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## Review

# Crowd behaviour and motion: Empirical methods

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## ABSTRACT

**Introduction:** The safety of humans in crowded environments has been recognised as an important and rapidly growing research area with significant implications for urban planning, event management, building design, fire safety engineering and rescue service to name a few. This stream of research is aimed at guiding safe designs and effective evacuation plans by simulating emergency scenarios and estimating measures such as total evacuation time. A large body of research has also been dedicated to the development of modelling tools with the capability to identify (and thus prevent) circumstances that lead to crowd discomfort, crashes or disasters in mass gatherings and public facilities. It has, however, been argued that the empirical knowledge in this area has lagged behind the theoretical developments and computational capabilities. This has left the descriptive power of the existing models for reproducing the natural behaviour of humans questionable given that in many cases there is a lack of reliable and well-conditioned data for model validation or calibration purposes.

**Methods:** With the vast majority of the empirical knowledge in this fast-growing and interdisciplinary field being very recent, a survey of the existing literature is still missing. Here, we gather together the existing empirical knowledge in this area in a comprehensive review (based on surveying more than 160 studies restricted to those published in peer-reviewed journals since 1995) in order to help bridge this gap. We introduce for the first time a categorisation system of the relevant data collection techniques by recognising seven general empirical approaches. We also differentiate between various aspects of human behaviour pertinent to crowd behaviour by putting them into perspective in terms of three general levels of “decision making”. We also discuss the advantages and disadvantages offered by each data collection technique. Major gaps and poorly-explored topics in the current literature are discussed.

**Findings and applications:** Our major conclusion is that the empirical evidence in this area is largely disperse and even in some cases mixed and contradictory, requiring a more unified system of terminologies and problem definitions as well as unified measurement methods in order for the findings of different studies to become replicable and comparable. We also showed that the existing body of empirical studies display a clear imbalance in addressing various aspects of human behaviour with certain (but crucial) aspects (such as “pre-movement time” and “choice of activity”) being poorly understood (as opposed to our knowledge and amount of data about “walking behaviour” for example). Our review also revealed that previous studies have predominantly displayed a stronger tendency to study the behaviour based on aggregate measures as opposed to individual-level data col-

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lection attempts. We hope that this collection of findings sets clearer avenues for advancing the knowledge in this area, guides future experiment designs and helps researchers form better-informed hypotheses and choose most suitable data collection methods for their question in hand.

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## 1. Introduction

How humans react to threats and emergencies in crowded spaces is a crucial question for disaster preparedness, emergency management and evacuation planning. Furthermore, identifying and understanding the mechanisms that may lead to crowd disasters and incidents (in the absence of external threats) has also been majorly important for assuring the safety of humans in crowded environments. These problems has received growing attention within the recent years in the light of the increasing frequency and scale of crowd incidents as well as the occurrence of major emergency incidents in high-rise buildings and pedestrian facilities around the world.

These questions have guided an area of research that aims at developing prediction models and simulation tools that can be used for assessing the effectiveness of evacuation plans, building designs and crowd management strategies. Significant advances have been made in terms of developing various methodologies and theories for this purpose. However, whether the descriptive power of such methodologies is reliable enough for practical applications has remained unclear. This has been largely attributed to the insufficiency of the evidence based on which one can validate the descriptive capability of their models or fine-tune them by estimating their essential parameters.

The abovementioned issue highlights the need for developing robust empirical knowledge on human crowds' behaviour. The problem is of particular importance in relation with the emergency escape behaviour for which observations in natural settings are extremely rare. With the current developments in the computational capacities and modelling techniques, it can be arguably claimed that tackling this problem would not be prohibitively difficult should the analyst has access to sufficient observations that offer the possibility of robust model calibration or validation.

The recent advancements in the image processing techniques have offered researchers in this area the possibility of gaining knowledge about certain aspects of this problem from naturally-occurring settings. It should however, be noted that although the past real events of emergency or past crowd incidents always offer the possibility of gaining useful insights, this does not necessarily guarantee that these observations can perfectly serve as modelling material (like calibration data) nor does it mean that they can cover the entire range of phenomena that the analysts need to understand in order to develop models with extensive range of applicability. This underlies the importance of experimentation in this field which, as will be shown by this study, has gained an increasing attention in the recent years.

Experimental attempts in this field, however, have often come under criticism on the account of their inherent limitations such as sample size, environmental realism, contextual realism, data extraction accuracy, measurement accuracy etc. Unlike many other areas of behavioural sciences, it is essential in many cases in this field to gather a large number of individuals in the experiment environment at the same time which proves costly and logistically difficult. Creating the contextual elements of an emergency scenario while observing the ethical requirements in an experimental setting also poses a major challenge.

These issues have made the extent of empirical knowledge in this field lag relatively far behind computational and modelling developments. Although the number of studies that have attempted to fill this gap has shown a sharp rise within the last ten years, a survey of the existing empirical knowledge has still been missing. Published studies have been scattered over a wide range of scientific journals (including disciplines like psychology and behavioural sciences, engineering, ergonomics, safety, transportation and applied physics to name a few) owing to the interdisciplinary nature of the problem. Scholars from a wide range of research backgrounds have contributed to this topic from various and often vastly different perspectives.

This study is set out to address this gap by making a comprehensive review of more than 150 studies that offer empirical insight and data contributions to crowd behaviour and emergency evacuation modelling. For the first time, we introduce an inclusive categorisation of the data collection techniques, and contrast the advantages and disadvantages of various methods. We aim to depict a clearer picture of the empirical knowledge and identify what do know and what we do not know so far about this multi-faceted problem. We hope that researchers working on this topic find this contribution useful as a benchmark for a making quick evaluation of the previous studies, finding the major knowledge gaps, identifying possible contradictory findings of earlier studies, forming hypotheses, designing their experiments and testing the accuracy of commonly-used theoretical assumptions in this field. We also hope that the method categorisation and the subsequent discussions help to identify the data collection approaches that suit the researchers' specific problems in the best way.

In the rest of this paper, we first itemise some of the major challenges in regard to modelling crowd behaviour in general and in emergency situations in particular. We then will have a brief overview of the existing review and meta-analysis studies that are to any degrees related to our topic in hand in order to further clarify the gap that this review study aims to bridge. The inclusion criteria and the scope of this review will be discussed next. We then introduce a general categorisation of the data collection methods in this field and look at the findings and the details of the relevant studies in each category

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