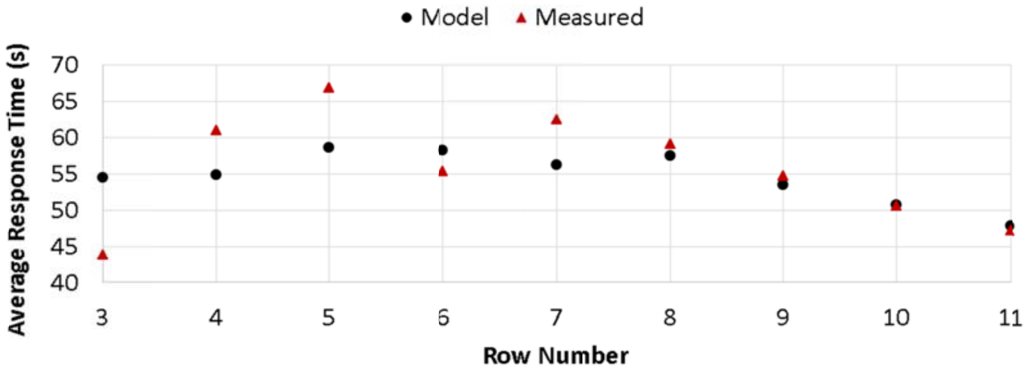
distribution is followed assuming that the RT increases from the outer seat locations inwards and from the outer seat rows inwards. Thus an allocation model as depicted in Figure 10 is suggested. The allocation model is here demonstrated for an auditorium with 6 seats per row and 5 seat rows. To achieve this, the required number of RTs are generated randomly according to the log-normal distribution presented in equation 1. The RTs are then ordered from the lowest to the largest and distributed according to the model presented in Figure 10.



(a) Seat number average response times



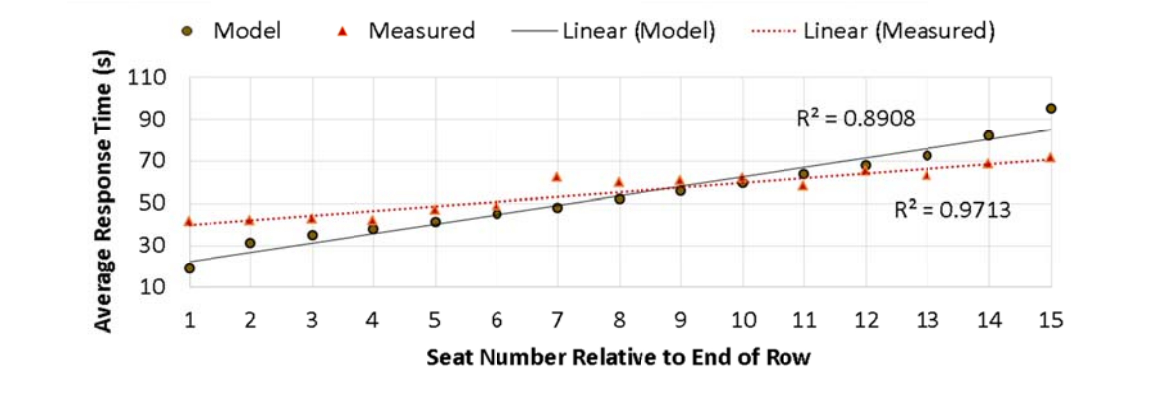
(b) Seat row average response times

Figure 9. Predicted and measured average response times based on seat number (a) and row number (b) assuming the standard random approach for allocating response times

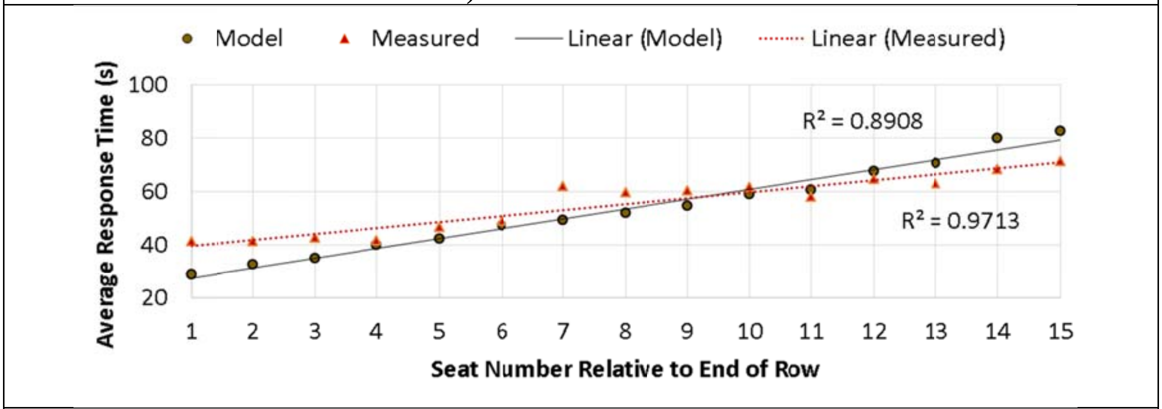
The allocation model presented in Figure 10 assumes that the RTs exactly follow the pattern described. However, it is clear from the observations that while the observed trends are generally followed they are not rigidly followed (see for example Figure 7 and Figure 8). In an attempt to introduce some of the violations to the observed general trends, a certain amount of randomisation can be introduced into the distributed RTs. So for example, once the RTs are distributed according to Figure 10, a certain percentage of the RTs can be randomly redistributed. Here we explore the impact of randomly distributing 10%, 20% and 30% of the RTs (see Figure 11 and Figure 12).

Row 5	3	13	23	24	14	4
Row 4	7	17	27	28	18	8
Row 3	9	19	29	30	20	10
Row 2	5	15	25	26	16	6
Row 1	1	11	21	22	12	2
SEAT	**1**	**2**	**3**	**4**	**5**	**6**

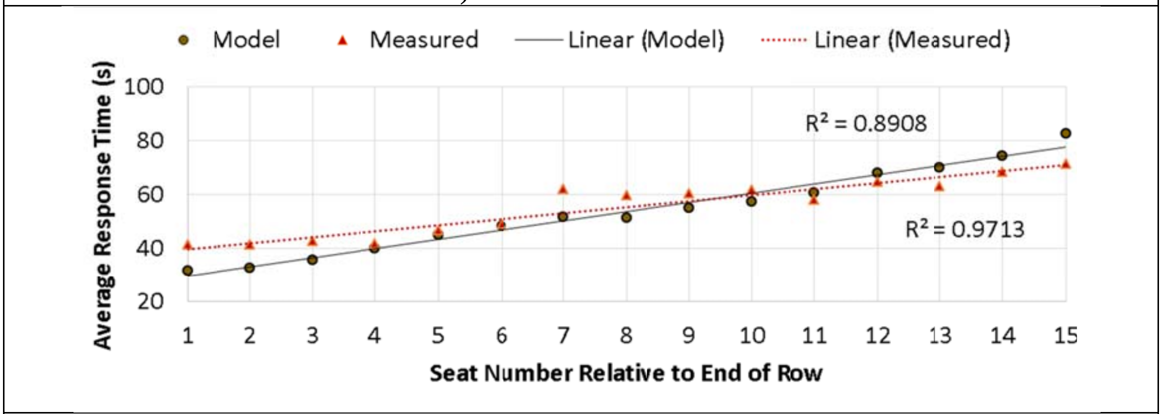
Figure 10. Response time allocation model demonstrated for an auditorium with 6 seats per row and 5 rows



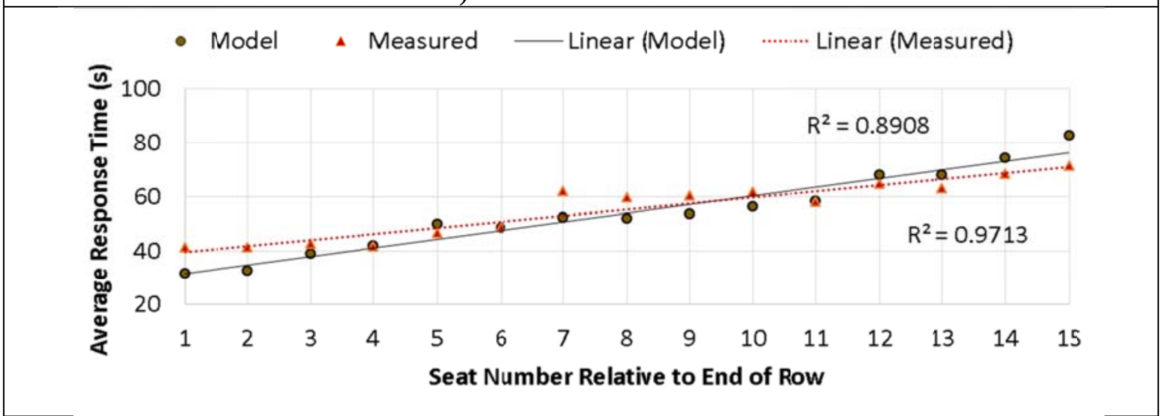
a) 0% Randomisation



b) 10% Randomisation

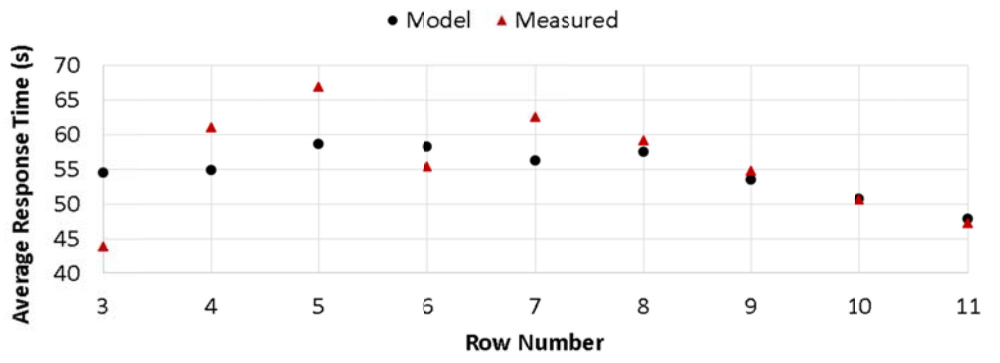


c) 20% Randomisation

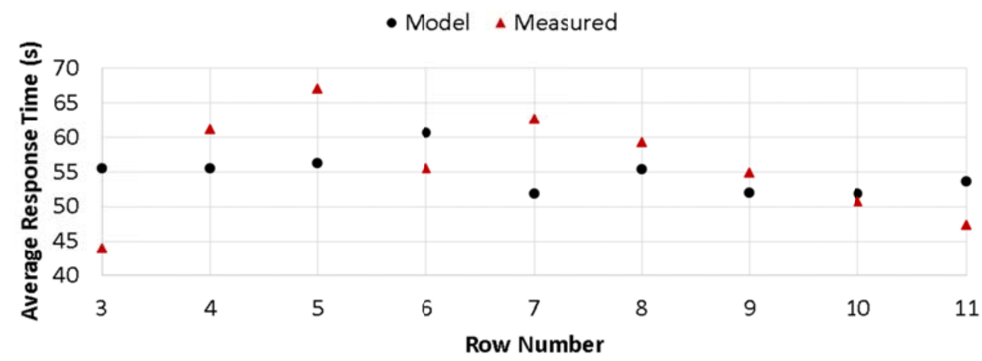


d) 30% Randomisation

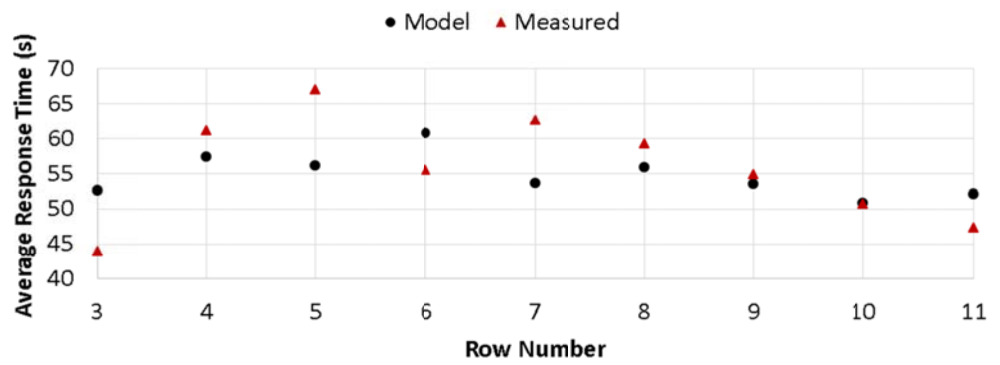
Figure 11. Average response time as a function of seat number (raw and model data)



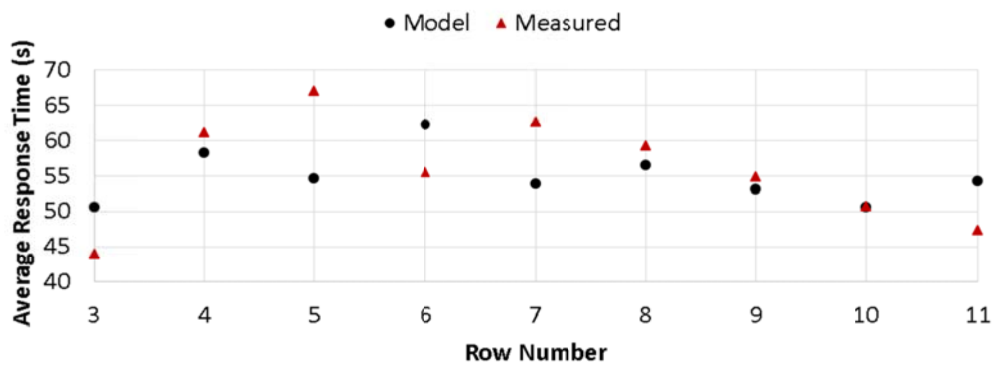
a) 0% Randomisation



b) 10% Randomisation



c) 20% Randomisation



d) 30% Randomisation

Figure 12. Average response time as a function of row number (raw and model data)

As can be seen from Figure 11a and Figure 12a, without randomised redistribution, the allocation model defined by Figure 10 works very well and maintains the general trends observed in the measured data regarding seat number (see Figure 11a) and row number (see Figure 12a). This is clearly a much improved representation than that generated by the purely random allocation of RT as depicted in Figure 9. The RT allocation according to the distribution model with a 10%, 20% and 30% randomisation is presented in Figure 11b and Figure 12b; Figure 11c and Figure 12c; and Figure 11d and Figure 12d respectively.

To determine which of the approaches fits the observed data best a measure of the goodness of fit between the model and observational data is required. Here we make use of the Euclidean Relative Difference (ERD) to measure the goodness of fit as presented in equation 2. The ERD is used to assess the average difference between the RT distribution model and the observed data, with the smaller the ERD the better the fit.

$$\frac{\|E-m\|}{\|E\|}=\frac{\sqrt{\sum_{i=1}^{n}(E_i-m_i)^2}}{\sqrt{\sum_{i=1}^{n}E_i^2}} \qquad (2)$$

Presented in Table 2 are the ERD values for the various distribution models. An ERD is determined for both the row RT distribution curve (see Figure 12) and the seat RT distribution curve (see Figure 11). Cleary the ERD will be different for each assessment and a given level of randomisation will not necessarily produce similar goodness of fit for each of the two assessments. This is because the observed trends that we are attempting to emulate are not as strong in both cases, with the observed trend in seat row not being as strong as the observed trend in seat number. Based on seat number, the best fit is achieved for the 30% randomisation model with the next best being the 0% randomisation model. Based on the row number the 0% randomisation model produces the best fit. To determine the best overall fit to the observed trends the ERD values for both curves are simply added, with the smallest overall value deemed to provide the best overall fit (see total column in Table 2). As can be seen from Table 2, the 30% randomisation model produces the best overall fit by producing the smallest total ERD. However, while the 30% randomisation model produces the smallest total ERD, the smallest ERD for the seat number and the second smallest ERD for the row number, the shape of the row number curve is best represented by the 0% randomisation model. This means the trends in row number are better represented by the 0% randomisation (compare Figure 12a (0%) with Figure 12d (30%)). Thus it is suggested that the 0% randomisation model produces the best overall results (and the second best agreement for seat distribution and the best agreement for row distribution).

Table 2 . ERD values for various randomisation models for the row and seat distributions

Model	Row Number	Seat Number	Total
Distribution Model with 0% randomisation	**0.098**	0.198	0.296
Distribution Model with 10% randomisation	0.130	0.226	0.356
Distribution Model with 20% randomisation	0.111	0.216	0.327
Distribution Model with 30% randomisation	0.117	**0.173**	**0.290**
Fully randomised allocation model	0.179	0.187	0.366

CONCLUSIONS

In an unannounced theatre evacuation involving some 1200 people in which a voice alarm system was used, in conjunction with several other cues including, house lights coming on, performance stopping and stage fire curtain descending, the average response time of some 321 people was determined to be 57.3 s. Thus on average 1 min was required to prepare the population to commence their physical evacuation. It must be emphasised that in this work the response time is not the time between the sounding of the alarm and when people begin purposeful movement towards an exit. This is because due to the nature of the geometry, while people may be ready to move towards an exit they may be prevented from doing so due to congestion within the seat rows.

On average people undertook 0.62 tasks during the response phase, which included activities such as putting on coats, collecting bags, etc however, over 55% of the population did not undertake a single task but simply stood up, after a Notification Delay and was ready to evacuate. While males undertake fewer tasks than females, they take longer to perform those tasks and require longer to disengage from the pre-evacuation task and engage in the evacuation and as a result, the average response time for males was 58 s and for females 55 s. The response times for the population were found to follow the typical log-normal distribution found for other building types. However, occupant response time was found to be related to a person's seat position, where seat position is considered to be a function of two variables, distance from an exit aisle and distance to an exit row.

These trends in response time distribution will have a profound impact on analysis of evacuation times and congestion levels determined by agent based evacuation models and so should be represented within these models. A methodology to distribute response time within the theatre was suggested which included an up to 30% randomisation to reflect the observation that the observed seat and row trends were not strictly adhered to in the measured results however, it was found that a 0% randomisation produced the best overall agreement. It is not clear if the proposed theatre response time distribution model can be generalised to other theatres and if so under what conditions. Further experimental analysis is required to determine whether these observations can be generalised, but if so, it would be a powerful approach with possible application to other seated venues such as cinemas, music venues and sports arenas.

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