



ELSEVIER

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Movement behaviour of pedestrians in knife-based terrorist attacks: An experimental approach[☆]

Alastair Shipman^{a,*}, Arnab Majumdar^a, Niki Boyce^a, Ruggiero Lovreglio^b

^a Civil and Environmental Engineering, Imperial College London, UK

^b School of the Built Environment, Massey University, New Zealand

A B S T R A C T

Terrorist attacks have become both more frequent and deadlier in recent decades. Knife attacks by terrorists in particular are both high impact and relatively frequent. Understanding how individuals move when confronted by an attacker can save lives by informing the planning of transportation hubs, entertainment venues and other spaces where large numbers of people congregate. Using pedestrian dynamics to predict responses to such attacks has the potential to further improve the survival of those involved by providing insights to emergency service responders when a terrorist situation has occurred in a crowded venue. However, given the lack of appropriate data, it is currently impossible to accurately predict pedestrian movement responses to terrorist attacks. This paper describes a practical study that developed a methodology and implemented a set of experiments examining responses to knife-based attacks by an unexpected and hostile individual. The experiments used financial incentives and an ‘aggressor’ to recreate a knife-based terrorist attack in an ethically viable setting. The participants of this study ($n = 80$) were tracked using ultra wide-band sensors to provide temporal and spatial positional data in relation to the attacker and to each other. Participants subsequently completed a questionnaire to report their psychological response during the experiment, thus allowing psychological perception and movement responses to be compared.

The results show that participants were stressed and reported fear during the experiment, indicating that the experimental approach is a potentially valid proxy for a real-life attack. The analysis highlights that participants’ decisions to stay or run away were strongly influenced by the actions of other nearby participants, while participants’ continuous movement response (movement speed) was highly dependent on relative position to the aggressor. Participant demographics were a factor with female participants less likely to move and slower moving, while older participants were also slower moving. From these results we have been able to construct a model of how pedestrians may react when faced with a sudden attack. We discuss our findings and their potential to contribute to emergency planning and response, finally we comment on opportunities for further study.

1. Introduction

Pedestrian dynamics is a multidisciplinary engineering field that is becoming increasingly crucial in the design of large-scale infrastructure and built environments likely to contain crowds. In particular, pedestrian dynamics aims at predicting the movement and the decision-making of pedestrians during normal or emergency conditions (Haghani and Sarvi, 2018). These predictions rely at present on computer models which were developed and specified using several theories (Lovreglio et al., 2020; Gwynne et al., 2016). On the other hand, pedestrian data collected using different empirical methods have been crucial in order to calibrate and validate these computer models with an acceptable level of accuracy (Haghani and Sarvi, 2018; Parisi and Dorso, 2005; Feng et al., 2021; Ronchi et al., 2016). Typical experimental setups to investigate pedestrian dynamics in normal conditions include the following:

[☆] This article belongs to the Virtual Special Issue on “Pedestrians & Crowds”.

* Corresponding author.

E-mail address: alastair.shipman@gmail.com (A. Shipman).

<https://doi.org/10.1016/j.trc.2024.104790>

Received 12 April 2023; Received in revised form 28 April 2024; Accepted 20 July 2024

Available online 26 July 2024

0968-090X/© 2024 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

quantifying maximum commuter flow rates through train stations or transportation termini (Bennett, 2024), assessing pedestrian exposure to artworks in galleries (<https://www.anylogic.com>, 2024), predicting typical flow through large infrastructure (Marin, 2016), predicting crossing behaviour at a road junction (Zhang and Fricker, 2020), understanding the impact of additional seating provision in stadia (Carattin, 2024), and crowd management for high-density events (Wilkinson, 2024).

Pedestrian dynamics is also commonly used in emergency contexts (Lovreglio et al., 2020; Kuligowski, 2016; Helbing and Mukerji, 2012). In this instance, the aim is to predict the movement and behavioural responses of pedestrians under stressful stimuli. These predictions can aid in improving the design of buildings and infrastructure, such as through the optimisation of the number and location of emergency doors or the placement of hostile vehicle mitigation measures. Furthermore, this body of knowledge can help in the development of crowd prediction and management techniques, as well as emergency response policies. However, while several studies have focused on fire and earthquake conditions (Gwynne and Boyce, 2016; Lovreglio et al., 2019; Bernardini et al., 2019), relatively few have investigated how pedestrians respond and move in terrorist scenarios (Bernardini and Quagliarini, 2021; Quagliarini et al., 2021; Zhu et al., 2020; Zhu).

While there are several definitions for terrorism currently, in this paper we use the definition proposed by Chaliand and Blin (Chaliand and Blin, 2007), in keeping with Neumann's (Neumann, 2009) definition of 'New Terrorism'. Hence this paper defines terrorism as the use of violence distinct from conventional and guerrilla wars. As such, within this paper, terrorism scenarios refer to specialised attacks carried out by small, non-state actors on political and public targets. Modern terrorist incidents include the use of handguns, bombs, vehicles, and, more recently, knives. Incidents usually involve a small number of terrorists who aim to cause significant harm to all nearby civilians and infrastructure. Unfortunately, the frequency of such events has been increasing over the past decades (Global terrorism database, 2024). Knife-attack scenarios have seen an increment in their frequency in recent years. Notorious instances of these types of attacks include Woolwich, UK (2013), Kuuming, China (2014), Westminster Bridge, UK (2017), Borough Market, UK (2017) and Toronto (2020). A knife attack has different features from other types of terrorist attacks adopting handguns and bombs as it requires physical contact between the aggressor and the victim. Additionally, a knife attack from one assailant results in a single attack vector, meaning that individual responses can be observed more easily. However, investigations on how pedestrians respond to these types of scenarios are unavailable in the literature, and consequently, understanding the pedestrian responses to these emergency scenarios is crucial to any mitigation efforts that aim to reduce their impact. Therefore, the overlap between pedestrian dynamics and terrorist attacks has a huge potential to mitigate the negative outcomes of such incidents and thereby save lives.

The purpose of this paper is to devise both an original and practical way to observe pedestrian decision-making and movement during sudden attacks. To achieve this goal, we designed and tested a new pedestrian experiment to mimic the conditions of knife attacks to find a compromise between ecological validity, experimental control, and ethical requirements. The designed experimental solution proposed in this paper includes an aggressor and financial stressors and we test the hypothesis that the experimental scenario elicits fear and provides a proxy for a real attack, before developing a model that may predict movement in such a situation. Furthermore, we collect data used to investigate decisions made by pedestrians either to move away from the aggressor or to remain still and how pedestrians move away from the aggressor in case they respond to the simulated threat. This experimental procedure was tested with 80 participants, and the collected data was used to model the decision to respond or stay still as well as to study participants' acceleration and velocity in total, tangential, and radial directions.

We begin this paper with an overview of previous research in Section 2 and then describe our proposed new experimental scenario and how it was tested in Section 3. We then present our results and analyses, including psychological and positional data in Section 4. We conclude by discussing the significance of these results and outline limitations and further investigations in Sections 5 and 6.

2. Background

Ensuring accurate representations of real-world pedestrian and crowd movement is an ongoing area of progress within pedestrian dynamics models, and the state-of-the-art in this area still fails to adequately accommodate emergencies (Kuligowski, 2016). This section details relevant studies in the domain of pedestrian behavioural responses to terrorist attacks in order to highlight both the existing research gaps and the need for new research on this topic.

Two major reviews have been conducted by Haghani et al. (Haghani et al., 2022) and Shipman and Majumdar (Shipman and Majumdar, 2018). The first review provides a general overview of the current and past temporal trends of the scholarly literature on terrorism during the past fifty years. This review highlights that there are only a few studies that have been focused on human responses to terrorist attacks. Such studies are relatively recent and investigate this subject by using video analysis of pedestrians' behaviour during terror attacks and simulations (Bernardini and Quagliarini, 2021; Lu et al., 2021). On the other hand, Shipman and Majumdar (Shipman and Majumdar, 2018) reviewed studies investigating the impact of fear on pedestrian responses and how these responses are currently modelled in pedestrian simulation tools. Their review also highlights the need for new data to generate simulation tools capable of modelling human responses during states of fear, such as terrorist scenarios. Furthermore, this second review acknowledges that this lack of studies is largely due to the ethical and practical barriers to performing this type of research. As such, both reviews agree on the need for new investigations on how pedestrians respond to terrorist attacks, as well as the need to generate new data; this requires experimental solutions that overcome ethical and practical barriers.

Focusing on the existing literature regarding human responses to hostile emergencies, it is possible to identify that the majority of prior approaches have involved simulations using models that have not been validated with appropriate data sources (Helbing et al., 2001; Zou et al., 2017; Tsai). These simulations used continuous modelling approaches, such as force-based models (Fa; Ma et al., 2016; Liu, 2020; Liu, 2018) and adapted velocity-based models (Zhou et al.), or discrete approaches such as cellular automata models (Chen et al., 2018; Faruqi and Mesgari, 2015; Lovreglio et al., 2015). There are also several theoretical models providing solutions to

define the different aspects of a simulation that should be considered when implementing behavioural responses in hostile scenarios. For instance, Hollmann et al. (Hollmann et al., 2011) used variable itineraries for agents to model behavioural changes owing to emotional states. Other studies (Tsai; Helbing et al., 2000) have introduced dependent parameters and factors to indicate the emotional state of an agent. These modelling approaches also often include the concept of emotional contagion (Zhou et al.; Zheng et al., 2019), where the emotional state of an individual agent can affect that of another.

Additionally, there have been examples of pedestrian dynamics research which attempt to implement the sociological theoretical constructs that have been established for crowd behaviour during emergencies (such as Emergent Norm Theory (McPhail, 1991), Social Attachment Theory (Mawson, 2005), Self-categorisation Theory (Turner et al., 1994), and the Protective Action Decision Model (Lindell and Perry, 2012)). For example, Aguirre et al. (Aguirre et al., 2011) write an account of how agent-based modelling can be used to replicate concepts from social sciences surrounding responses to emergencies. They conclude with seven different recommendations to computer modellers, finally arguing for the use of video footage to design and calibrate these approaches.

The recurring feature within the simulation approaches discussed in the previous paragraphs is the reliance on assumptions about how agents move in response to both emotional states and hostile threats. These assumptions are not based on observed behaviour, and while it may seem an obvious choice for a modeller to implement movement behaviour away from a threat (for example), this does not necessarily agree with the data (Cannon, 1915). There still remain significant questions regarding these computational approaches, and without underpinning data or other validation, they remain completely theoretical.

The difficulty that lies in validating these different pedestrian modelling solutions is largely due to the lack of available data, either from real-world or experimental sources (Shipman and Majumdar, 2018). However, some efforts have been made to generate new insights from different terroristic case studies. One of these rare studies is that by Li et al. (Li et al., 2017) who performed a targeted approach analysing the November 2015 terrorist attack in Paris, France, thereby generating a behavioural and decision-making model for individuals. They use video footage to extract data and analyse various concepts, including how the level of perceived threat changes with attack vector and distance from the source. However, this approach was limited by the available data, and only used three separate trajectories for evaluation of the model. It was also impossible for Li et al. (Li et al., 2017) to collect information relating to the level of the emotional response of the individuals, and consequently the importance of social interactions in these scenarios. A similar approach was adopted by Bernardini et al. (Bernardini and Quagliarini, 2021) when facing the same challenges and limitations experienced by Li et al. (Li et al., 2017). Another example is the work by Tsai et al. (Tsai et al., 2013) who performed calibration by comparing a pedestrian dynamics model, combined with an emotional transmission model, with CCTV footage of two separate incidents. By analysing the difference in pixel location of several agents within the footage and within the model, they evaluated the performance of both the behavioural and the emotional transmission models. However, a major limitation in the use of real-world data is that the factors affecting pedestrian responses are inherently uncontrolled. Therefore, researchers do not have the possibility to have a comprehensive analysis of all the possible factors affecting these responses as they are constrained by what actually happened in the investigated case studies.

Experimental approaches give researchers control over the factors that could affect pedestrian responses in terroristic scenarios. To date, there are a few studies that have used this approach. For instance, Li et al. (Li et al., 2017) investigated the initial movement responses of single participants to a hostile, knife-wielding actor from a range of different starting positions. However, this study did not measure the participants' emotional states nor did it investigate social influences, which is a critical factor in emergencies. Finally, the ecological validity of this experiment can be questioned as the participants were fully informed of the experimental protocol, thereby reducing the ecological validity. More recently, Virtual Reality (VR) has become an emerging tool in this field in order to investigate pedestrian responses. For instance, Awada et al. (Awada et al., 2021) assess emotional responses in VR, while participants moved in response to an active shooter. Additionally, Zhu et al. (Zhu et al., 2022) performed VR experiments investigating countermeasures for school shooting scenarios. Finally, Lovreglio et al. (Lovreglio, 2022) performed an analysis in the area of Serious Games, investigating how to effectively train civilians in courses of action during active shooter events. In summary, recent experimental studies have provided new insights into pedestrian responses to hostile emergencies. However, most of this research has a relatively low level of ecological validity as the participants were either informed about the scope of the experiment or were aware that the emergency was not real as they were in a virtual reality experience.

This brief review therefore highlights the need for new data that can be used in the future to calibrate and validate pedestrian models that can simulate responses in hostile emergencies. To date, several case studies have been used to meet this need using real-world or experimental sources. While investigating real case studies generates data with a high level of ecological validity, there are several limitations on what can be investigated in previous terrorist attacks. Using experimental data represents one of the most useful approaches to investigate the impact of different factors on human responses. In this case, all the previous attempts show a clear limit in terms of ecological validity, given the barriers due to the ethical requirements in this type of experiment. Given both the sensitivity and lack of availability of real-world data relating to terroristic incidents together with the lack of control that any such data would provide, there is the need to simultaneously identify new experimental procedures to gather ecologically valid data and address ethical requirements. This requirement forms the motivation for the current paper in that it aims to identify and test a new generation of experiments that mimic the conditions of knife attacks and to generate valid and accurate data. The next section details the method used to define a realistic experimental setup that can investigate pedestrian responses to hostile emergencies and how it was subsequently implemented and tested.

3. Methods

This section outlines the steps to design and test an experiment setup that can allow for the investigation of pedestrian responses to

sudden attacks. Our goal was to design an experiment that mimics the conditions of individual knife-based terrorist attacks. The design of such an experiment focuses on finding the balance between ecological validity, experimental control, and ethical requirements. The steps to define the proposed experiment are described in [Sections 3.1 and 3.2](#) focusing on the definition of the attack vector and the selection of the stressors to mimic knife-based attacks. [Section 3.3](#) describes how the experiment was set up and the experimental procedure, while [Sections 3.4 and 3.5](#) describe the sample of this study and what was measured during the experiment. Finally, [Section 3.6](#) illustrates the tools and solutions adopted to analyse the data.

3.1. Attack vector definition

When designing an experiment to measure human behaviour in response to stressful scenarios, it is necessary to consider the nature of the stressor, as it is expected that different responses will present in the face of different stressful stimuli. This is a significant part of the experimental design as it is not practical to simply recreate the conditions of a hostile emergency; ethics committees will not allow experiments where participants believe they are at risk of significant harm. Therefore, the stressor utilised in these experiments must recreate these conditions as faithfully as possible, while remaining ethically viable.

Previous pedestrian dynamics approaches have claimed that it is impossible to experimentally examine hostile emergencies such as terrorist attacks ([Shipman and Majumdar, 2018](#)), since it is necessary to provide appropriate stressors to perform experiments in an ecologically valid manner, producing a painful, unexpected stimulus where participants genuinely fear for their safety. However, this

Table 1
Attack vector characteristics.

Characteristic	Vector description	Bladed attack?	Proposed approach?	Comments
Intensity	Defines the level of intensity of the emotional and physical responses. High intensity example: blade, firearm Low intensity example: non-caustic radiological attack	High	✓	Financial stressor is limited by ethical concerns and experimental funding. Hostile aggressor will not approach participants that are visibly struggling.
Unannounced or declared	Notice is provided of the attack ahead of time, or not. Unannounced example: Almost all modern terrorist attacks. Declared example: Historical (e.g. 1960s-1990s bombings in the Troubles conflict, Northern Ireland).	Undeclared	✓	Ensure provision of information is controlled.
Physical nature: tactile or remote	Is transmitted by touch or from a distance. Tactile example: knife Remote example: firearm	Tactile	✓	Hostile aggressor must touch participants to cause financial loss.
Physical nature: painful or pain-free.	Causes immediate pain, or does not immediately affect those involved. Painful example: almost all modern terrorist attacks. Pain-free example: some CBRN, some gas-based attacks.	Painful	No	Not ethical to cause unexpected pain. Therefore Hostile aggressor to only touch participants lightly.
Mobile or stationary	The attacking agent is either able to move or not. A further subdivision is the sentience of a mobile stressor. Mobile example: vehicle (sentient), or CBRN (non-sentient). Stationary example: Bomb.	Mobile	✓	Hostile aggressor is able to move.
Binary or progressive	The danger posed is either constant or incremental. Binary example: Knife/gun/vehicle. Progressive example: CBRN.	Binary	✓	All-or-nothing implementation, rather than partial financial losses.
Number of stressing agents	Attacks can have any number of hostile agents. Individual example: Bombing Multiple example: group MTFA.	Depends	Individual	Single hostile aggressor in experiment.
Number of targets: individual or group	Can target either selected individuals, or all members of a group. Individual example: assassinations. Group example: bombing.	Depends	Group	Experiment will have groups of participants.
Non-selective or targeted	For group targets, either specific subsets of a group, or all members are equally at risk. Non-selective example: bombing, arson. Targeted: race-based attacks.	Non-selective	✓	Hostile aggressor selects next target based on proximity only.
Temporal scale: short or sustained	The timescale over which the incident occurs. Short example: bomb Sustained example: hostage scenario	Depends	Short	Experiment limited to 10 min.
Competitive nature	The survival capacity of individuals does not come at the cost of others, or it does.	Depends.	No	Participant success in experiment is independent of other participants.

difficulty may be addressed by the use of proxy stressors to approximate the stimulus of a terrorist attack. The use of these proxy stressors can simulate many of the characteristics of a terrorist attack, providing that they are controlled and empirically measured. It is necessary to design these stressors to mimic the proposed terrorist attack as accurately as possible, while also both inducing emotional responses to the highest ethically-permitted degree and then accurately measuring them.

For this study, our solution was to design a situation that placed participants in a crowd scenario and then introduced a sudden stressor and a need to avoid 'damage' during the attack without inducing actual fear of physical damage. While causing participants pain is occasionally sanctioned in modern experiments (Mintz, 1951; Keinan et al., 1987; Kelley et al., 1965), it is not possible to do so without first informing the participants. This would involve explaining the process in advance, removing the unannounced 'sudden attack' characteristic, and would therefore reduce the ecological validity of the experiment.

For the purpose of designing a stressor that mimics a terrorist attack, it was necessary to define the attack vector and any associated characteristics. This characterisation was a significant part of the experimental design. The proposed characteristics of modern terrorist attacks are detailed in Table 1, including the definition of a typical knife-based attack and the proposed experimental approach. These include defining the nature and number of the stressing agents, and the nature of the targets. This analysis shows that a bladed attack is well-defined for the majority of these characteristics, such as intensity and physical nature. However, in Table 1 we have identified three separate areas where a knife-based vector can be defined by a range of characterisations, depending on the incident itself. These areas include the following: Number of targets, Temporal scale, and Competitive nature. For instance, a knife-based incident can involve individuals (e.g. Woolwich, London, 2013 (BBC, 2024)), or groups (e.g.: Paris, 2015 (Naudet and Naudet, 2018)). In addition, the duration of such a knife attack can vary, from a few minutes (e.g.: Borough Market, London, 2017 (BBC. London bridge attack, 2024) to several days (e.g.: Mumbai, 2008 (CNN, 2024)).

3.2. Experimental stressors definition and validation

The stressors selected in this study to mimic knife-based attacks are naïve participants, a financial stressor, and an unexpected hostile aggressor.

Naïve participants: The participants in this experiment were not informed of the true aim of the research, as that would contradict the 'unannounced' stressor characteristic, and thereby bias any collected data. Instead, the participants were provided with several pieces of information. First, the experiment will investigate movement responses to cognitive and physical tasks. Second, these tasks will potentially be stressful in nature. Third, both individual and social responses will be investigated. Fourth, participants are allowed to go anywhere inside the building, or indeed leave the building. Fifth, initial tasks are provided, but these have no impact on an individual's completion of the experiment. Finally, further information will be provided later in the experiment.

Financial stressors

The participants were informed of the potential for variable financial payments for their experiments. This financial stressor was used to ensure that participants had a potential 'loss' as part of the experiment. The financial incentive was binary, using the following two principles: A high financial payment (£40-at time of experiments, this was worth approximately \$50USD) upon successful completion of the experiment. A low financial incentive (£5) for participants who failed to complete the experiment. However, all participants were awarded a high financial payment regardless of their performance in the experiment.

The unexpected hostile aggressor: In this experiment, a single actor was used as the hostile aggressor, to represent an individual terrorist. The actor was trained during the pilot study, the same actor was used throughout the study, and careful choreography ensured that the 'attack' had the same format each time the experiment was conducted. The participants would perform distractor tasks for five minutes, at which point a hostile aggressor was introduced to the experiment, who told the participant group that he would attempt to touch them and that if they were touched, they would lose their financial incentive for the experiment. It was determined from the pilot study that the aggressor should satisfy several constraints in order to provide a sudden and unexpected threat that would be both immediately identified and would induce stress in the participants while remaining within the ethical guidelines of the experiment. These required the hostile aggressor to: be previously unseen; be an explicitly identifiable member of the experimental team; act aggressively, initially shouting and moving at a slow speed (up to a jog); not approach participants who are visibly struggling with the experiment; touch participants lightly on the shoulder; select next target based on proximity only. The hostile aggressor always approached the same participant first, another actor (the 'actor-participant') who was standing in an identical position for each experiment.

As part of the design process, a pilot study was conducted in order to: understand the different interpretations of the participants, finalize the proxy stressor design, and ascertain the ethical viability of the experiment via a presumptive consenting process. This pilot was based on previous research that studied data generation for emergencies using narrative structures (Lawson, 2011). The pilot study was performed in conjunction with the People's Panel, a dedicated group at Public Health England (PHE). Twelve members, comprising six men and six women of the People's Panel were interviewed in three separate group focus sessions, performed over Skype, on the 21st and 22nd May 2018. The focus sessions lasted approximately an hour each and took the form of a narrative-based interview, in which the participants were provided with chronologically ordered information on the experimental protocol. Participants provided their impressions on the experimental design at various stages throughout the interview. Finally, each participant answered as to whether they would consent to be part of the experiment (presumptive consent). Unanimous presumptive consent was achieved, with multiple participants stating that an increased stressor would be both acceptable and desirable. The results of the pilot study support the validity of generating the appropriate environment and emotional responses using three separate elements: naïve participants, a financial stressor, and an unexpected hostile aggressor.

A final outcome of the pilot study was of an ethical nature: the need for the presence of a doctor during the data collection. Although

considered unlikely, the possibility of unforeseen medical outcomes was addressed by the presence of a doctor at all experimental sessions.

3.3. Experimental setup and procedure

The physical environment selected to carry out the experiment was a sports hall, approximately 30 m by 18 m, with one exit. A dividing wall was placed along the central line of the environment, and a central column was in the main section. The purposes of the central column were to improve participant positioning accuracy, provide a physical wall for the distraction task and also to provide a hiding place during the main task. There were five positioning anchors for use with the Ultra-WideBand (UWB) positioning system, four of which were placed in the corners of the environment, with the fifth on the central column. This is shown in Fig. 1.

The experiment timeline was split into three phases: the introduction, the experiment and the debrief. For the introduction, participants were brought into the hall where the experiments were being conducted and asked to complete the relevant paperwork needed for the study. This included a participant information sheet, a consent form, and a State Trait Anxiety Inventory (STAI-T) questionnaire. Finally, they were informed that they were allowed to go anywhere inside – or indeed outside – the building. During the experiment phase, the participants were asked to complete distractor tasks located at various positions around the area. These tasks were a means of engaging them with the experiment, as well as a method of disguising the true aims of the experiment. These distractor tasks comprised cognitive (e.g.: mental arithmetic) and physical tasks (e.g.: walking around the environment), designed to be sufficiently distracting but not mentally taxing. This phase lasted a fixed duration of five minutes, after which the actor-aggressor entered the environment. The participants were informed that these tasks had no bearing on the success or failure of their experiment.

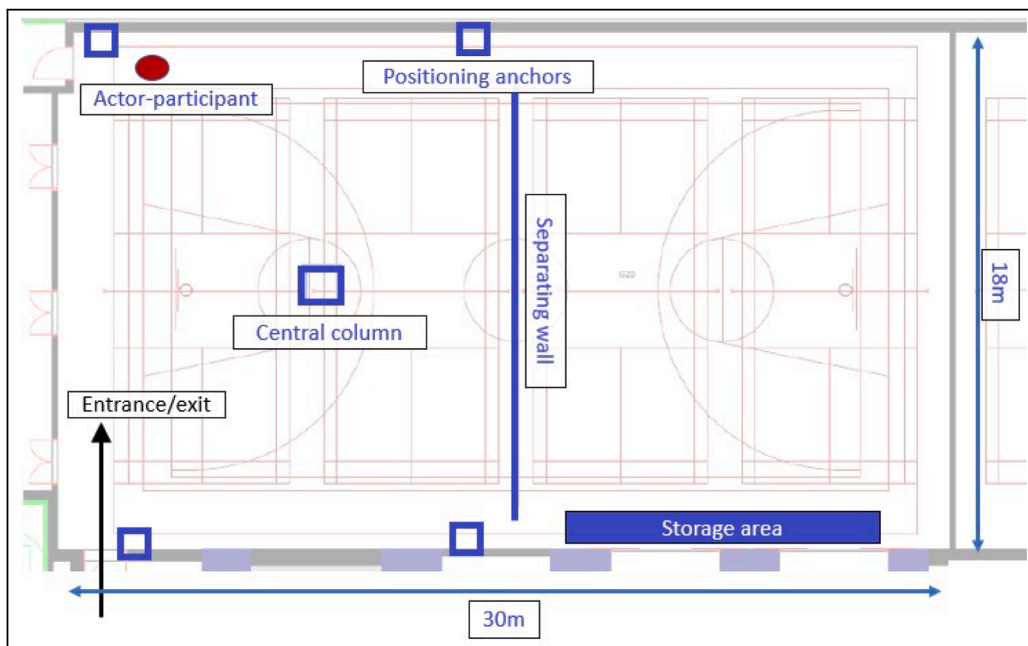
The actor-aggressor always entered at the same time (Fig. 2.a), and targeted the actor-participant first, who was always standing in the same position. Initially the actor-aggressor walked into the room (Fig. 2.a), pointed at the actor-participant, and shouted:

“HEY YOU FUCKER, AND EVERYONE ELSE! I’M GOING TO TRY TO TOUCH YOU NOW. IF I SUCCEED, YOU WILL FAIL THE TASK AND LOSE ALL YOUR MONEY.”

He (in this case) then continued to touch the actor-participant on the shoulder.

In half of the experimental sessions the actor-participant was directed to stand still prior to being approached (Fig. 2.b), and to act as if confused and irritated after being touched by the actor-aggressor, before sitting down. In the remaining sessions, the actor-participant was directed to attempt to evade the aggressor by running a few steps away. The purpose of varying the actor-participant response was to investigate whether a defiant response (prompt) by the actor-participant was a sufficient intervention in order to influence the subsequent behaviour of participants, as this suggests a significant effect of emotional contagion in the model from the actor-participant.

After the actor-aggressor approached and touched the actor-participant, he continued to approach the other participants, selecting



Physical environment

Fig. 1. Physical environment.

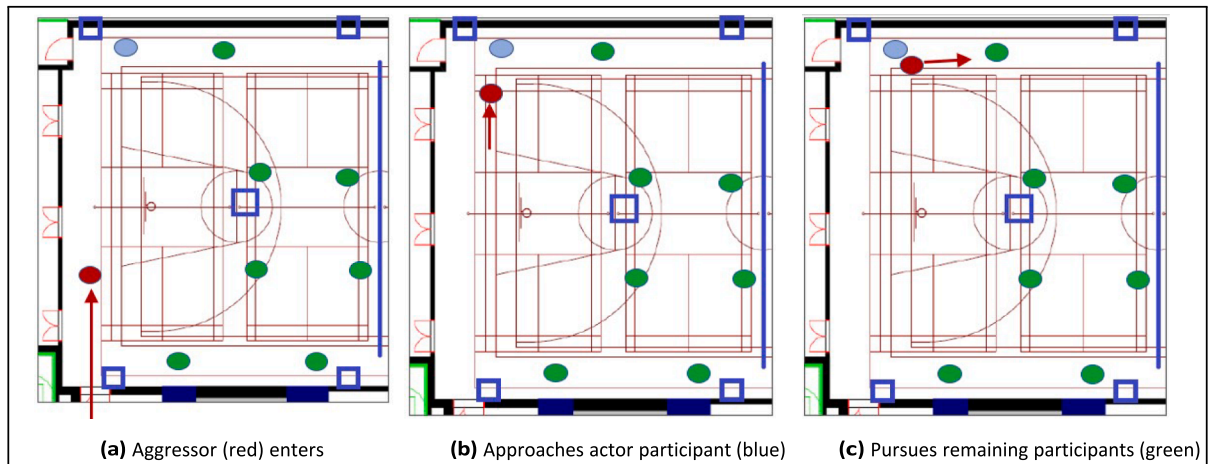


Fig. 2. Aggressor actions.

the next target by locating the nearest participant, and touching each of them in turn, moving no faster than a quick jog. If at any point a participant left the initial experimental area (either through the entrance/exit, or by going behind the separating wall), the actor-aggressor would stop pursuing them and move to another participant. If a participant left the environment through the entrance/exit, they were taken aside by a member of the experimental team and informed that they had completed the experiment, that they would be paid the full amount, and that they should remain in place until the experiment was completed.

The experiment finished after all the participants had either been touched by the actor-aggressor or had left the experimental area. At this point the participants were debriefed, and provided with a re-consenting procedure where they could provide consent with full information about the experiment before providing further survey responses. They were also informed that they were guaranteed the full payment for the experiment.

Two separate control experiments were developed, a 'Financial Control', and an 'Aggressor Control' (Table 2). These were implemented in order to understand the impact of the various experimental interventions. Financial Control participants were simply informed that they were guaranteed £40, thereby removing any financial stressor. During the experiment, the aggressor entered the room and explained that he was going to try to touch them, and if they were touched, they should remain still (this is similar to the game of 'tag'). Aggressor Control participants were presented with the same initial stage instructions as the main experimental group, but the hostile aggressor was not introduced at any point. Instead, the experiment was called to an end after ten minutes and debriefing performed.

For the purposes of the internal analysis (e.g., psychological state), both experiments were coded as 'control', and used as a baseline for the comparison between stressed and non-stressed responses. For the purposes of external analysis (e.g. movement responses), the financial control was used as a comparison in the discrete behavioural choice analysis. The aggressor control was not included, as by definition, it could not yield any relevant movement behaviour.

3.4. Participants

Participants were recruited from Imperial College London staff and student populations. They were contacted using specifically designed adverts and emails sent to all faculties and departments, along with a set of exclusion and inclusion criteria. 135 respondents were sent a demographic survey to perform and then randomly allocated to separate groups. Of these respondents, in total 80 (54 Male, 26 Female) participants attended, with group sizes ranging in size from 5 to 11 participants (mean: 8, standard deviation: 1.79). The participants had a mean age of 25.0 (standard deviation: 3.88 yrs). The experiments were performed over the period 17th-21st December 2018, over ten separate sessions, between 17:30–20:30 local time.

Table 2
Breakdown of experimental sessions and participants (n).

Branch	Description	Sessions	n
Financial control (control)	Participants have no financial stressor, as they are told they are guaranteed their financial incentives prior to the experiment, and the aggressor is directed not to be hostile. Therefore, the hostile aggressor does not represent a potential loss.	1	8
Aggressor control (control)	Participants are never exposed to the hostile aggressor, and consequently are not exposed to the financial stressor.	1	11
Experimental group (stress)	Participants are exposed to both financial stressor and hostile aggressor.	8	61

3.5. Measurements

This section details the measurements obtained during these experiments. These are split into three subsets: External, Internal subjective, and Internal Objective. These measurements are summarized in Table 3.

The first subset, External, measures the position and orientation of participants throughout the experiment, allowing for a full trajectory extraction. This was obtained using readings from a state-of-the-art Pozyx UWB indoor positioning system. UWB is a widely used system which uses electromagnetic waves with mobile tags and fixed anchors to allow for accurate positioning and orientation. This system was selected due to its robustness, accuracy and strong track record of usage in high-data commercial applications. Significant limitations experienced by other localisation methods can be overcome by UWB, such as not relying on line-of-sight, being dependent on resolution and avoiding occlusion issues. Each participant wore a helmet with a tag attached, and data from these tags provided 3D location measurements (x, y, z) with an accuracy of 10 cm. The UWB system also enabled measurement of rotations ($a + bi + cj + dk$) with a rotational accuracy of 0.5 %. Both 3D location and rotation measurements had a 10 Hz temporal resolution. Readers can refer to the supplier's website for further information (<https://www.pozyx.io/>). Examples of the location data of the aggressor (in red) and one of the participants (in blue) are visualized in Fig. 3. This UWB data was combined with information from multiple RGB cameras. These cameras were used to both run qualitative verification of the data generated with UWB and to investigate the behaviours of participants by observing their body pose and movement (see the example in Fig. 4).

The second subset, Internal, focuses on the measurements which the participant needs to actively provide, including demographic and psychological state. Two well-established surveys were used to assess psychological responses: the State-Trait Anxiety Inventory (STAI) and the Positive and Negative Affect Schedule (PANAS). The STAI survey assesses negative emotional states (anxiety) in either Trait (STAI-T) or State (STAI-S) form. Both were used, with the STAI-T survey performed by participants prior to the experiment, and the STAI-S performed post-experiment. The difference in the scores of these surveys ('Delta-STAI') provides a quantitative measure of the level of emotional response as a result of the experiment.

3.6. Analysis techniques

This section details the analysis performed on the obtained datasets. The initial analysis assesses the validity of the experiments, by quantifying the emotional state of the participants using psychological approaches. Using comparisons with the control experiments, a stress response is shown to be a direct result of the introduction of the hostile aggressor and financial incentive.

The second analysis performed investigates the movement responses of participants undergoing these emotional responses. This analysis is split into the different discrete choices made by participants, and a characterisation of the continuous movement responses observed.

The psychological approach used three measures for assessing the emotional state: the change between STAI score before and after the experiment (Delta-STAI), the positive PANAS score (PANAS-P), and the negative PANAS score (PANAS-N). These scores provided a quantitative point of comparison between the different experimental branches. The main statistical test performed was the two-sided Welch's *t*-test, unless a dataset was deemed non-normally distributed using both Kolmogorov-Smirnov and Shapiro-Wilk tests. In this instance, any differences were analysed using a Mann-Whitney *U* test, indicated by the prefix 'MW'.

The main behavioural observation from the experiments was the tendency for participants to either move away or remain still after being confronted by the hostile aggressor, analogous to the 'fight-or-flight' response coined by Cannon (Turner et al., 1994). This discrete movement response was modelled using a binary logistic, where a participant is defined as remaining still until they move more than one metre from their initial position at the point of entry of the hostile aggressor. This model, utilising several predictor variables (detailed below), predicts whether participants would move, or remain still, given specific stimuli, providing a powerful insight into the typical response types. Data for this model was obtained by taking snapshots of the experiments at each discrete event, defined as either 1) the aggressor touching a participant, or 2) a participant's decision to move. Each snapshot was then analysed, providing the dataset for the logistic regression, similar to the method used by Lovreglio et al. (Liu, 2018). The information collated from every snapshot included: participant ID, demographic information, the number of participants who are moving, the number of participants who have been caught, the distance between the aggressor and each participant and whether the participants are within the aggressor's field of view, defined as within $\pm 60^\circ$ of the direction of travel. An example of this is shown (not to scale) graphically in Fig. 5. In order to find the relevant factors in making this choice, a binary logistic regression was performed, predicting whether a participant was moving or standing still. The model used all of the variables obtained detailed above.

Another action type was crypsis ('playing dead'), where participants sat down and pretended to have been taken out of the

Table 3
Summary of measurements obtained.

Subset	Method	Approach	External reliability
External	Position	Measures obtained for all participants, measuring position (x,y,z) and rotation ($a + bi + cj + dk$) every 0.1 s (10 Hz)	Physical position obtained using proven, state-of-the-art UWB system.
	Orientation		
Internal	Demographics	Measurements were obtained for all participants.	Standard demographics were measured.
	Personality	The difference between STAI-T (pre-experiment) and STAI-S (post-experiment) produces 'Delta-STAI'.	Established surveys were chosen based on a large basis of evidence for validity.
	STAI-S, STAI-T,		
	PANAS		
Social responses			

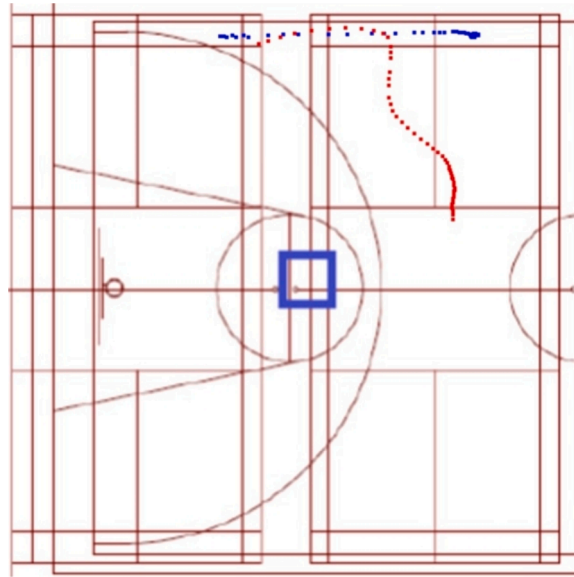


Fig. 3. Example of the location data of the aggressor (in red) and one of the participants (in blue).



Fig. 4. Experiment example screenshots.

experiment already. Three participants performed this action during the experiment and data from these participants during periods of crypsis was excluded from the analysed movement data. A final action type was altruistic interventions, where a single participant, after having been touched by the aggressor, attempted to prevent the aggressor from touching other participants. As this participant had already been touched, their data was irrelevant to the analysis at this point.

The position data for each participant was obtained using an ultra-wideband (UWB) system as detailed above. In order to understand the continuous movement characteristics of pedestrians in response to the hostile aggressor, each participant's position and rotation data was centred and reorientated to the perspective of the aggressor. An initial qualitative investigation of this dataset showed indications that participants moved faster when nearer the aggressor, with some discernible front-back asymmetry with respect to the direction of the aggressor. These preliminary findings suggest that the absolute movement speed might not be only related to the absolute distance to the aggressor, but also to the direction in which the aggressor is moving (relative to the participant).

Multiple regression models were created to characterise this movement by combining data from all moving participants across all stressful experiments, until they were either: removed from the experiment by the aggressor, left the environment through the door, or moved behind the dividing wall. The data of any participant engaged in crypsis was also filtered from this analysis. The X and Y axes form the basis of all positional independent variables. The full correct term used for these variables is 'Heading-corrected relative X' and 'Heading-corrected relative Y'; however, these terms are simplified to X and Y. The independent variables used to capture linear and non-linear effects in two dimensions, as well as to account for any symmetric (rotational or mirror) and asymmetric effects, are detailed in Table 4. In order to understand the movement behaviour shown above, several different movement types will be analysed. These are split into acceleration and velocity, from a total and radial perspective.

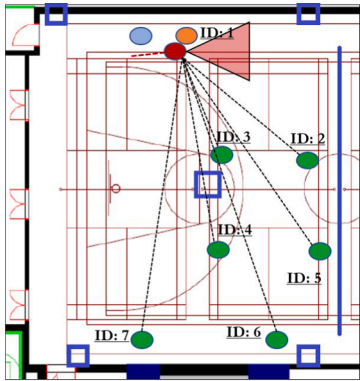
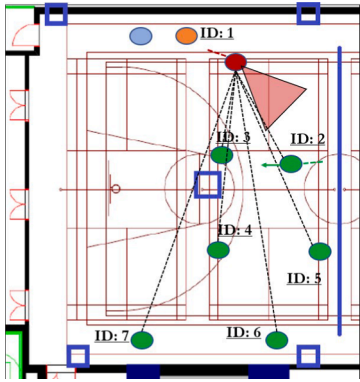
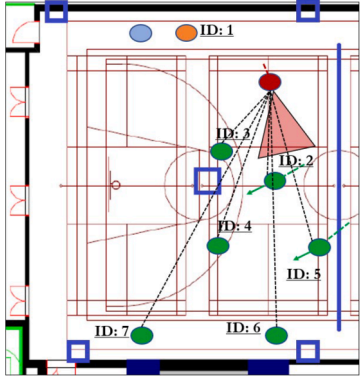
<p>Event 1: Participant 1 is caught</p> 	<p>Event 1</p> <p>Collected data: Number moving: 0 Number caught: 1 Distances: {ID1:NA, ID2: 5.2m, ID3:7.2m, ...} Within Agg FOV: {ID1: NA, ID2: False, 3: False...} Moving: {ID1: NA, ID2: False, ID3: False, ...}</p>
<p>Event 2: Participant 2 starts moving</p> 	<p>Event 2</p> <p>Collected data: Number moving: 0 Number caught: 1 Distances: {ID1:NA, ID2: 5.4m, ID3:5.1m, ...} Within Agg FOV: {ID1: NA, ID2: True, ID3: False...} Moving: {ID1: NA, ID2: True, ID3: False, ...}</p>
<p>Event 3: Participant 5 starts moving</p> 	<p>Event 3</p> <p>Collected data: Number moving: 2 Number caught: 1 Distances: {ID1:NA, 2: ID3.8m, ID3:2.9m, ...} Within Agg FOV: {ID1: NA, ID2: True, ID3: False...} Moving: {ID1: NA, ID2: True, ID3: False, ...}</p>

Fig. 5. Discrete data collection examples. The red dot represents the aggressor, the orange dot represents a participant who has been caught, the green dots represent the participants who have not been caught, and the blue dot represents the actor participant. The red triangle represents the field of view of the aggressor.

4. Results

This section reports the results in three categories: psychological (emotional) responses, discrete movement responses, and continuous movement responses. For the analysis in this section, the following significance codes are used: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and † $p < 0.1$. Any result that lies between 5–10 % significance will be referred to as marginally significant.

Table 4
Variables used for continuous response analysis.

IV/DV	Subset	Variable	Comments
Independent variables (IV)	Positional	Constant	N/A
		X, Y	Linear asymmetry
		X ² , Y ²	Non-linear mirror-symmetry
		X ³ , Y ³	Non-linear asymmetry
		Abs(X), Abs(Y)	Linear mirror-symmetry
		Distance	Linear rotational symmetry
	Demographic	Distance ²	Non-linear rotational symmetry
		Gender (F)	N/A
		Age	N/A
		Exercise level	Self-assessed on a scale 1–5 (1 = Not at all, 5 = More than three times a week)
Dependent variables (DV)	Total	Acceleration	Useful for simulation model calibration, e.g.: Social Force Model or Optimal Steps Model
		Velocity	
	Radial	Acceleration	Both absolute and positive/negative radial responses considered, as a clear difference in signed directions
		Velocity	

4.1. Psychological responses

The self-assessed psychological responses show that the experimental group participants experienced significantly higher levels of fear than those of the control groups (Fig. 6). The experimental group recorded an average Delta-STAI score of 4.39, against a control group value of -2.41 (p = 0.0017). The participants’ PANAS-N scores were deemed as non-normally distributed, and so were analysed using the Mann-Whitney U test. The average PANAS-N value is significantly higher in the experimental group at 20.18 compared to 14.05 (U=199.5; p = 8.61e-6). The measure of positive emotions, PANAS-P, showed no impact from the experiment. These responses, together with the results of the pilot study, support the validity of the proxy stressors in constructing an attack simulation; the limitations of this approach and potential opportunities for further refinement are discussed later in this paper.

4.2. Discrete movement responses

The different observed discrete movement responses are detailed in Table 5, comparing the combined data from the stress experiments with the control experiments where participants had no financial incentive to avoid the hostile aggressor. To model the movement of the aggressor in an attack, only data from the stress experiments was used in the subsequent regression.

Participant actions were ascertained manually, and with the exception of remaining still, if the participants undertook any of the actions at any point in the experiment, they were placed in the appropriate classification. No distinction was made when a participant took any of the actions more than once.

The primary observed action was for participants to either move (66 %) or remain still (34 %), where a participant is defined as remaining still until they move more than one metre from their position at the moment of the entrance of the hostile aggressor. These

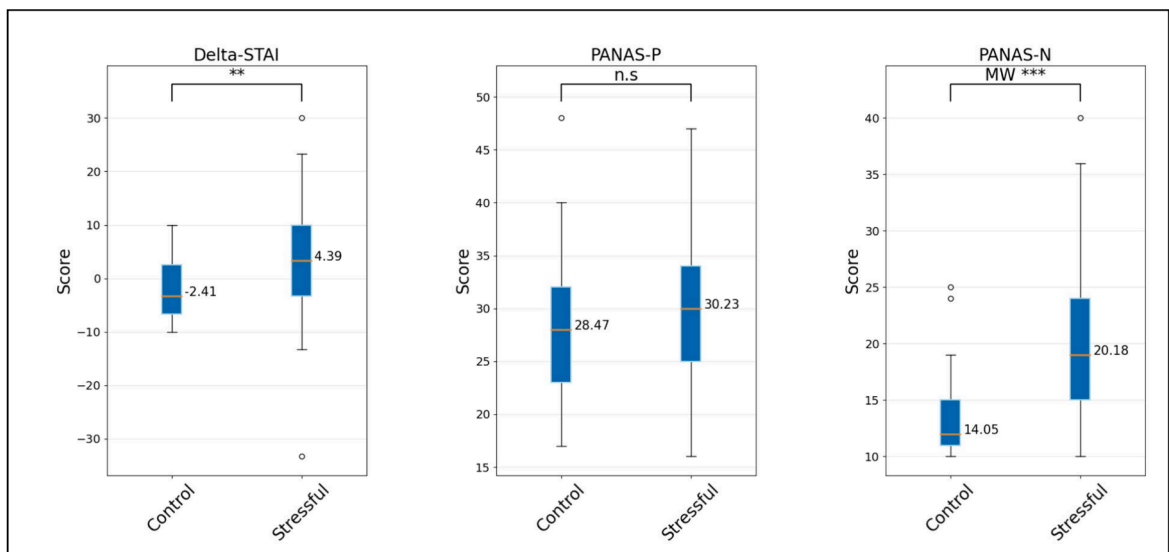


Fig. 6. Psychological survey scores comparing the main experiment (stressful) with control groups.

Table 5
Number of observed action types, by branch.

Observed action	Stressful Experiments	
1) Remain still	21 (34 %)	0
2) Move	40 (66 %)	8
2.1) Central column	36	8
2.2) Dividing wall	2	0
2.3) Leave room	5	0
3) Crypsis	3	0
4) Altruistic intervention	1	0

observations were taken from UWB positioning data and verified by camera data. These primary actions were also the only mutually exclusive actions and, therefore, used for the logistic regression. Subsequent movements (e.g. crypsis/altruistic intervention) are not mutually exclusive.

Within the stressful experiments 21 participants remained still throughout, while 40 participants moved away from the aggressor at some point. Within the Financial Control experiment, all of the participants moved away from the aggressor. These movement responses had further subtypes, including participants who moved behind the central column (36 participants in the stressful experiments, all participants in the Financial Control), thus placing an impassable object between themselves and the aggressor. The final movement subtypes included participants moving behind the dividing wall (2 participants in the stressful experiments, none in the Financial Control), and leaving the room completely (5 in the stressful experiments, none in the Financial Control).

The results of the logistic regression are shown in Table 6, where a positive coefficient indicates a positive relationship with the probability of a person moving. The model's confusion matrix, shown in Table 7, shows a model sensitivity of 83.6 %, and a specificity of 79.6 %.

This logistic model indicates that the decision to move is initially strongly unlikely (Constant coefficient = -3.616, $p < 0.001$), as well as strongly influenced by: the number of observed moving people (0.614, $p < 0.001$), the number of people that have previously been touched by the aggressor (0.289, $p < 0.001$), participant gender (female participants less likely, coefficient = 0.779, $p < 0.001$) and the exercise level of the participant (0.306, $p < 0.001$). The model suggests that the decision to move is only marginally dependent on whether the aggressor is currently moving towards the participant (0.430, $p = 0.062$). However, the model also suggests that this decision is independent of the distance between the participant and the aggressor (-0.018, $p = 0.413$), as well as of the age of the participant (-0.020, $p = 0.495$).

4.3. Continuous movement responses

The continuous models, detailed in Table 8, were created using a bidirectional stepwise variable selection process. These models were created for acceleration and velocity in total, tangential and radial directions. This stepwise process ensured that only significant independent variables are used in populating the models, while all non-significant variables are removed. Consequently, only some of the proposed fourteen variables were used in the regression models, indicated by blank spaces in Table 8.

Fig. 7 shows isometric field lines of participant speed and acceleration from the perspective of the aggressor (placed at the origin), as defined by the models generated in Table 8. The plots show higher values in red and lower values in blue. Fig. 7.a shows the model of total acceleration, which has a local maximum approximately located at the origin, indicating that the acceleration of participants increases as the aggressor approaches them. This acceleration model has an approximate front-back symmetry and left-right asymmetry, with an indication of a rising level of acceleration on the aggressor's right-hand side. According to Table 8, the model also indicates that older participants accelerate at a lower rate, while female participants accelerate at a higher rate.

The total velocity model (shown in Fig. 7.b) has a local maximum located at a small offset from the origin, indicating that participant velocity decreases with distance from the aggressor. Furthermore, the model shows approximate left-right and front-back symmetry. Similar to the total acceleration model, the model indicates that velocity increases with self-reported exercise levels and

Table 6
Logistic regression results for discrete movement analysis. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and † $p < 0.1$.

Logistic Discrete Choice Model					
Variable	Coefficient	Std error	Odds-ratio	Z-value	p-value
Constant	-3.616	0.993	0.027	-3.643	0.0003***
Number moving	0.614	0.049	1.848	12.486	8.92e-36***
Number caught	0.289	0.061	1.335	4.736	2.18e-06***
Distance to aggressor	-0.018	0.022	0.982	-0.818	0.413
Within FOV	0.430	0.231	1.538	1.867	0.062†
Gender (F)	-0.779	0.220	0.459	-3.544	0.0004***
Exercise level	0.306	0.090	1.358	3.390	0.0007***
Age	-0.020	0.030	0.980	-0.683	0.495
Mcfadden's pseudo r^2			0.382		
Log-likelihood (LLR p-value)			-319.84 (2.284e-81***)		

Table 7
Confusion matrix for logistic model (absolute numbers).

Logistic model confusion matrix		Actual classification	
		Move	Remain still
Move		411	57
Remain still		81	223
Sensitivity		0.836	
Specificity		0.796	

Table 8
Models of movement response (*p < 0.05, **p < 0.01, ***p < 0.001, and †p < 0.1).

Subset		Multiple regression models of movement responses based on positional and demographic predictors					
		Total		Radial (Absolute)		Radial (Directional)	
		Acceleration	Velocity	Acceleration	Velocity	Acceleration	Velocity
Positional	Constant	7.2912***	3.5655***	4.7197***	2.5909***	-0.5432***	1.2203***
	Distance						0.0823***
	Distance ²	-0.0052***			-0.0020***		-0.0076***
	X						
	X ²			-0.0035**			
	X ³						
	Abs(X)		-0.0555***				
	Y		-0.0159***		-0.0153***		-0.014***
	Y ²		-0.0059***				
	Y ³	-0.0005***		-0.0004***			
Demographic	Abs(Y)	-0.0826*		-0.0995***	-0.0281***		
	Age	-0.0965***	-0.0620***	-0.0642***	-0.0463***		-0.0339***
	Exercise level		0.0931***				
	Gender (F)	0.5112*			-0.1100*		
	Adjusted r ²	0.009	0.038	0.007	0.022	0	0.012
	F-statistic	15.7166***	64.852***	15.002***	37.812***	N/A	26.047***
	Omnibus test	8438.704***	6021.877***	9533.032***	12243.562***	6420.399***	4303.792***

decreases with age.

The radial acceleration (absolute) model (Fig. 7.c) indicates a local maximum approximately located at the origin, suggesting that radial acceleration increases as the aggressor approaches. Further to this, the model shows a saddle point to the right-hand side of the aggressor, indicating some left–right asymmetry, while maintaining approximate front-back symmetry. The model also suggests a decreasing relationship with age. The radial velocity (absolute) model (Fig. 7.d) shows a decrease in radial velocity with increasing distance, with front-back and left–right symmetry. Furthermore, the model indicates that radial velocity (absolute) decreases with age, and that female participants move slower than male participants in this direction. No significant input to the model was obtained from the Prompt/No-prompt scenarios, suggesting that participants were not influenced by the behaviour of the actor-participant and that emotional contagion from the actor-participant was not a significant factor.

The radial acceleration (directional) variable selection process produced a null model, suggesting that radial acceleration (directional) is independent of position and demographic. This is the only occurrence of complete independence within the continuous analysis section, and consequently means that there are no features to report and no graphic to display. The radial velocity (directional) model (Fig. 7.e) has a maximum value near the origin, and appears to have front-back symmetry, and some degree of left–right symmetry. The model also suggests a negative relationship between age and radial velocity (directional).

5. Discussion

This paper details an approach for investigating the immediate spatiotemporal movement responses to knife-based hostile emergencies, including developing the characterisation of these stressors and the required measurements. As such, this work proposes an ethical approach to investigate these types of responses by using both financial incentives and an ‘aggressor’ to recreate a knife-based terrorist attack in an ethically viable setting. In fact, the proposed method is ethically viable, having been assessed by the independent Imperial College Research Ethics Committee board (ICREC, reference number 18IC4637). As such, a main contribution of this work is to propose an experimental solution that overcomes the constraints highlighted in previous studies (Shipman and Majumdar, 2018), which considered the examination of human behaviour in stressful conditions, such as terrorist attacks. Given the ethical challenges for this type of study, there has been limited progress over recent decades in data collection and subsequent analyses of human responses. The main contribution of this work is to show that it is possible to create experimental conditions mimicking a knife-based attack using several stressors that can be carried out without breaching ethical requirements. As described in section 3.2, this was achieved in this work by using *financial stressors* and an *unexpected hostile aggressor*, including the use of deception as the participants were not informed

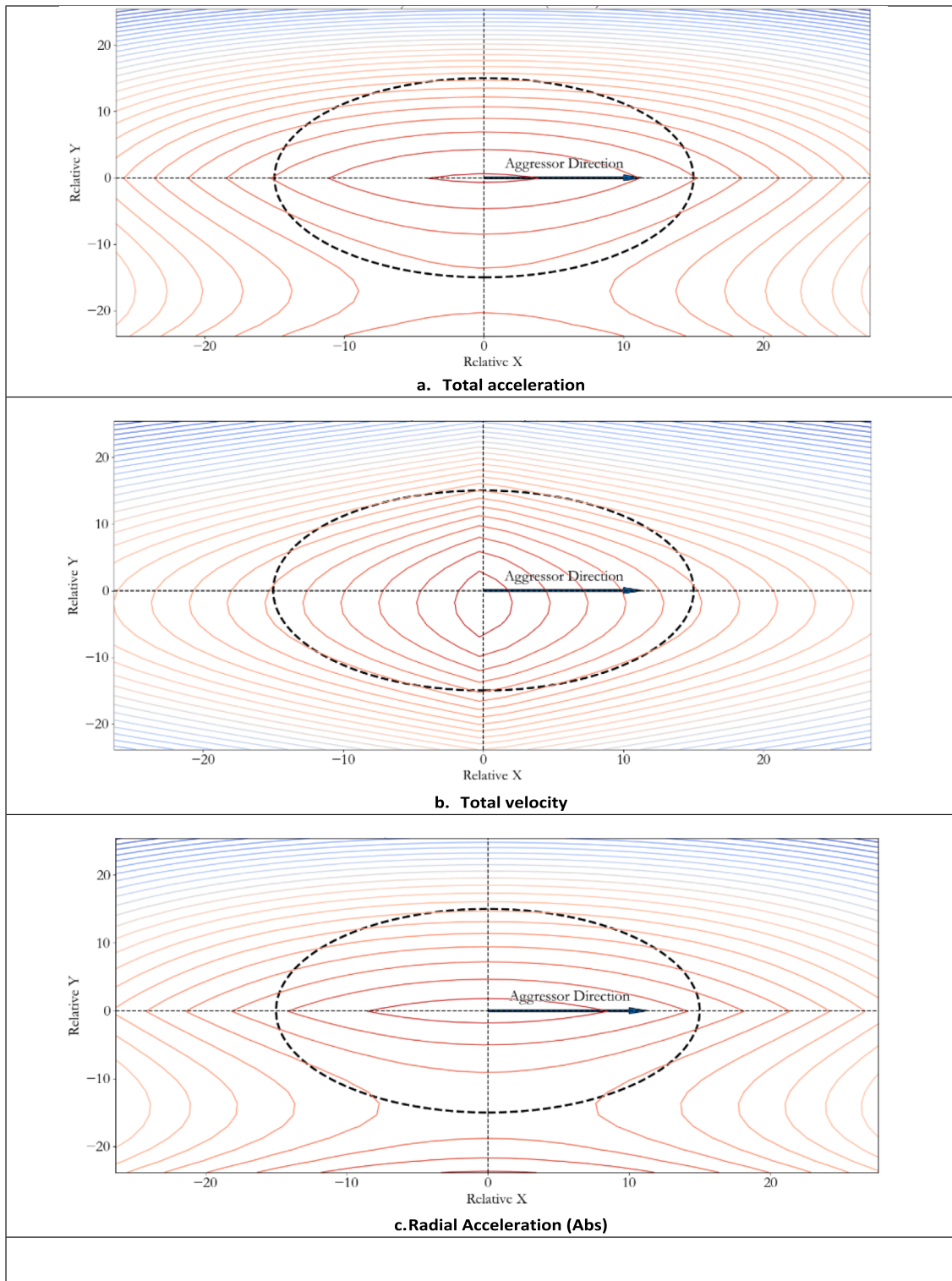


Fig. 7. Visualization of the continuous movement models in Table 8.

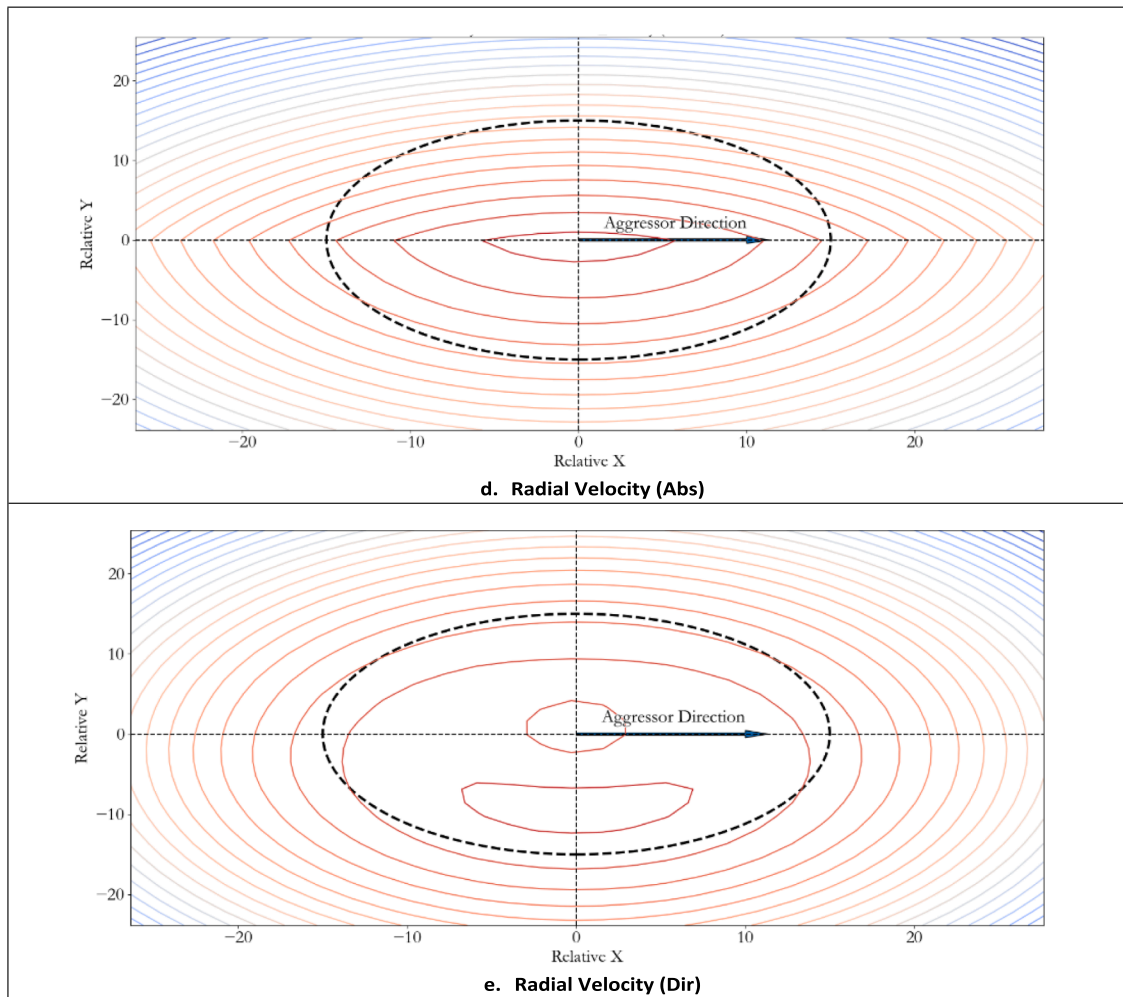


Fig. 7. (continued).

of the true aim of the research. This was essential to preserve the ecological validity of this study.

The second contribution of this work is to assess the validity of the proposed experimental solution by assessing the psychological response of the participants and verifying the participants' change in anxiety, and positive and negative emotions. This was done in this work using well-established questionnaire tools, i.e., the State-Trait Anxiety Inventory (STAI) and the Positive and Negative Affect Schedule (PANAS). The results in Section 4.1 show that the levels of emotion reported by the participants indicate that they experienced an increase in their levels of negative emotion, measured across two separate surveys. This is highlighted in Fig. 6, which shows that the stressful condition is significantly different from the control condition for both measures of negative emotion. Interestingly, there was no discernible difference in the measure of positive affect (PANAS-P). These findings suggest that these experiments produced stress responses in the participants. Additionally, the design of the experiment ensures that the stressor mimicked the conditions of a knife-based hostile attack, similar to the types seen in previous terrorist incidents. These two facts combine to suggest that the responses shown are indicative of those that would occur during an actual hostile emergency, supporting the hypothesis that our experimental scenario elicits fear and provides a proxy for a real attack. A potential limitation of self-assessed responses is their subjective nature, which may leave them liable to cognitive biases on behalf of the participants. As such, physiological responses may be measured in the future, for instance, by assessing the level of cortisol. However, these measurements introduce new practical and ethical challenges as well as new levels of uncertainties, as discussed in a previous study (Shipman, 2021).

The final contribution of this work is the use of the collected data to investigate how participants responded to the aggressor. Specifically, this work investigated if and how factors such as social influences and distance from the threat impact these responses. This was done in this work by estimating a discrete choice model as well as several continuous regression models. In fact, the data collected in the proposed experiment allowed the investigation of the participants' decisions to either move or remain still. This was done by using discrete choice modelling. The finding of this analysis (see Section 4.2) shows that there was a low initial probability of a participant running away from the aggressor, shown by the strongly significant negative constant coefficient in Table 6. However, strongly significant positive coefficients were also seen in the Number Reacted and Number Caught variables, indicating that

participants were influenced to a large extent by social interactions. Interestingly, no significance was observed for either the Within FOV, or Distance to Aggressor predictors, suggesting that participant responses were far more influenced by their neighbours' responses than by the aggressor. It is worth noting, however, that the presence of the aggressor was required to produce these, therefore placing the participants into a state where they are strongly influenced by their neighbours. The differences in discrete behaviours observed within the financial control experiment and the stressful experimental branch (Table 5) are noteworthy in that no remaining still, crypsis, or room evacuation was observed within the financial control experiment. Unfortunately, there is insufficient data to investigate why this occurred, and indeed, this was not the primary aim of the experimental protocol. However, future experiments could look at the effect of financial stressors to understand these differences.

The continuous data analysis in Section 4.3 compared the movement speed of participants with respect to the perspective of the aggressor. This continuous analysis was performed with a bidirectional stepwise selection process on a range of positional and demographic predictor variables, providing relationships for movement speed and acceleration in terms of absolute and radial components. The regression model results show significant relationships between movement responses and positional and demographic predictor variables. Further, the models suggest that their respective dependent variables (i.e. velocity and acceleration) decrease with relative position, either as a function of X and Y, or by overall distance. This is a particularly useful result for simulation models, indicating that agents in these models reduce their levels of acceleration or velocity as they get further from an aggressor. A further interesting result is the apparent independence of Radial acceleration (directional) on relative position and demographic. This runs contrary to many of the previous models, especially force-based models. It is considered that this independence is at least partially due to the signed nature of the variable, which increases variation in the data (and which disappears when taking absolute values). Further data gathering would serve to corroborate or negate this point.

This study suffers from some unavoidable limitations. The primary limitation is the use of proxy stressors, which will only ever approximate the effect of a real-world terrorist attack. While the proxy stressors used in these experiments can be developed to increase the levels of stress experienced (for example by having the hostile aggressor carrying a plastic blade, being covered in paint, or another method), the participants will always be aware that they are in an experiment, and that there is no real risk. However, as this study has shown, the proxy stressors can approximate the actual stressor well, providing a valid scenario for investigating revealed choices.

These models had relatively low explanatory power (adjusted r^2 values ranging from 0.7 % to 3.8 %), and the residuals were significantly non-linear as measured by an omnibus test, suggesting that a different approach could be used. One such approach might be to use machine learning techniques for time-series data, such as Long Short-Term Memory (LSTM) or Transformers. However, these approaches would require vast amounts of data to be fully trained. A further consideration is the fact that the datasets included both walking and running behaviour, which represents a multi-modal response. This combination of the different modes may contribute to the high level of unexplained variation. It is suggested that further limitations, including the participant sample and noise within the positional measurements, would be mitigated by repeating this experiment.

To the authors' knowledge, these are the first results of such a type of experiment and the proposed results can provide new insights and knowledge for both mitigation and advisory manuals for agencies concerned with public safety. Furthermore, these results can also be used to enhance future simulations to better reflect public behaviour in alternative knife-based terrorism scenarios. However, in order to fully implement these results, further work is required. One fruitful avenue would be the investigation of the transition between walking and running behaviour, as a multi-modal response was observed during the experiments. The mobile nature of the stressing agent also suggests that another avenue would be the characterisation of movement where the goal of the agent is dynamically defined. Furthermore, future studies can usefully consider multiple agents/hazards and examine the effect on the model when it is extended to other types of attack such as firearm, explosion, or fire, as these are likely to elicit different responses from those involved in an attack. Further research by this team has used a virtual reality (VR) environment to immerse participants in a more realistic scenario and allow more sophisticated intervention and potentially less reliance on proxy stressors. To date, the proposed experimental solution has been already tested as part of the original PhD work by Shipman (Shipman, 2021) the findings comparing participants' responses to the physical and virtual reality setups are published in this companion paper (Shipman et al., 2024).

6. Conclusion

This paper proposes a set of experiments examining responses to knife-based attacks by an unexpected and hostile individual. This was achieved through financial incentives and an 'aggressor' to recreate a knife-based terrorist attack in an ethically viable setting. The results indicate that the proposed experimental setup can produce stress responses in the participants, creating a psychological state mimicking the conditions of a knife-based hostile attack.

The main finding of this paper highlights that the participants' decisions to either move or remain still were affected by several factors: social influences (i.e., the response of other participants), if participants were in the field of view of the aggressor, and the participants' gender and exercise level. In addition, the results provide insights into the participants' responses in terms of speed and acceleration (i.e., continuous movement responses). The proposed models show that the distance of the aggressor and a range of positional variables affected the speed and acceleration of the participants. Finally, the continuous movement responses were also affected by the participants' age and exercise level.

Author contributions statement

A.S. conceived and implemented the experiments. A.S. and R.L. conducted the analysis. All authors reviewed the manuscript. The investigations and findings of this paper formed part of a PhD study (Shipman, 2021) completed at Imperial College London by the first author.

Ethics and data availability

All experimental protocols were approved by the Imperial College London Research Ethics Committee, all methods were carried out in accordance with relevant guidelines and regulations, and sufficient informed consent was obtained from all participants. As a result of these mitigation efforts, the study fully satisfied the ethical review board committee.

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

CRedit authorship contribution statement

Alastair Shipman: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Arnab Majumdar:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Niki Boyce:** Writing – review & editing. **Ruggiero Lovreglio:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis.

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.

Acknowledgements

A.S. was funded by EPSRC grant EP/L016826/1.

References

- Aguirre, B.E., El-Tawil, S., Best, E., Gill, K.B., Fedorov, V., 2011. Contributions of social science to agent-based models of building evacuation. *Contemp. Soc. Sci.* 6, 415–432. <https://doi.org/10.1080/21582041.2011.609380>.
- Awada, M., Zhu, R., Becerik-Gerber, B., Lucas, G., Southers, E., 2021. An integrated emotional and physiological assessment for vr-based active shooter incident experiments. *Adv. Eng. Informatics* 47, 101227. <https://doi.org/10.1016/j.aei.2020.101227>.
- BBC. Lee Rigby murder: How events in Woolwich unfolded. <https://www.bbc.co.uk/news/av-uk-25444080> Accessed on 16/02/2024.
- BBC. London bridge attack: What happened. <https://www.bbc.co.uk/news/uk-england-london-40147164> Accessed on 16/02/2024.
- S. Bennett. Paddington station legion modelling. [Online]. Available: https://learninglegacy.crossrail.co.uk/wp-content/uploads/2018/06/Paddington-Station-Legion-Modelling-C130-SWN-T1-XMO-B071-50001_Rev3.0.pdf Accessed on 16/02/2024.
- Bernardini, G., Lovreglio, R., Quagliarini, E., 2019. Proposing behavior-oriented strategies for earthquake emergency evacuation: a behavioral data analysis from New Zealand, Italy and Japan. *Saf. Sci.* 116, 295–309. <https://doi.org/10.1016/j.ssci.2019.03.023>.
- Bernardini, G., Quagliarini, E., 2021. Terrorist acts and pedestrians' behaviours: First insights on European contexts for evacuation modelling. *Saf. Sci.* 143, 105405. <https://doi.org/10.1016/j.ssci.2021.105405>.
- Cannon, W.B., 1915. *Bodily changes in pain, hunger, fear and rage: An account of recent researches into the function of emotional excitement* (D Appleton and Company, New York, NY, US, 1915).
- Carattin, E. Dynamic crowd modelling for better stadium design. <https://www.oasys-software.com/news/dynamic-crowd-modelling-better-stadium-design/> Accessed on 16/02/2024.
- Chaliand, G., Blin, A., 2007. *The history of terrorism: from antiquity to al Qaeda* (University of California Press, Berkeley, Calif.; London, 2007).
- Chen, C., Tong, Y., Shi, C., Qin, W., 2018. An extended model for describing pedestrian evacuation under the threat of artificial attack. *Phys. Lett. A* 382, 2445–2454. <https://doi.org/10.1016/j.physleta.2018.06.007>.
- CNN. Mumbai terror attacks fast facts. <https://edition.cnn.com/2013/09/18/world/asia/mumbai-terror-attacks/index.html> Accessed on 16/02/2024.
- Fa, Z., Songchun, W., Zhihua, S. Evacuation during violent attacks: Agent-based modeling and simulation. In: *IEEE 9th International Conference on Software Engineering and Service Science (ICSESS)*, 412–415, DOI: 10.1109/ICSESS.2018.8663758.
- Farooqi, H., Mesgari, S., 2015. Agent-based crowd simulation considering emotion contagion for emergency evacuation problem. *ISPRS - Int Arch. Photogramm. Remote. Sens. Spatial Inf. Sci. XL-1-W5* 193–196. <https://doi.org/10.5194/isprsarchives-XL-1-W5-193-2015>.
- Feng, Y., Duives, D., Daamen, W., Hoogendoorn, S., 2021. Data collection methods for studying pedestrian behaviour: a systematic review. *Build. Environ.* 187. <https://doi.org/10.1016/j.buildenv.2020.107329>.
- Global terrorism database. <https://www.start.umd.edu/gtd/> Accessed on 16/02/2024.
- Gwynne, S., Boyce, K., 2016. *Engineering Data*, 2429–2551 *SFPE Handb. Fire Prot. Eng.*, Springer, New York, New York, NY, pp. 2429–2551, DOI: 10.1007/978-1-4939-2565-0_64 (2016).
- Gwynne, S.M.V., Hulse, L.M., Kinsey, M.J., 2016. Guidance for the model developer on representing human behavior in egress models. *Fire Technol.* 52 (775–800), 2016. <https://doi.org/10.1007/s10694-015-0501-2>.
- Haghani, M., Kuligowski, E., Rajabifard, A., Lentini, P., 2022. Fifty years of scholarly research on terrorism: intellectual progression, structural composition, trends and knowledge gaps of the field. *Int. J. Disaster Risk Reduct.* 68, 102714. <https://doi.org/10.1016/j.ijdrr.2021.102714>.
- Haghani, M., Sarvi, M., 2018. Crowd behaviour and motion: Empirical methods. *Transport. Res. Part B: Methodol.* 107, 253–294. <https://doi.org/10.1016/j.trb.2017.06.017>.
- Helbing, D., Farkas, I.J., Molnár, P., Vicsek, T., 2001. Simulation of pedestrian crowds in normal and evacuation situations. In: Schreckenberg, M., Sharma, S.D. (eds.) *Pedestrian and Evacuation Dynamics*, Duisburg, Germany, April 4–6, 2001, 58 (Springer).
- Helbing, D., Mukerji, P., 2012. Crowd disasters as systemic failures: analysis of the love parade disaster. *EPJ Data Sci.* 1, 7. <https://doi.org/10.1140/epjds7>.
- Helbing, D., Farkas, I., Vicsek, T., 2000. Simulating dynamical features of escape panic. *Nature* 407, 487–490.
- Hollmann, C., Lawrence, P.J., Galea, E.R., 2011. *Introducing Emotion Modelling to Agent-Based Pedestrian Circulation Simulation*, 799–803 (Springer US, Boston, MA, 2011).
- Using pedestrian library to create a new look for an art gallery. <https://www.anylogic.com/resources/case-studies/the-ametria-project-using-pedestrian-library-to-create-a-new-look-for-an-art-gallery>. Accessed on 16/02/2024.
- Keinan, G., Friedland, N., Ben-Porath, Y., 1987. Decision making under stress: Scanning of alternatives under physical threat. *Acta Psychol.* 64, 219–228. [https://doi.org/10.1016/0001-6918\(87\)90008-4](https://doi.org/10.1016/0001-6918(87)90008-4).
- Kelley, H., Condry, J., Dahlke, A., Hill, A., 1965. Collective behavior in a simulated panic situation. *J. Exp. Soc. Psychol.* 1, 20–54. [https://doi.org/10.1016/0022-1031\(65\)90035-1](https://doi.org/10.1016/0022-1031(65)90035-1).

- Kuligowski, E.D. (2016). Computer Evacuation Models for Buildings. In: Hurley, M.J., et al. SFPE Handbook of Fire Protection Engineering. Springer, New York, NY. DOI: 10.1007/978-1-4939-2565-0_60.
- Kuligowski, E., 2016. Computer Evacuation Models for Buildings, SFPE handbook of fire protection engineering 2152–2180 (2016). Kuligowski, E. D. (2016). Lawson, G. Predicting human behaviour in emergencies. Thesis (2011). University of Nottingham. <https://eprints.nottingham.ac.uk/12027/>.
- Li, S., Zhuang, J., Shen, S., 2017. A three-stage evacuation decision-making and behavior model for the onset of an attack. *Transp. Res. Part C: Emerg. Technol.* 79, 119–135. <https://doi.org/10.1016/j.trc.2017.03.008>.
- Li, S., Zhuang, J., Shen, S., Wang, J., 2017. Driving-forces model on individual behavior in scenarios considering moving threat agents. *Phys. A: Stat. Mech. Its Appl.* 481, 127–140. <https://doi.org/10.1016/j.physa.2017.04.011>.
- Lindell, M.K., Perry, R.W., 2012. The protective action decision model: theoretical modifications and additional evidence. *Risk Anal.* 32, 616–632. <https://doi.org/10.1111/j.1539-6924.2011.01647.x>.
- Liu, Q., 2018. A social force model for the crowd evacuation in a terrorist attack. *Phys. a: Stat. Mech. Its Appl.* 502, 315–330. <https://doi.org/10.1016/j.physa.2018.02.136>.
- Liu, Q., 2020. A social force approach for the defensive strategy of security guards in a terrorist attack. *Int. J. Disaster Risk Reduct.* 46, 101605 <https://doi.org/10.1016/j.ijdrr.2020.101605>.
- Lovreglio, R., et al., 2022. Prototyping and testing a virtual reality counterterrorism serious game for active shooting. *SSRN Electron. J.* <https://doi.org/10.2139/ssrn.3995851>.
- Lovreglio, R., Ronchi, E., Nilsson, D., 2015. Calibrating floor field cellular automaton models for pedestrian dynamics by using likelihood function optimization. *Phys. A: Stat. Mech. Its Appl.* 438, 308–320. <https://doi.org/10.1016/j.physa.2015.06.040>.
- Lovreglio, R., Kuligowski, E., Gwynne, S., Boyce, K., 2019. A pre-evacuation database for use in egress simulations. *Fire Saf. J.* 105, 107–128. <https://doi.org/10.1016/j.firesaf.2018.12.009>.
- Lovreglio, R., Ronchi, E., Kinsey, M.J., 2020. An online survey of Pedestrian evacuation model usage and users. *Fire Technol.* 56, 1133–1153. <https://doi.org/10.1007/s10694-019-00923-8>.
- Lu, X., Astur, R., Gifford, T., 2021. Effects of gunfire location information and guidance on improving survival in virtual mass shooting events. *Int. J. Disaster Risk Reduct.* 64 (2021), 102505.
- Ma, L., Chen, B., Qiu, S., Li, Z., Song, Z., 2016. Agent-based modeling of emergency evacuation in a railway station square under sarin terrorist attack. *Int. J. Model. Simulation, Sci. Comput.* 8, DOI: 10.1142/S1793962317500222 (2016).
- Marin, D., 2016. Modelling pedestrian movement with SenseTM: Old science, new approach. *Impact 2* (2), 34–38. <https://doi.org/10.1080/2058802X.2016.11964010>.
- Mawson, A.R., 2005. Understanding mass panic and other collective responses to threat and disaster. *Psychiatry: Interpers. Biol. Process.* 68, 95–113. <https://doi.org/10.1521/psyc.2005.68.2.95>.
- McPhail, C. *The Myth of the Madding Crowd* (Walter de Gruyter, Inc., 1991).
- Mintz, A., 1951. Non-adaptive group behavior. *J. Abnormal Psychol.* 46, 150–159.
- Naudet, G. & Naudet, J. November 13: Attack on Paris (2018). Distributed by Netflix.
- Neumann, P. R. *Old and new terrorism: late modernity, globalization and the transformation of political violence* (Polity, Cambridge, UK, 2009).
- Parisi, D.R., Dorso, C.O., 2005. Microscopic dynamics of pedestrian evacuation. *Phys. A: Stat. Mech. Its Appl.* 354, 606–618. <https://doi.org/10.1016/j.physa.2005.02.040>.
- Quagliarini, E., Fatiguso, F., Lucesoli, M., Bernardini, G., Cantatore, E., 2021. Risk reduction strategies against terrorist acts in urban built environments: Towards sustainable and human-centred challenges. *Sustainability* 13. <https://doi.org/10.3390/su13020901>.
- Ronchi, E., Kuligowski, E.D., Nilsson, D., et al., 2016. Assessing the verification and validation of building fire evacuation models. *Fire Technol.* 52, 197–219. <https://doi.org/10.1007/s10694-014-0432-3>.
- Shipman, A., Majumdar, A., 2018. Fear in humans: a glimpse into the crowd-modeling perspective. *Transp. Res. Rec.* 2672, 183–197. <https://doi.org/10.1177/0361198118787343>.
- Shipman, A., Majumdar, M., Feng, Z., Lovreglio, R., 2024. A quantitative comparison of virtual and physical experimental paradigms for the investigation of pedestrian responses in hostile emergencies. *Scientific Reports - Nature.* <https://doi.org/10.1038/s41598-024-55253-9>.
- Shipman, A. *A Generalised Methodology for the Investigation of Human Behavioural Responses to Hostile Attacks*. Thesis (2021). DOI: 10.25560/91981. Imperial College London.
- Tsai, J., Bowring, E., Marsella, S., Tambe, M., 2013. Empirical evaluation of computational fear contagion models in crowd dispersions. *Auton. Agents Multi-Agent Syst.* 27, 200–217. <https://doi.org/10.1007/s10458-013-9220-6>.
- Tsai, J. et al. Escapes: evacuation simulation with children, authorities, parents, emotions, and social comparison. In: *The 10th International Conference on Autonomous Agents and Multiagent Systems - Volume 2*, 457–464 (International Foundation for Autonomous Agents and Multiagent Systems).
- Turner, J.C., Oakes, P.J., Haslam, S.A., McGarty, C., 1994. Self and collective: cognition and social context. *Pers. Soc. Psychol. Bull.* 20, 454–463. <https://doi.org/10.1177/0146167294205002>.
- Wilkinson, G. Crowd safety at hajj- simulation modeling. <https://www.anylogic.com/blog/crowd-safety-at-hajj-simulation-modeling/> Accessed on 16/02/2024.
- Zhang, Y., Fricker, J.D., 2020. Multi-state semi-markov modeling of recurrent events: estimating driver waiting time at semi-controlled crosswalks. *Anal. Methods Accid. Res.* 28, 100131 <https://doi.org/10.1016/j.amar.2020.100131>.
- Zheng, L., Peng, X., Wang, L., Sun, D., 2019. Simulation of pedestrian evacuation considering emergency spread and pedestrian panic. *Phys. a: Stat. Mech. Its Appl.* 522, 167–181. <https://doi.org/10.1016/j.physa.2019.01.128>.
- Zhou, M., Dong, H., Zhang, J., Sun, X., Yao, X. Effect of assailants on crowd evacuation: a fuzzy logic approach. In: *2015 IEEE 18th International Conference on Intelligent Transportation Systems*, 1098–1103, DOI: 10.1109/ITSC.2015.182.
- Zhu, R., Becerik-Gerber, B., Lucas, G., Southers, E., Pynadath, D. V. Information Requirements for Virtual Environments to Study Human-Building Interactions during Active Shooter Incidents, 188–195. <https://ascelibrary.org/doi/pdf/10.1061/9780784482445.024>.
- Zhu, R., Lucas, G.M., Becerik-Gerber, B., Southers, E.G., 2020. Building preparedness in response to active shooter incidents: results of focus group interviews. *Int. J. Disaster Risk Reduct.* 48, 101617 <https://doi.org/10.1016/j.ijdrr.2020.101617>.
- Zhu, R., Lucas, G., Becerik-Gerber, B., Southers, E., Landicho, E., 2022. The impact of security countermeasures on human behavior during active shooter incidents. *Sci. Reports* 12. <https://doi.org/10.1038/s41598-022-04922-8>.
- Zou, H., Li, N., Cao, L., 2017. Emotional Response-Based Approach for Assessing the Sense of Presence of Subjects in Virtual Building Evacuation Studies (2017).