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An investigation of how context affects the response of pedestrians to the movement of others

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ABSTRACT

Identifying how pedestrians respond to the movement of others in emergencies is an essential topic that is directly relevant to building evacuation and safety management. Here, we hypothesise that pedestrian following behaviour depends on the context. We identify three essential contextual factors: spatial information, the size of crowds and the distribution of individuals across exits. We conduct a virtual experiment with over 500 participants who have to decide whether to follow a crowd in scenarios capturing these different contextual factors. Our findings suggest pedestrians have an innate preference to avoid the exit chosen by a majority of people but also that they prefer exits that are associated with shorter escape routes, even if these exits are used by more people. However, if one exit is not used at all, these preferences are altered and pedestrians prefer following others regardless of exit properties. In contrast to the relative usage of exits, the overall size of the crowd does not affect pedestrian exit choice in our experiment except for the case when all pedestrians choose the same exit. We call the change in exit choice behaviour depending on how pedestrians are distributed across exits "split effect". Simulation results show how the split effect can lead to unbalanced route usage and reduce the efficiency of pedestrian flow in certain circumstances, such as when the arrival rate of pedestrians is low. Our work adds to a growing body on pedestrian exit choice and highlights the importance of precise control of contextual factors in research.

1. Introduction

Pedestrians are often faced with a choice between route alternatives in emergencies. Making efficient and effective spatial decisions is the key to protecting pedestrians from disasters. In order to make such a decision, pedestrians require to perceive all possible directional information, especially when they have little knowledge about their surrounding. Therefore, identifying the attributes affecting pedestrian decision-making and exploring their influence on human exit choice has become a central task for understanding human evacuation in buildings.

Research on pedestrian exit choice reveals the role of environmental attributes in the process of decision-making of pedestrians, especially what has been described as static information (e.g. building layout and placement of evacuation signs) (Kubota et al., 2021; Lovreglio et al., 2016a) and dynamic information (e.g. movements of the crowd) (Okaya et al., 2013). In emergencies individuals respond to the behaviour and in particular the movement of others, making crowd evacuations an example of social behaviour (Drury, 2003). This social context influences pedestrian dynamics at different spatio-temporal scales, including, for example, both the tactical level (pedestrian decision on where to go) and the operational level (e.g. small-scale pedestrian decisions to avoid collisions) (Schadschneider et al., 2012). At the operational level, pedestrians may show competitive or cooperative behaviours (Drury et al., 2009). For example, a pedestrian may try to overtake others or even push others in high-density situations (Hu et al., 2020). In other cases, pedestrians may help others (Bode et al., 2015a) or simply walk together (Hu et al., 2020). In contrast to this work at the operational level, how pedestrians respond to others at the tactical level, the focus of this contribution, has not been investigated at the same level of detail.

Previous work on the responses of pedestrians to the movement of others has produced diverse results. In pedestrian dynamic models, pedestrians are often assumed to have a tendency to follow others (Low, 2000; Helbing et al., 2000). This can reduce pedestrian evacuation efficiency because the effectiveness of the exit is not fully utilised due to unbalanced exit usage caused by following behaviour (Haghani and Sarvi, 2019a). Other modelling work suggests this tendency can be beneficial, as moderate degrees of following behaviour can help optimise the evacuation system and shorten evacuation times (Kirchner and Schadschneider, 2002). In contrast, some studies assume pedestrians display a behaviour opposite to following — they try to avoid others

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when making exit choices (Zia and Ferscha, 2009; Liu et al., 2009). In addition, in exit choice models that can describe heterogeneity among pedestrians, pedestrian exit choice is assumed to be influenced by individual characteristics such as demographic variables (Song and Lovreglio, 2021) and individual cognition (Li, 2017), and thus whether the individual follow others or not varies among the crowd. For example, Tang et al. (2015) employ the degree of rationality to determine the tendency of following others.

Similar to the various assumptions made in models, empirical findings on how pedestrians respond to the movement of others are diverse. Some studies found that the direction preferred by a majority does not have a significant effect on human exit choice in isolation but that it can be relevant combined with other factors (Bode et al., 2014; Haghani and Sarvi, 2017c). Other research found that pedestrians spontaneously tend to follow others (Tong and Bode, 2021) and it has been suggested that this tendency gets stronger as stress levels increase (Moussaï d et al., 2016). Following behaviour is also observed in pedestrian evacuations under zero visibility conditions (Guo et al., 2012). However, other empirical evidence suggests that instead of following others, pedestrians prefer to search for an alternative exit and avoid smoke when faced with a fire (Li et al., 2016). It has also been suggested that pedestrians are more likely to follow the minority and that increased stress levels or crowding amplifies that behaviour (Haghani and Sarvi, 2019b). Lovreglio et al. (2016b) suggest that pedestrians follow the minority in order to minimise their evacuation time.

Most previous research considers the movement of others only as one factor amongst other attributes relevant to pedestrian exit choice. An exception is the study by Haghani and Sarvi (2017a) which centres on whether pedestrians follow or avoid a crowd in an emergency via a human crowd experiment. This work reveals whether participants follow the crowd or avoid it depends significantly on their knowledge about the route chosen by the crowd. The experiment simulates a crowded condition and additional stress is only imposed on participants via the notification about an emergency. Therefore, this work can explain the influence of crowds on pedestrian exit choice in specific scenarios. However, how pedestrians respond to the crowd in other contexts, especially where the crowd has various conditions, as mentioned above, has not been examined comprehensively.

The preceding discussion highlights the importance of further empirical research on how people respond to the movement of others in various contexts. In this contribution, we use a virtual experiment to investigate the effects of contextual factors on pedestrians' response to the movement of others. Virtual experiments permit a highly controlled setting and this experimental paradigm has been used widely and is well-accepted in pedestrian behaviour research (Ronchi et al., 2016; Kinateder et al., 2014), even though the ecological validity of such experiments should be considered carefully (Lovreglio and Kinateder, 2020). There are several virtual reality technologies with different characteristics for pedestrian exit choice, such as desktop VR, head-mounted display (HMD) and cave automatic virtual environment (CAVE) (Feng et al., 2022). We use desktop VR in this work, because compared to other methods, it is cheaper and, more importantly, allows participants to take part remotely. Previous research has established pedestrians show similar exit choice behaviours in virtual environments implemented by different virtual reality methods, suggesting the validity of desktop VR (Ruddle and Péruch, 2004; Feng et al., 2022; Li et al., 2019). While many contextual attributes may affect pedestrian behaviour, we select the three essential factors identified and discussed below and investigate their primary influence and interactions on pedestrian exit choice.

To further demonstrate the implications of our findings, we conduct simulations of a simple model for pedestrian dynamics in a facility with two exits. We propose a model in the framework of mathematical queuing theory (Shortle et al., 2018). It consists of arrival process which describes the properties of pedestrian arrival, exit choice process which illustrates pedestrian exit choice at the strategy level and service process which captures the interactions between pedestrians at the operational level by using the fundamental diagram for pedestrian dynamics.

The remained of this contribution is structured as follows. First, we review relevant work on how contextual factors affect pedestrian exit choice. Then, we describe our experiment and data collection. Finally, we present our empirical findings and introduce our model, before discussing our results.

2. Literature review

The discussion above suggests that how pedestrians respond to the movement of others when deciding where to go may depend strongly on the specific context. Based on the literature, we identify three essential contextual attributes: spatial information about the location of exits, the size of crowds in a given setting, and the distribution of individuals across exits. In the following, we discuss previous findings on these attributes. Moreover, we review the role of stress and socio-demographic factors in pedestrian exit choice.

In terms of spatial information, pedestrians are reported to prefer familiar exits (Shortle et al., 2018). Two examples from the literature suggest pedestrians prefer not to follow others when they have sufficient or informative spatial information about the environment they are in. In the first example, previous work found that most pedestrians treat other people as potential sources of congestion and additional delay and thus try to avoid crowds when there is little uncertainty about where exits are (e.g. when all exits are visible). However, if the uncertainty increases (e.g. either exit becomes invisible), pedestrians prefer the direction of the majority (Haghani and Sarvi, 2017a,b,c). In the second example, experimental work suggests that pedestrians who tend to follow others in the absence of additional information are more likely to choose the direction indicated by exit signs when these are visible (Tong and Bode, 2021).

Considering the size of crowds in a given setting, this can directly affect congestion levels and associated queue shapes, such as approximately straight line queue (Lovreglio et al., 2016b), arched congestion around an exit (Bode et al., 2015b), and no congestion near exits (Tong and Bode, 2021). Such visible differences in queues may affect the exit choice of pedestrians and it has been suggested that pedestrians prefer faster-moving queues (Bode et al., 2015b). Kinateder and Warren (2021) found participants show different tendencies to follow others when the crowd size changes, indicating that the size of crowds may play an essential role in pedestrian exit choice. In terms of the distribution of individuals across exits, the uneven split of individuals across exits is commonly used for testing whether participants follow the majority or the minority (Bode et al., 2014; Lin et al., 2020). Some studies investigate the influences of different split levels of the crowd and have diverse results. Lovreglio et al. (2014) found that participants tend to choose less crowded exits, and the greater the difference in the number of simulated pedestrians between the two exits, the less likely participants are to follow the majority. In contrast, Kinateder and Warren (2021) find a non-linear relationship between crowd proportion and exit choice and suggest that whether pedestrians follow the majority is influenced by both crowd size and crowd proportion. Most importantly for this work Kinateder and Warren (2021) found that when all people choose the same exit and leave the other exit unused, pedestrians are more likely to follow the crowd.

Previous work has established that individual characteristics are critical for determining which exit pedestrians choose (see Tong and Bode (2022) for a review). Socio-demographic factors are essential aspects of individual characteristics and have been extensively studied. For example, it has been suggested that female participants are more likely to follow the crowd than male participants (Rosenthal et al., 2012). Students are less predisposed to show following behaviour compared to other groups (Lovreglio et al., 2014) and participants from

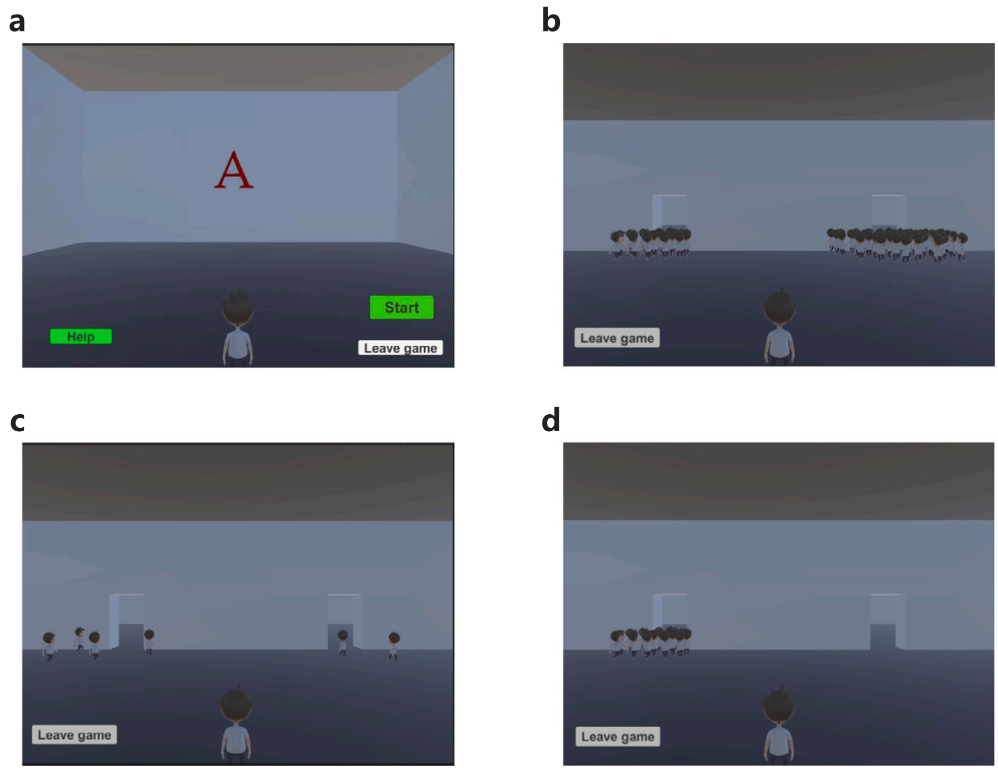

Fig. 1. Still images of the virtual experiment as seen by participants on screen for the training phase (a) and for the exit choice phase (b)–(d). We show different experimental conditions: uneven split of the crowd in the busy state, where there is congestion in front of both exits (b), and the free state, where there is no congestion (c), and an example for a 0–1 split of pedestrians across exits, where one exit remains unused (d).

different cultural backgrounds do not show significant differences regarding following behaviour (Lin et al., 2020). Moreover, the influences of other socio-demographic factors such as age, income, ethnicity and occupation, have been investigated (Basu et al., 2021).

Time pressure or other factors that lead to behavioural or physiological responses commonly described as stress present additional important contextual factors that have been identified in previous work (Moussaï d et al., 2016; Bode and Codling, 2013). Stress can increase the vigilance of pedestrians and may be beneficial for evacuations. For example, Haghani et al. (2020) found that compared to low urgency conditions, high urgency conditions can trigger a more instant response and faster rush to exits, resulting in shorter individual and total evacuation times. In contrast, other studies found that as the level of stress increases, it may impair pedestrian information processing ability and thus pedestrians may make decisions that are far from optimal at both the individual and group levels. For example, pedestrians tend to choose the familiar exit rather than the closer one under stress, which can be detrimental to their evacuation time (Bode and Codling, 2013). However, in this work we have not investigated stress. A key problem in investigating this is the experimental difficulty of achieving consistent and desired participant responses or stress levels in virtual environments. In previous work, participants were informed of an emergency via a message (Lin et al., 2020; Lovreglio et al., 2016b), or they were given an evacuation order or signal (Haghani and Sarvi, 2017a). Some studies impose additional stress by imposing time limits (Bode and Codling, 2013), monetary penalties, or by implementing stress-inducing elements in the virtual environment, such as lower luminosity and flashing lights (Moussaï d et al., 2016). However, the validity of such methods to impose stress has been questioned, because participants are aware that they are moving and acting within a virtual environment, facing no real danger (Feng et al., 2021). Therefore, we suggest further work should be done to investigate pedestrian exit choice in contexts with different stress levels, combined with data from a real-life environment where pedestrians have no or little knowledge of being tracked and are thus more likely to behave more naturally.

3. Experiment

3.1. Virtual environment

We conducted a virtual experiment with human participants to investigate whether pedestrians would follow other pedestrians when making exit choices in different contexts. Participants had a three-dimensional first-person view of a virtual environment and could control the movements of an avatar by using the arrow keys on the keyboard to move forward and backwards, turn left and right. The presence of the virtual pedestrian allowed participants to identify their position in the room and relative position to other pedestrians. Our experiment consisted of a training phase and a exit choice phase. In the training phase, participants could move freely within a room to familiarise themselves with how to control the movement of the avatar. In the exit choice phase, participants had to complete a simulated evacuation under one of the experimental conditions, which were designed to introduce different contextual factors, as discussed in detail below.

The virtual environment was implemented in Unity 3D (Version 2020.3.20f1). The avatar controlled by participants and the virtual pedestrians were animated using the same Unity Character Pack (sample Sam, Version 2.0.0) (Unity, 2020), to reduce the possible influence of virtual characters on participant exit choice. The walking and rotation speeds were set to 1.7 m/s and 80 degrees per second, respectively. A video of the virtual environment can be found in Appendix A.

In the training phase, participants received instructions on how to control the avatar by using the keyboard and could move freely inside a square room. Landmarks, letters from the Latin alphabet, were shown on the four walls of the room, so that participants had a clearer perception of controlling the avatar in terms of movement direction and speed (see Fig. 1a). Participants only moved on to the exit choice phase when they confirmed they were confident in being able to control the

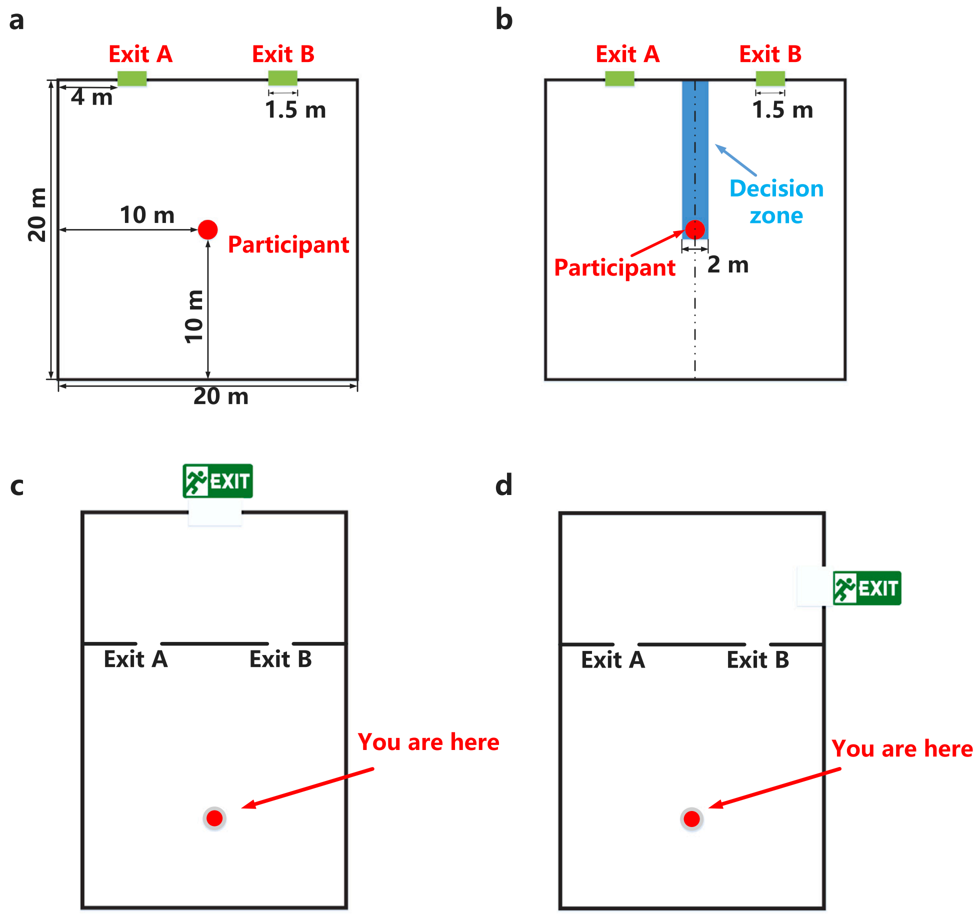

Fig. 2. Map of the virtual environment for the exit choice phase (a). Map indicating the positioning and extent of the decision zone defined for this study (b). Maps shown to participants before the start of the simulated evacuation with equal exit utility (c) and biased exit utility where the right door has a higher utility, as it is closer to the indicated exit (d).

avatar movement. We did not record the movements of participants inside the virtual environment during this training phase.

In the exit choice phase, the avatar controlled by participants was situated inside a room with two exits and it was facing these exits. Fig. 2a shows the starting point of the avatar and the layout of the room. Participant avatars were positioned equidistant from both exits and at a sufficient distance from exits to ensure participants could fully see both exits and the area immediately in front of the exits before they started to move (see Fig. 1b–d for examples). Participants received the following instructions at the start of the exit choice phase and before they could start to move the avatar: "Suddenly, there is a fire alarm, please go to the exit as quickly as possible". Participants would see simulated pedestrians evacuating through the exits, as described below, and were thus faced with a choice between the two exits. Once participant avatars reached the outside of one of the exits, the exit choice phase and therefore the experiment ended. This phase was designed to investigate the influence of contextual factors on pedestrian exit choice. The movements and exit choices of participants in the virtual environment were recorded during this phase.

3.2. Experimental design

We adopted a factorial experimental design with three between-subjects variables that we refer to as: spatial information (what information participants have about the exit routes), crowd state (whether the size of the crowd causes congestion) and crowd split level (how simulated pedestrians are distributed across exits). Participants were randomly assigned to an experimental condition that represented one of three types spatial information, two crowd states and three crowd split scenarios.

For the variable of spatial information, participants were provided either with no spatial information or with information provided via a map indicating building exit locations before they started to move. If a map was provided, it showed the relative position of the exits of the room where the participant avatar was positioned to the final destination of participants, an exit marked with an exit sign. Participants saw one map out of a set of three maps that all suggested different room exit utilities: a map where both room exits were equidistant from the final exit (equal exit utility, see Fig. 2c) and maps where the left exit or right exit was closer to final exit (biased exit utility, see Fig. 2d for an example). The spatial information variable was thus used to establish how the existence of spatial information and exit utility influence pedestrians' response to the movement of others.

The crowd state variable indicated the congestion level of simulated pedestrians around the exits and could take the values referred to here as busy or free. In the busy state, the simulated crowd would cause congestion at the exits and participants were expected to wait before they could go through their preferred exit. In the free state, the simulated crowd was small and would thus not hinder the movement of the participant. We implemented the different states by changing the number of people around the exits. The crowd size chosen for our experiment needed to meet the following conditions: (1) The crowd should not completely obstruct participants' view of exits, especially when the crowd size is large. (2) The difference between two levels of crowd size in each state should allow participants easily and quickly to identify the exit used by the majority. After testing, we allocated 20 or 40 simulated pedestrians to exits in the busy state (see Fig. 1b for

Table 1
The number of simulated pedestrians using each exit for each of the 36 experimental conditions (16 conditions with an uneven split of pedestrians between exits, 16 conditions that switch the imbalance between exits compared to the previous set, and 4 conditions with an even split of pedestrians across exits).

Variables				Original scenario		Mirror scenario	
Spatial information		Crowd state	Split level	Left exit	Right exit	Left exit	Right exit
No information		Busy	Uneven	20	40	40	20
			0-1 split	20	0	0	20
			Even	20	20	\	\
		Free	Uneven	2	4	4	2
			0-1 split	2	0	0	2
Map with equal exit utility		Busy	Uneven	20	40	40	20
			0-1 split	20	0	0	20
			Even	20	20	\	\
		Free	Uneven	2	4	4	2
			0-1 split	2	0	0	2
Map with biased exit utility	Left exit has a higher utility	Busy	Uneven	20	40	40	20
			0-1 split	20	0	0	20
			Even	20	20	\	\
		Free	Uneven	2	4	4	2
			0-1 split	2	0	0	2
	Right exit has a higher utility	Busy	Uneven	20	40	40	20
			0-1 split	20	0	0	20
			Even	20	20	\	\
		Free	Uneven	2	4	4	2
			0-1 split	2	0	0	2

an example), and 2 or 4 simulated pedestrians to the exits in the free state (see Fig. 1c for an example). The movements of the simulated crowd were under the control of Unity's physics engine, which allowed them to move, react to collisions with each other and form congestion in a physically realistic way. The crowd state variable was used to test whether the response of pedestrians to the crowd is affected by congestion levels.

For the crowd split variable, we implemented three ways in which simulated pedestrians were distributed across exits: even or uneven split (see Fig. 1b–c for examples), and what we refer to as 0–1 split, where all simulated pedestrians present used one exit (see Fig. 1d for an example). An even split implied that the same number of pedestrians used either exit. An uneven split meant that different numbers of simulated pedestrians used the two exits (2 and 4 in the free crowd state or 20 and 40 pedestrians in the busy crowd state). The crowd split variable was designed to investigate how the distribution of other pedestrians across exits affects pedestrian exit choice.

To establish whether participants have an innate preference for choosing the left or right exit, we implemented mirror versions of all experimental conditions considering how simulated pedestrians were distributed across exits and the information provided about exits (see Table 1). Assuming that an even split of simulated pedestrians across exits was uninformative for exit choice, we only implemented a busy crowd state for this experimental condition but varied the spatial information. As a result, 36 experimental conditions were implemented, as shown in Table 1.

3.3. Data collection and analysis

We recruited participants using the online platform Prolific,[1] between the 24th and the 28th of October 2021. Participants received a payment of £0.9 per person (equivalent to £7.5 per hour based on the estimated completion time). Participants had to download an executable file for the virtual experiment to their computer and submit an output file via Typeform,[2] a website that provides online survey services. The experiment file could only be executed once. All participants were briefed on the broad purpose of the experiment. Ethical approval for our experiment was granted by the Ethics Committee of the Faculty of Engineering at the University. All data collected for this study is openly available.[3]

A total of 1178 participants signed up for our experiment on Prolific. Six-hundred participants completed their submission, 507 participants decided to leave the experiment early, and 71 participants exceeded the maximum time allowed without completing their submission. Of the 600 participants who completed the experiment, 53 participants failed to upload the correct output file. Therefore, the data from 547 participants were analysed. Table A.1 in the appendix shows details on the sample size for each experimental condition.

Reported ages ranged from 18 to 35 years, with a median, average age and standard deviation age of 23 years, 24.6 years and 5.8 years, respectively (5 participants (0.9%) did not disclose their age). The gender distribution of participants included 234 female participants (56.75%), 307 male participants (43.25%) and 6 participants who either did not want to disclose gender information or did not subscribe to either of the aforementioned gender categories.

To assess participant behaviour quantitatively, we defined α as the ratio of decision time to the total finishing time of participants. The decision time was the time the participant spent in the decision zone where we assumed that the participant had not chosen an exit yet. The horizontal distance from the starting position of the participant to each exit was 4.5 m, and we selected the band within 1 m of the horizontal distance from central axis of two exits as the decision zone (see Fig. 2b). We used a ration for the decision time rather than a direct measurement to account for differences between pedestrians in terms of their speed of movement inside the virtual environment. For example, participants more used to this type of virtual environment may move faster on average both overall and whilst making their decision. We used generalised linear models (GLMs) for data analysis and confirmed the appropriateness of these models by examining residual plots.

4. Results

We first examined whether participants had an innate preference for choosing the left or right exit. Table A.2 in the appendix shows Chi-squared tests on differences in exit choice between mirrored scenarios.

[1] Prolific: Online participant recruitment for surveys and market research URL: https://prolific.co/ accessed 24 November 2021.
[2] Typeform: People-Friendly Forms and Surveys. URL: https://www.typeform.com/, accessed 24 November 2021.
[3] University of Bristol data repository: https://doi.org/10.5523/bris.3kn82h2aamsfw2eplor4v2ewk0.

Table 2
The effect of α (proportion of overall time in decision zone), gender, and contextual factors on whether pedestrians follow the majority of simulated pedestrians. Positive parameter estimates indicate that it is more likely that people choose the exit used by the majority. P-values less than 0.05 are shown in bold. The last entry, 'Crowd state : 0-1 split' indicates an interaction term.

Effect	Estimate	SE	F	P
Intercept	−1.4083	0.3286	−4.2855	$\mathbf{1.8232} \times 10^{-5}$
Crowd state (busy)	−0.4203	0.3320	−1.2658	0.2056
0-1 split	1.1522	0.3037	3.7943	**0.0001**
No map	0.3967	0.3097	1.2809	0.2002
Map with a higher utility exit the majority choose	0.6176	0.3089	1.9992	**0.0456**
Map with a lower utility exit the majority choose	−0.6593	0.3464	−1.9035	0.0570
Gender (female)	0.5749	0.2004	2.868	**0.0041**
Crowd state (busy) : 0-1 split	−1.0350	0.4574	−2.2630	**0.0236**

No significant differences were found. This suggests that participants did not show an innate left or right preference. We thus combined all data in the following analysis and did not account explicitly for whether left or right exits had higher utility or were used by larger numbers of simulated pedestrians.

4.1. Context determines following behaviour

We next investigated how contextual factors affect whether pedestrians follow the crowd. We used a generalised linear model with Binomial error structure and logit link function for our statistical analysis. The response variable was a Boolean indicating whether participants chose the exit more simulated pedestrians used (value 1) or not (value 0). The categorical explanatory variables included in the model were an intercept, the different levels of spatial information (with a map showing equal exit utility being the baseline absorbed in the intercept), and Boolean variables indicating the gender of the participants (0 for male, absorbed in the intercept; 1 for female), crowd state (0 for free, absorbed in the intercept; 1 for busy) and 0–1 split suggesting whether all simulated pedestrians chose to the same exit (0 for no, absorbed in the intercept; 1 for yes).

Our statistical analysis (see Table 2) shows that on average, in the absence of other factors, participants had the tendency to avoid the exit the majority selected (negative intercept estimate). However, when all simulated pedestrians chose the same exit, this trend was reversed (0–1 split parameter estimate). Considering the spatial information provided, we could not rule out that showing no map to participants had no effect, compared to a baseline of participants seeing a map suggesting equal exit utility (p-value for 'No map' parameter). This can be explained by the fact that not seeing a map may have increased the uncertainty of participants (see also below), but it did not provide them with directional information. When one exit had a higher utility, participants tended to follow this information, even when it meant they then had to follow the majority of simulated pedestrians. Depending on the significance threshold chosen, the case when the exit used by the majority of simulated pedestrians also had a lower utility may not have an effect ($p = 0.0631$). Nevertheless, these results suggest that exit utility is important in directing exit choice behaviour of pedestrians, as expected.

We found that an interaction term between crowd state and 0–1 crowd split improved model fit. This indicates that the effect of the crowd state and the 0–1 crowd split were linked. When all simulated pedestrians in the busy state selected the same exit, participants were less likely to choose the exit the crowd preferred. Considering the relative size of estimated parameters this suggests that the 0–1 split effect is substantially reduced if there is congestion. However, on its own, congestion did not have a clear effect on exit choice in our experiment (Crowd state, $p = 0.1712$). This suggests that when the crowd is unevenly split across exits and both exits are used, participants were affected by the relative split across exits rather than the number of simulated pedestrians or congestion levels in our experiment.

We found that gender had a statistically significant effect on the exit choice of participants. Female participants were more likely to follow the majority than male participants, an effect that has been observed in previous work (Rosenthal et al., 2012). We suggest that such gender effects need to be treated with caution, however, as we did not control for additional individual characteristics in our participant sample, such as training, professional or cultural background, which could also explain this finding.

4.2. Uncertainty increases decision times

The quantity α is an approximate measure to indicate the length of time participants take to make their exit choice and it could thus give insights into the decision-making process. We used a generalised linear model with Normal error structure and identity link function to investigate how contextual factors affect pedestrian decision time ratio. The response variable was α, the ratio of decision time of participants to the total evacuation time in the experiment. Explanatory variables were an intercept, the different types of spatial information provided, crowd state, and 0–1 split, which were all implemented as previously described for the analysis of participants' exit choices.

We found that on average participants spent just under a third of the total time it took them to complete the evacuation task inside the decision zone (intercept= 0.2799, see Table 3). This time increased when all simulated pedestrians selected the same exit, when participants were not presented with a map, or when they were presented with a map suggesting higher exit utility for the busier exit (see Table 3). We suggest that a possible explanation for these findings is that each of these three factors is likely to increase the uncertainty of participants about the environment compared to the other scenarios. Faced with higher uncertainty, participants required more time to process the decision making, leading to a larger α in these cases.

4.3. Exploring implications of the findings via simulations

Our experiment reveals that participants had an innate preference to avoid the busier exit but also that this trend was reversed when one exit remained unused and there was no congestion (0–1 split and the crowd was in the free state). We refer to this change in following behaviour "split effect". To further explore the implications of this effect on pedestrian exit choice we propose a model based on queuing theory (Shortle et al., 2018).

In this model, the journey of pedestrians from arrival to departure is described as a queuing system as shown in Fig. 3. Pedestrians first arrive with a specified arrival rate (β), determined by the assumption of the arrival process, and then choose one of several routes according to the probability p in the exit choice process. If more than one pedestrian chooses the same route, the time it takes then to pass through the exits is modelled akin to the service process in queuing models, parameterised via the service time, w, that indicates the time cost incurred by pedestrians. We describe the arrival process, exit choice process and service process in detail below.

Arrival process We assume that the arrival of pedestrians can be described as a Poisson process, a common assumption in queuing

Table 3
The effect of contextual factors on α, the proportion of time participants spend inside the decision zone. Positive parameter estimates indicate that people spend more time in the decision zone. P-values less than 0.05 are shown in bold.

Effect	Estimate	SE	F	P
Intercept	0.2799	0.0183	15.285	**4.2186** $\times 10^{-44}$
Crowd state (busy)	−0.0024	0.016	−0.1489	0.88174
0-1 split	0.0634	0.0158	4.0068	**7.0177** $\times 10^{-5}$
No map	0.0521	0.0199	2.623	**0.009**
Map with a higher utility exit the majority choose	0.0694	0.0221	3.1439	**0.0018**
Map with a lower utility exit the majority choose	0.0182	0.0216	0.8422	0.4

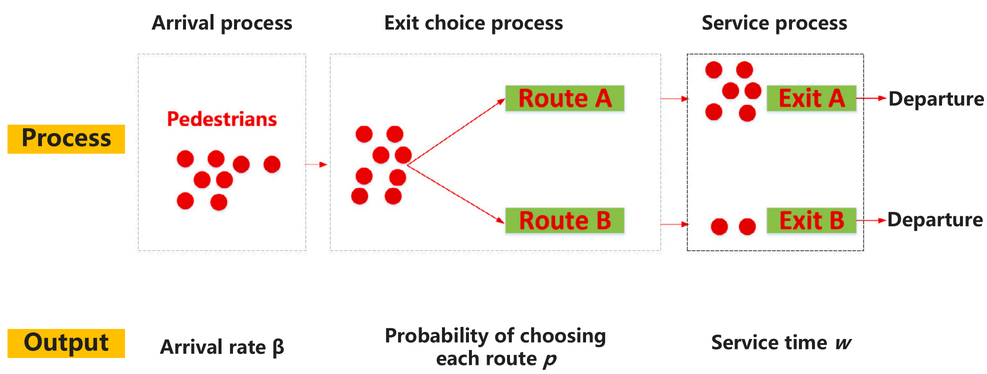

Fig. 3. Description of the queuing model for pedestrian exit choice between two possible routes.

theory (Bhat, 2008). The Poisson process implies that (1) pedestrians arrive one at a time (2) the probability that each pedestrian arrives at any time is independent of when other pedestrians arrived and (3) the probability that each pedestrian arrives at a given time is independent of the time. These assumption have been verified empirically to approximately represent many real unscheduled arrivals (Green et al., 2006). In terms of our application, these assumptions imply that pedestrians do not arrive in groups and that there is no underlying scheduling process for arrivals, such as the arrival of trains at stations of a perfectly synchronised departure following an alarm during emergencies. Eq. (1) describes the probability of the number of arrivals in any given time period $N(t)$ which follows a Poisson distribution where β is the arrival rate representing the expected number of arrivals per unit time. In this work, we characterise the Poisson process by setting the time between consecutive arrivals, called the inter-arrival time (I) to have an exponential distribution (Ross, 2000), as shown in Eq. (2).

$$Probability\{N(t)=n\}=\frac{e^{-\beta t}(\beta t)^n}{n!} \tag{1}$$

$$Probability\{I\leq t\}=1-e^{-\beta t}. \tag{2}$$

where n is the number of arrivals, I is the inter-arrival time of a Poisson process with rate β, and $1/\beta$ is the average time between arrivals.

Exit choice process To model the exit choice process, we directly use our experimental findings. We implement the exit choice process in the model with and without split effect, but do not consider different types of information provided to pedestrians. In the latter version of the model, pedestrians avoid following the majority and the probability of choosing a route is based on the frequency with which participants had chosen each route in the experiment. For example, the probability that pedestrians follow the majority when there are fewer than 20 pedestrians in total, is given by the proportion of people among all participants across all experimental conditions (except the 0–1 split) who decided to follow the crowd. This is based on the assumption that exit utilities tested in the experiment average our across experimental conditions. In the former version of the model (with split effect), pedestrians respond to the crowd differently as the distribution of the crowd across exits changes. More specifically, participants generally tend to avoid the crowd but prefer to follow the crowd if only one exit is used unless the state of the crowd became busy (the threshold for the number of pedestrians is 20) when they start to avoid the crowd. All the probabilities in the models are obtained directly from the experimental data, as described above. The first pedestrian to arrive is allocated a route, as the probabilities from our experiment do not describe this situation.

Service process After pedestrians have made their exit choice, they start to move along their chosen route. The service time (w) represents the time required for each pedestrian from arrival to departure and can be calculated by Eq. (3). We incorporate Weidmann's fundamental diagram to describe the relationship between density k (pedestrian/m^2) and speed v (Kunwar et al., 2016; Zhang and Seyfried, 2013), as shown in Eq. (4).

$$w=\frac{d}{v} \tag{3}$$

where d is the distance of the route, set to $d=1$ m throughout.

$$v=\begin{cases} v_{max}\left(1-e^{-1.913\left(\frac{1}{k}-\frac{1}{k_{max}}\right)}\right), & k\leq k_{max} \\ v_{min}, & k>k_{max}\end{cases} \tag{4}$$

where the maximum speed v_{max} is 1.34 m/s, the maximum density k_{max} is 5.4 pedestrian/m^2, and the minimum speed v_{min} is 0.04 m/s, as suggested in Kunwar et al. (2016).

Using this model, we first investigated the implications of the split effect when the pedestrian arrival rate was low (see Fig. 4a–e). We found that when the split effect was present, on average pedestrians took longer to depart (see Fig. 4a) and the usage of the two routes was unbalanced (see Fig. 4b). In contrast, without the split effect the number of pedestrians on the two routes was almost the same over time (see Fig. 4c). This unbalanced exit choice explained the longer departure times when the split effect was present, because pedestrians tended to choose the crowded exit, leaving the other route empty and thus reducing the average speed of the pedestrian flow. Moreover, overall more people chose the route selected by the first person and the exit choice process was more unpredictable when considering the split effect (compare the standard deviation in Fig. 4d and e).

We next considered the implications of the split effect when the arrival rate was high (see Fig. 4f–j). We found that the split effect still caused an imbalance in route usage (compare Fig. 4b and g). However, it did not lead to a longer overall departure time as observed in the low

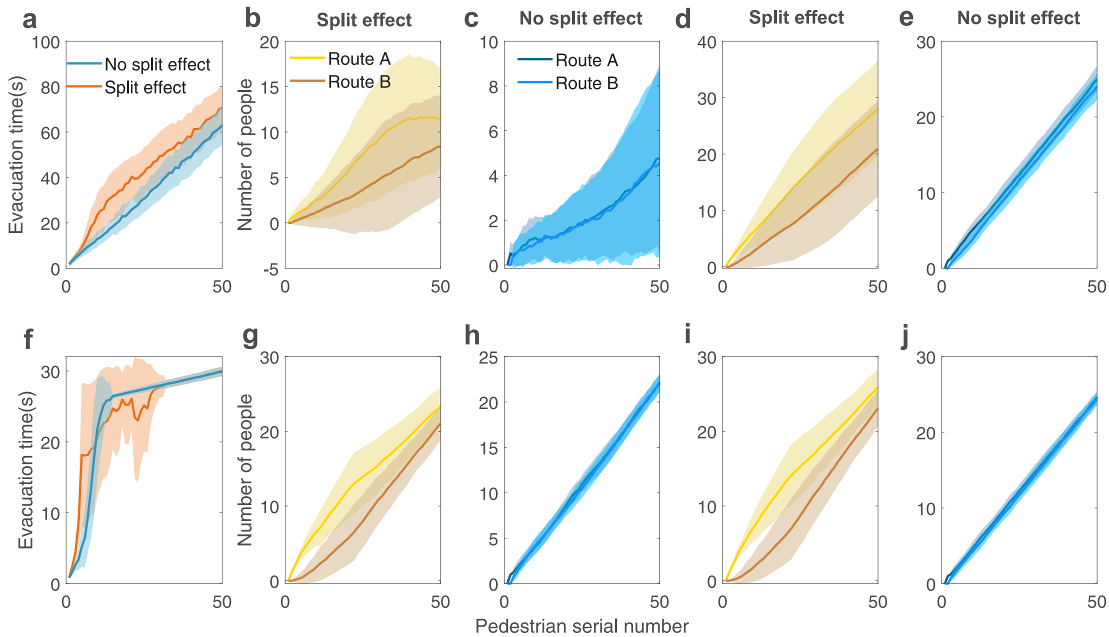

Fig. 4. Simulations on the impact of the split effect on pedestrian flow when the arrival rate is low (a–e) or high (f–j). The abscissa, pedestrian serial number, describes the sequential order in which pedestrians arrive. Panels a and f show the time at which each pedestrian reaches their destination. Panels b, c, g and h show the number of pedestrians in routes A and B at the moment each pedestrian arrives when the split effect is present (b and g) or not present (c and h). Panels d, e, j and j show the accumulated number of pedestrians in routes A and B over the whole simulation when the split effect is present (d and i) or not present (e and j). We show the average value across 100 simulations and shaded regions indicate one standard deviation. Simulation parameters are $\beta = 1$ per second for the low arrival rate and $\beta = 10$ per second for the high arrival rate. In simulations, the first pedestrian is set to choose route A.

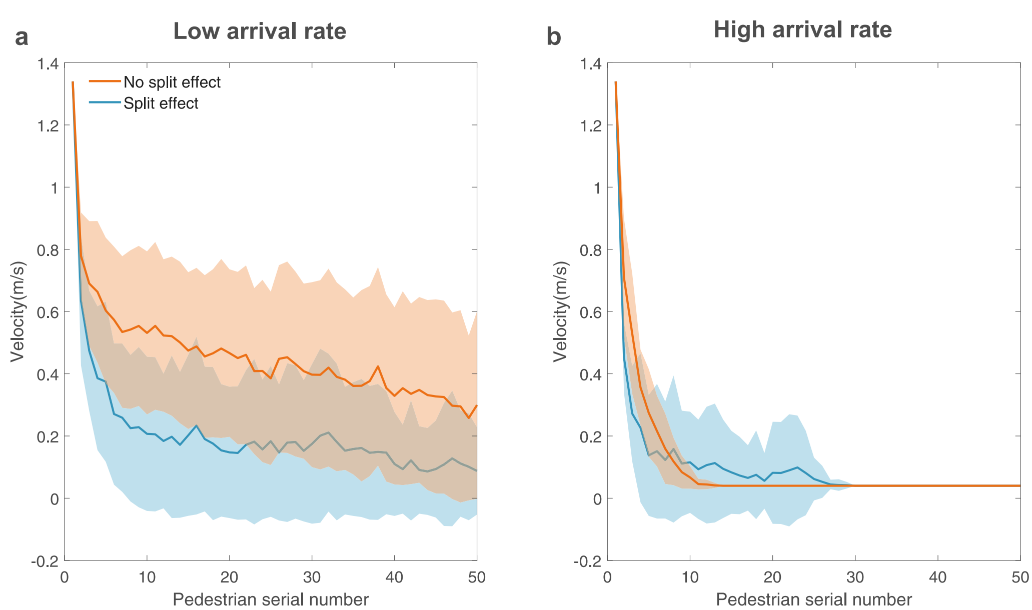

Fig. 5. The speed of each simulated pedestrian when the arrival rate is low (a) or high (b). The abscissa, pedestrian serial number, describes the sequential order in which pedestrians arrive.

arrival rate scenario, only the first few pedestrians needed more time to depart when the split effect was considered (see Fig. 4f). The reason for this was under the high arrival rate both routes were congested quickly. This meant that with the exception of the first arrivals at the exits, most pedestrians in simulations evacuated at the minimum speed and thus the speed difference induced from the imbalance in the number of pedestrians was reduced. Fig. 5 compares the average pedestrian speed over the course of simulations in the low and high arrival scenarios and provides evidence for this explanation. When the arrival rate was low, pedestrians maintained a higher speed when the split effect was not present. However, when the arrival rate was high, pedestrian speed both with and without the split effect dropped rapidly to the minimum value. In addition, we found that a higher arrival rate made pedestrian exit choice more predictable (compare the size of the standard deviations in Fig. 4b–e with g–j, respectively). Fig. A.1 provides more details on how the arrival rate can affect pedestrian dynamics. We found that as the arrival rate increased, pedestrians took less time to evacuate and the split effect had less of an influence on evacuation time. This was because when pedestrians arrived quickly, the whole crowd (50 pedestrians) could start to evacuate early, on average, leading to a shorter overall evacuation time. Meanwhile, in high arrival scenarios the number of pedestrians could reach the threshold for a busy state at one exit in a short time and thus the impact of the split effect gradually diminished. Furthermore, when the arrival rate was high, there was less variability in the summary statistics we recorded, indicating that a high arrival rate made pedestrian dynamics more predictable.

In summary, we found the split effect could result in unbalanced usage of routes. It could reduce the average speed of pedestrian flow when the arrival rate was low, but for higher arrival rates this reduction became small in size. A higher arrival rate also made pedestrian exit choice more predictable in our simulations.

5. Discussion

Our work has found evidence that the response of pedestrians to the movement of others during exit choice depends on the context. In agreement with previous work, participants in our experiment have an innate preference of avoiding busier exits (Zia and Ferscha, 2009; Liu et al., 2009; Haghani and Sarvi, 2019b). However, additional spatial information can mean that exits with a higher utility are preferred, even when they are used by more pedestrians than alternative options. Our experiment also shows that this behaviour changes when one exit is not used at all suggesting the tendency of pedestrians to avoid empty exits which has been observed in previous work (Lovreglio et al., 2014). A possible explanation for this finding is that pedestrians may perceive exits that are not used by others as not viable or safe (Lovreglio et al., 2014). Our simulations show that this effect can lead to unbalanced route usage, but they also show that how this influences pedestrian flow depends on the context, such as the arrival rates of pedestrians. We suggest that more empirical data are needed for determining the size of this effect and its possible consequences in real-life situation.

We compare our work in detail with three previous relevant studies. One is the work by Kinateder and Warren (2021) where they investigate the effect of crowd proportion and size on pedestrian exit choice. They found pedestrians tend to follow the majority when the crowd size is small or the exit width is narrow but prefer the less-crowded exit if the crowd becomes larger or the exit is wider. In contrast, our experiments do not show a significant effect of crowd size on pedestrian exit choice. We can only speculate what causes the difference. A possible reason is that the trade-off between exit utility and estimated congestion caused by the crowd may influence their choice, which is not a consideration in our experiment. The previous work also found the tendency of pedestrians to avoid an empty exit because pedestrians tend to eschew unknown exits that no one chooses. A non-linear relationship between crowd proportion and exit choice is found. In contrast, our work only considers uneven and even crowd split, without implementing additional proportions of how the crowd is distributed across exits. Therefore, we cannot give more details on the influence of crowd proportion. The second is the work by Tong and Bode (2021) where they investigate following behaviour in sequences of consecutive pedestrian route choices. They assume pedestrians do not have prior knowledge about the building, so we only compare situations where participants are not presented with the map in our experiment. Our findings have two main consistent conclusions. First, compared to the information indicated by the crowd, pedestrians rely more on other directional information (exit signs in their work and maps in our experiment). Second, both this and our previous study found that when all pedestrians choose the same exit, pedestrians who have no spatial information tend to follow others. The third is the work by Haghani and Sarvi (2019a) where they found that following behaviour hinders the efficiency of crowd evacuation processes in simulations where pedestrians prefer to follow the crowd. In contrast, in our simulations pedestrians tend to follow the crowd due to the split effect when numbers are low, but start to avoid others when the number of pedestrians reaches the threshold. Our results show that following the crowd may cause unbalanced usage of exits and thus hinder pedestrian flow. However, this still depends on the context. For example, the split effect has little influence on pedestrian dynamic when the arrival rate is high. The comparison with these three studies suggests that even though the role of the crowd in pedestrian exit choice is highly context-dependent, we still can find some consistency across scenarios and make predictions based on appropriate contextual factors.

We have explored possible implications of our experimental findings through modelling. Our model assumes that the arrival of pedestrians can be described as a Poisson process. While only applicable in certain circumstances, we argue our model is still useful for investigating implications of the split effect for crowd dynamics.

Control over extraneous variables was essential in our experiment. Extraneous variability was unavoidable but could be reduced by appropriate measures. First, when we recruited participants we did not set any criteria for their socio-demographic factors, aiming to obtain a truly representative sample. Second, participants were assigned to a scenario randomly and could only take part in the experiment once, which helps to create a balanced participant pool regarding known and unknown individual characteristics. Third, except for the treatments, experimental settings for each participant remained identical (e.g., initial position, room size and exit properties), which could be easily implemented using desktop virtual reality, in order to standardise the experimental procedure for all participants.

In this work, we assume that the time pedestrians spend in a decision zone is relevant for capturing aspects of their decision-making process and measure the ratio α of the total time it takes participants to complete the experiment. We argue that while α is not a direct measure of the decision-making process, it can still capture and reflect pedestrian intentions in the exit choice process. Previous work describes pedestrian intentions by their movement direction, body orientation, or head turns (Liao et al., 2017). The decision zone measures pedestrian intention based on the location, which is effective for situations where details of individuals' movement that are commonly used to determine their intentions are difficult to measure. More work and data are needed to establish the general validity of this measure but we argue that it is reasonable in our carefully controlled experiment where pedestrians start at the midpoint of the horizontal line of two geometrically identical exits.

There are limitations to our study that need to be pointed out here and resolved in future research. First, we investigate pedestrian exit choice in virtual environments. While some previous work has directly demonstrated the validity of the virtual experiment paradigm for pedestrian exit choice and decision making in some contexts (Li et al., 2019), our experiment should not be interpreted as a direct test of pedestrian decision-making in real environments. Specifically for our experiment, the fact that participants have a third-person rather than first-person perspective, the fact that all simulated pedestrians appear to be male, the instructions given, the mouse and keyboard steering mechanisms, and the environmental features are examples of aspects that could influence the decision making of participants. While these aspects do not affect the internal validity of our experiment, as they are remain fixed within the experiment, further investigation using real-world data is therefore needed to establish if our findings extend to human exit choice in reality. Second, we recruited participants on a dedicated scientific research platform and the experiment was conducted online. Although online recruitment allowed us to gather data in an effective, flexible and controlled way, this approach has limitations. For example, the self-selected group of participants may not represent the general population, because on average certain groups of people might be more likely to participate in online research than others. Research on online recruitment for research indicates that the data quality is reasonably high and compares well to laboratory research but important caveats remain (Crump et al., 2013).

Our work confirms the key role of contextual factors in explaining the response of pedestrians to the movement of others during exit

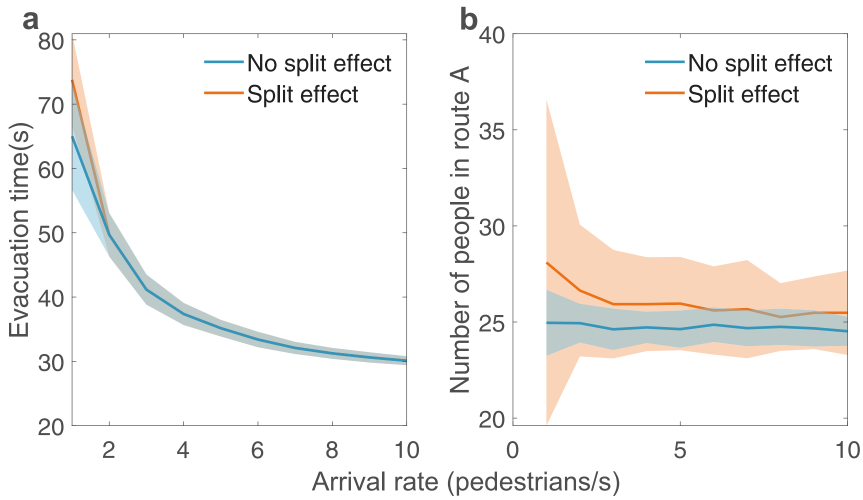

Fig. A.1. Simulations on the impacts of the split effect on evacuation time (a) and the number of pedestrians in route A (b) as the arrival rate changes.

Table A.1
Sample size for each experimental condition described in Table 1.

Variables				Original scenario	Mirror scenario	Age	Male (%)
Spatial information		Crowd state	Split level	Sample size	Sample size		
No information		Busy	Uneven	15	13	23.2	60.7
			0-1 split	14	14	23.1	50.0
			Even	26		24.3	50.0
		Free	Uneven	13	16	23.9	41.4
			0-1 split	16	12	23.8	53.6
Map with equal exit utility		Busy	Uneven	14	14	25.3	60.7
			0-1 split	13	16	24.2	44.9
			Even	29		25.8	48.3
		Free	Uneven	12	12	22.7	58.3
			0-1 split	13	13	24.6	53.9
Map with biased exit utility	Left exit has a higher utility	Busy	Uneven	15	11	24.9	53.9
			0-1 split	15	13	24.4	53.6
			Even	29		24.7	50.0
		Free	Uneven	13	15	28.3	50.0
			0-1 split	14	15	26.6	55.1
	Right exit has a higher utility	Busy	Uneven	11	13	24.0	33.3
			0-1 split	15	12	23.7	55.6
			Even	28		23.4	50.0
		Free	Uneven	14	13	22.9	37.0
			0-1 split	12	14	24.2	42.3

choice. Therefore, when we attempt to explain the mechanism of following behaviour, we should consider the context and be cautious about generalising across contexts. In particular, when designing an experiment, we should carefully consider and control for the interference of other attributes that may affect pedestrian behaviour in addition to the factor we aim to investigate. For example, in a pedestrian exit choice experiment, displaying spatial information to participants may be more advisable than not displaying any spatial information, because participants who are not given spatial knowledge about an environment may have certain unknown expectations of the space, which may affect their choices.

6. Conclusions

Our work confirms the importance of contextual factors for how pedestrians respond to the movement of others during exit choice and adds to a growing body of work on pedestrian exit choice. Our findings suggest that on average pedestrians tend to avoid the crowd and are influenced significantly by exit utility when presented with spatial information about the environment. However, when there are few other pedestrians who all move towards the same exit, pedestrians become more likely to follow them, suggesting their preference of avoiding an empty exit even if this exit has a higher utility in terms of a shorter exit route. Based on our simulations, this following behaviour can result in unbalanced route usage and lead to a reduction in the efficiency of pedestrian flow when pedestrians arrive slowly but only lead to negligible effects on pedestrian flows when arrival rates are high. These findings not only provide a deeper insight into how contextual factors affect pedestrian spatial behaviour that may be useful for pedestrian evacuation management, but they also highlight the importance of researchers considering the characteristics of context before conducting experiments and discussing research finding within the restrictions of the context considered. Future research should be carried out to determine the role of other potential attributes such as stress in human response to the crowd using evacuation experiments in a real environment.

Table A.2
Chi-squared statistic for tests on differences in exit choice between mirror versions of otherwise identical experimental conditions to test for innate preferences for the left or right exit.

Spatial information	Crowd state	Split level	Statistic	P
No information	Busy	Uneven	0.4308	0.5116
		0-1 split	0.1905	0.6625
	Free	Uneven	0.6073	0.4358
		0-1 split	2.0538	0.1518
Map with equal exit utility	Busy	Uneven	0.2435	0.6217
		0-1 split	0.7375	0.3904
	Free	Uneven	1.8151	0.1779
		0-1 split	0.6190	0.4314
Map with biased exit utility	Busy	Uneven(the majority in higher utility exit)	1.1966	0.2740
		Uneven(the majority in lower utility exit)	0.6977	0.4036
		0-1 split (the majority in higher utility exit)	0.5197	0.4710
		0-1 split (the majority in lower utility exit)	0.0967	0.7558
	Free	Uneven(the majority in higher utility exit)	0.3453	0.5568
		Uneven(the majority in lower utility exit)	0.7778	0.3778
		0-1 split (the majority in higher utility exit)	0.1603	0.6889
		0-1 split (the majority in lower utility exit)	3.2833	0.0700

CRediT authorship contribution statement

Yunhe Tong: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Nikolai W.F. Bode:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are available at the University of Bristol data repository, at https://doi.org/10.5523/bris.3kn82h2aamsfw2eplor4v2ewk0

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Appendix A. Supplementary tables and figures

See Tables A.1–A.2 and Fig. A.1.

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ssci.2022.105919.

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