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A Scoping Review

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Gaps in Human Behaviour in Fires Research: A Scoping Review

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Abstract
When developing a research roadmap for human behaviour in fires, it is necessary to identify areas that require additional research. A general overview – from a multidisciplinary perspective – of gaps in human behaviour in fires research across multiple contexts is missing. The goal of this paper was to perform a scoping review to identify research gaps and themes in all aspects of human behaviour in fires across contexts. This scoping review included 17 articles. In total, 37 research gaps and 11 research themes for the built environment and community context were identified. The main research gaps are related to cognitive factors, behavioural responses, environmental factors and physical/physiological factors. Also, for all research themes, additional research involving heterogenous populations is required. Furthermore, there is an imbalance in human behaviour in fires studies: most articles were focused on the built environment rather than the community context. Finally, the topic of intoxication has received limited research attention, and data collection methods lack diversity. Future research should not only be done from a multidisciplinary perspective but also interdisciplinary research efforts are required. The availability of more data and knowledge on human behaviour and responses in fires could be beneficial to simulation model developers/users, the general public and fire safety managers.

Keywords Human behaviour · Evacuation · Fires · Built environment · Community context · Scoping review

1 Introduction

Human behaviour in fires is a multidisciplinary research field in which engineers, psychologists, architects, computer scientists, sociologists, and many more are involved [1].

Detailed documented research into human behaviour in fires was developed in the second half of the previous century [2, 3]. John Bryan and other researchers initiated several studies on human behaviour in fires, which were mainly focused on fires in the built environment. Notable examples are the study of the fire at the Arundel Park Hall in Maryland, United States in 1956 [4], followed by other studies in the United States on the Beverly

Extended author information available on the last page of the article

Hills Supper Club fire in 1977 [5] and the MGM Grand Hotel fire in 1980 [6, 7]. Bryan and his colleagues also studied and documented human behaviour in fires for hundreds of other fire incidents in the Project People and Project People II reports [8–11]. The books about fires and human behaviour, edited by David Canter, should also be mentioned here [12, 13]. These books contain several important contributions of researchers in the field of human behaviour in fires, such as Jonathan Sime, Peter Wood, Jake Pauls and Ian Donald. These studies, reports and books revealed that people in fire incidents may ignore or misinterpret fire cues, search for information, may not observe exit signs, move through smoke, and also fight the fire, alert and help others and do not panic. Studies of more recent fire incidents, such as in the WTC towers on 9/11 [14–16], in The Station nightclub in 2003 [17–19] and in the Grenfell tower in 2017 [20, 21], confirm these behaviours. In addition, research into human behaviour in wildfires (or bushfires in Australia), urban fires and/or wildland-urban interface fires (hereafter also referred to as "fires in the community context") shows that residents tend to underestimate the danger, delay their evacuation and defend their homes, but it also shows that decision-making in these situations is more complex than just the options of "stay" or "go" [22, 23].

When developing a research roadmap for human behaviour in fires, it is necessary to identify areas that require additional research. Therefore, this is *not* a review about human behaviour in fires, because there are already multiple reviews on this topic [3, 24–27]. These reviews often concentrate on a specific aspect of human behaviour in fires (e.g., evacuation, pedestrian dynamics) in a specific context: the built environment or the community context. However, the goal of our review is to identify *gaps* in *all aspects* of human behaviour in fires *research* in *multiple contexts*. Identifying research gaps is challenging, because reviews usually collect information and data that is already available and oftentimes neglect reporting comprehensively on data that is missing. After several brainstorm sessions in the Human Behaviour in Fires (HBiF) working group of the International Association for Fire Safety Science (IAFSS), it was decided to conduct this scoping review. Scoping reviews are similar to systematic reviews in that they follow a structured process, but they are performed for different reasons. Systematic reviews require rigorous methods that minimise the risk of bias of the evidence and provide reliable findings from which conclusions can be drawn [28]. Scoping reviews can determine the scope of a body of literature on a certain topic and give a clear indication of the available literature and studies as well as an overview of its focus [28]. Also, scoping reviews are a useful tool to identify knowledge gaps [28]. Likewise, a scoping review can also be a precursor to a precise systematic review [28]. Therefore, a scoping review is deemed a suitable approach for this study.

As fire safety science requires expertise from both social and technical domains [29], it is also necessary to address research gaps in the literature from a multidisciplinary perspective [30, 31]. A summary of research gaps in human behaviour during fires could inspire researchers across various fields to develop new research methods and proposals. Understanding these behaviours is crucial, as it involves not only documenting actions but also exploring the cognitive processes, social influences, and environmental interactions that shape responses in fire situations. It is also important to include both the built environment and community context in this respect, because of the potential differences in human behaviour. For instance, the onset of a life-threatening fire generally occurs far more quickly in buildings than in wildfire situations [23]. Also, it is not likely that people would evacuate a building before a fire starts as might be the case in wildfires [23]. Furthermore, in wildfire

situations evacuation warnings and/or (mandatory) evacuation orders from (local) governmental organisations might apply [32]. A focus on human behaviour in fires in both the built environment and community context is therefore relevant.

In summary, the goal of this scoping review is to provide an overview of the research gaps that are identified by scholars in the human behaviour in fires research field for both the built environment and the community context. The focus hereby is on all aspects of human behaviour in fires, ranging from protective actions, decision-making and evacuation movement to individual and group behaviours of different populations and cultures. To be clear, the term gap in this scoping review does not necessarily mean that information and/or data is completely missing. It could also mean that information on a certain topic is rare or the topic is not extensively investigated and therefore requires more studies and/or data. To the knowledge of the authors, this is a first attempt to identify gaps in human behaviour in fires research for multiple contexts in a structured way.

2 Methods

To identify relevant research gaps about human behaviour in fires, this paper adopts the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement [33] and its extension for scoping reviews (PRISMA-ScR) as presented by Tricco et al. [34]. A scoping review follows a systematic approach to synthesize evidence on a topic and identify knowledge gaps [28].

2.1 Search Strategy

For this scoping review, a structured approach was used to search for peer-reviewed articles about human behaviour in fires in which research gaps are mentioned. The articles were retrieved from the Web of Science, Scopus and PubMed databases. The first search on 5 July 2022 in Web of Science was based on a combination of keywords, such as “fire”, “wildfire”, “evacuation”, “human behaviour”, “evacuation response” and a publication date between 1 January 2010 and 5 July 2022. See Appendix A for the complete search strings. This Web of Science search resulted in a selection of 389 articles. An additional search in Web of Science was performed on 24 August 2022. This time, the search terms “human behaviour” and “fire” were used and articles with a publication date between 1 January 2010 and 24 August 2022 were selected. This resulted in 139 articles, from which three duplicate records were removed, leaving an additional 136 articles. On 3 February 2024, this last search in Web of Science was updated for articles with a publication date between 1 January 2010 and 3 February 2024 and a similar search was performed in the PubMed and Scopus databases. These three database searches resulted in a selection of 661 articles, from which 271 duplicate records were removed, leaving an additional 390 articles. Also, 18 articles were added to the selection through the snowball method. This resulted in a total selection of 933 articles for screening (see also Fig. 1).

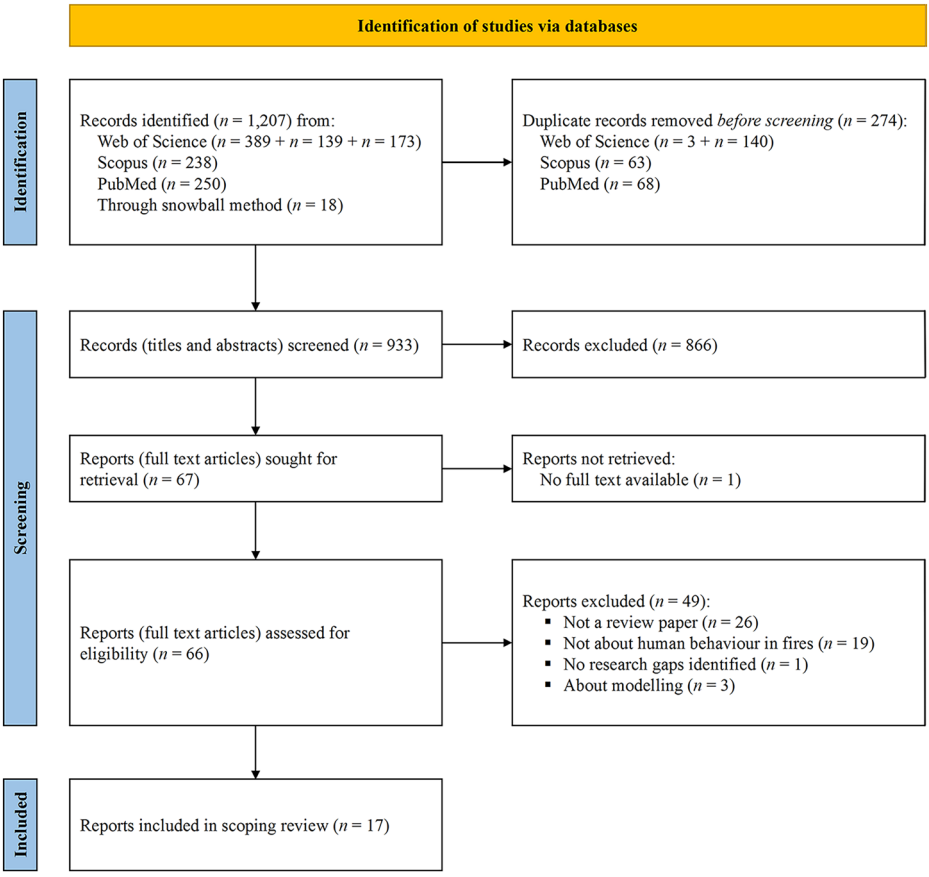

Fig. 1 PRISMA flow chart for the search and screening process

2.2 Article Selection

The first step in the screening process was to judge the titles and abstracts of the articles. This was done independently by two reviewers of the authorship team. Inclusion criteria were: English review papers, meta-analyses, and/or overviews regarding human behaviour in fires, because these types of articles typically provide a list of research gaps on the discussed topic(s). Book chapters, dissertations, conference proceeding papers and grey literature were excluded because these sources are not always included in databases and/or the full text cannot be accessed (online). Other exclusion criteria were: case studies, policy and modelling and/or simulation articles. The interrater reliability at titles and abstract screening was substantial [35], kappa = 0.75. Any disagreements between the two reviewers were resolved through discussion until consensus was reached. In total, 66 articles met the inclusion criteria.

The second step was to read and judge these 66 articles in full. This was also done independently by the same two reviewers. Reasons for exclusion were the following: the articles were not actually review papers ($n = 26$), the articles did not include specific overviews of

human behaviour in fires ($n=19$), no research gaps were identified in the article ($n=1$) and/or the article was focused on modelling ($n=3$). The interrater reliability at full text screening was almost perfect [35], kappa = 0.81. Again, any disagreements between the two reviewers were resolved through discussion until consensus was reached. Finally, 17 articles were selected for this scoping review. The process of article selection is also shown in Fig. 1.

Most review papers were published between 2017 and 2023 (see Fig. 2). There was one publication from 2010 [36]. It was decided to keep this review in the selection due to its strong citation record and its thorough examination of human behaviour in fire within the built environment.

2.3 Extraction of Article Information

The following information was extracted from the selected review papers: research gaps, research themes, fire context, research focus and important findings/results. This information was independently extracted by two reviewers and cross-checked using a predefined, standardized spreadsheet. Inconsistencies in data extraction were resolved between these reviewers through discussion and consensus was reached. Figure 3 provides an overview of the extraction process of the article information.

The first step was to identify and register all research gaps that were mentioned in the selected review papers. Also, the research focus and important findings/results of the selected papers were identified and registered (these results are presented in Table 4 in Appendix B). Next, a list of 75 research gaps was composed. Then, duplicates were removed and overlapping research themes in these gaps were identified by three reviewers. After this, two reviewers independently further defined the research themes and fire contexts discussed in the research gaps. This resulted in the identification of the following 11 research themes: aids/means of evacuation, behavioural responses, cognitive factors, communication/information, cultural factors, data collection methods, demographics, environmental factors,

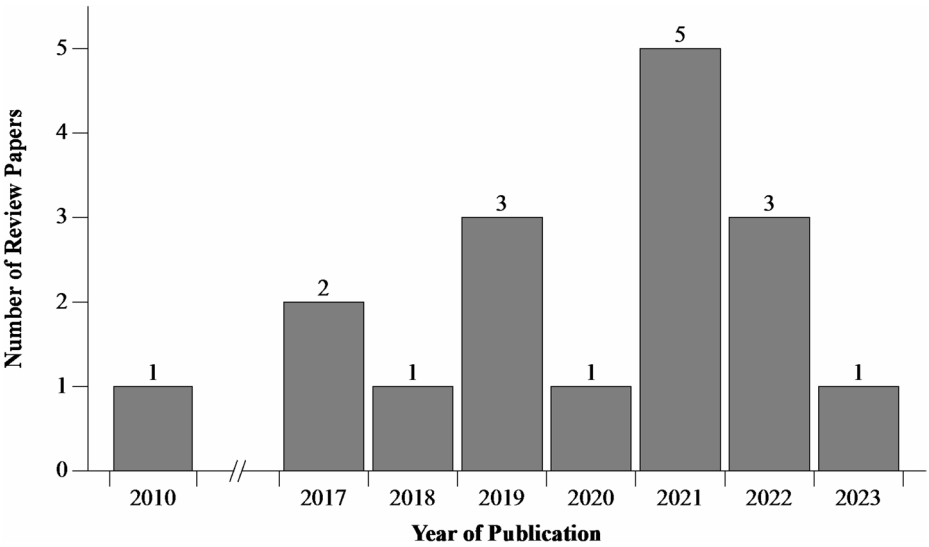

Fig. 2 Year of publication of selected review papers

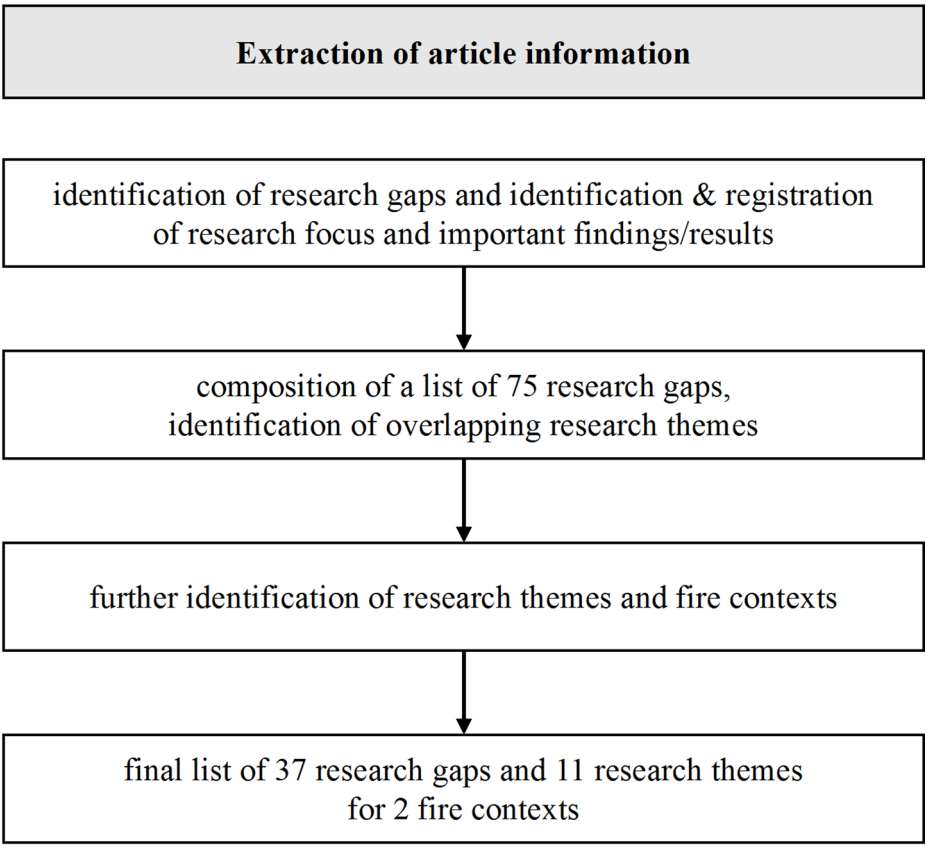

Fig. 3 Procedure of how the article information was extracted

group/social factors, intoxication and physical/physiological factors. Also, two fire contexts in the research gaps were identified: (1) fires in the built environment and (2) community fires (e.g., wildfires). Lastly, the list of 75 research gaps was re-evaluated and consolidated into a final list of 37 research gaps, 11 research themes and two fire contexts.

3 Results

3.1 Descriptions of Research Themes and Fire Contexts

We first present the research themes and fire contexts, as they give a good overview of the research landscape. The descriptions of the identified 11 research themes and two fire contexts are provided in Table 1.

In this review, the term "functional limitations" is used to refer to people with disabilities and/or limitations in certain functions. This term has been widely used by the World Health Organization [38] and Centers for Disease Control and Prevention [39].

Table 1 Descriptions of the research themes and fire contexts

Research themes and fire contexts	Descriptions
Research themes	
Aids/means of evacuation	Usage of evacuation aids such as evacuation chairs, occupant evacuation elevators or transportation modes, such as cars, buses, etc. for evacuation
Behavioural responses	Types of observable tasks/activities/behaviours that are performed during fire events and/or evacuation, such as firefighting, collecting personal items, searching for people, alerting others, etc.
Cognitive factors	Not observable factors related to personality characteristics, functional limitations in cognition (such as in sensation and perception, attention, memory, decision-making, problem-solving), cognitive disorders (such as dementia, amnesia), subjective experience of mental fatigue, emotions and stress, but also the cognitive components of wayfinding
Communication/information	(Emergency exit) signage, fire alarms/notifications, voice messages, etc., as well as forms of communication between evacuees and information that evacuees receive about the (emergency) evacuation/situation
Cultural factors	These factors are defined as socio-cultural (i.e., related to different groups of people in society, such as children, older adults, etc.) or cross-cultural (i.e., related to differences between cultures/countries)
Data collection methods	Suggestion for change or addition in how to investigate human behaviour in fires
Demographics	Personal characteristics, such as age and gender
Environmental factors	Factors related to building layout, community facilities, weather, smoke, reduced oxygen, etc.
Group/social factors	Factors related to social influence, forming of groups, merging, physical dynamics of groups, group size, following, etc.
Intoxication	Drugs, alcohol or other substances influencing behaviour and cognition
Physical/physiological factors	Physical and physiological both refer to bodies, but physical means the body itself while physiological refers to the body's functions [37]. Factors could relate to physical and/or functional limitations in mobility and/or lower/upper extremities, biomechanics of movement, movement speeds, physical fatigue, but also the physical/physiological components of stress (e.g., high blood pressure, elevated heart rate) and physical/physiological components of wayfinding (e.g., touching and using the walls as guidance during evacuation)
Fire contexts	
Built environment	Fires in the built environment (i.e. public/commercial/industrial/office/residential buildings, dwellings, nightclubs, schools, arenas/stadiums, transportation infrastructure, tunnels, etc.)
Community	Fires on open terrains, in urban and/or wildland (and their interface with urban areas), such as in forests, grasslands, peri-urban or suburban settings, informal settlements, etc.

Also, since this is a multidisciplinary research field, terms that are or will be used in this paper may not be familiar to all readers. Therefore, in Table 5 in Appendix C several terms are defined and/or explained.

3.2 List with Identified Research Gaps across Research Themes and Fire Contexts

In Table 2, the list of the 37 research gaps that were identified from the 17 selected review papers is presented. First, research gaps related to the influence/impact/effect of certain factors or variables on a type of behaviour in fire (evacuation) are presented. Second, research gaps related to the presence or emergence of certain phenomena in fire (evacuation) are presented. Finally, other topics related to human behaviour in fire (evacuation) are presented. To distinguish more easily between the research themes and fire contexts, the research themes are marked with the sign '✓' and the fire contexts are marked with the sign '■'.

3.3 Identified Research Gaps in Research Themes and Fire Contexts

In Fig. 4, a visualisation of the 37 identified research gaps per research theme among the two fire contexts is presented. The numbers in the squares refer to the specific research gaps listed in Table 2.

In this scoping review, most research gaps are identified for the built environment, especially for the following themes: cognitive factors, environmental factors, physical/physiological factors, group/social factors and cultural factors. There is, however, one exception. The communication/information theme has more identified gaps for the community context than for the built environment (two versus one). Three themes have the same number of identified gaps for the two fire contexts: behavioural responses, aids/means of evacuation and demographics.

It is notable that most identified research gaps were related to cognitive factors (16 gaps), followed by behavioural responses (9 gaps) and environmental factors and physical/physiological factors (both 7 gaps). Themes with the least identified research gaps are intoxication and data collection methods (both 1 gap).

In Sect. 3.3.1–3.3.11, important findings for each research theme are discussed (see also Table 3, which provides an overview of the main findings per research theme on topics that require more data). Please note that these findings represent the results at the moment the specifically discussed review papers were published. In the meantime, newer studies may have been published that address some of the identified research gaps. Therefore, in the general discussion (Sect. 4.1) some examples of these recent studies will be highlighted.

3.3.1 Cognitive Factors

In this scoping review, the majority of the identified research gaps are about the knowledge scarcity regarding cognitive factors, such as the impact of cognitive functional limitations and personality characteristics on building evacuation performance. Also, knowledge gaps on which factors influence the decision-making process before and during evacuation, in the built environment as well as in the community context, were mentioned often.

Our findings show that several researchers reported a lack of studies on the impact of cognitive functional limitations in smell or speech on building evacuation performance,

Table 2 Identified Research Gaps About Human Behaviour in Fires, Based on Research Themes and Fire Contexts

No.	Research gaps human behaviour in fires		References	Research themes											Fire contexts	
	More data needed on …			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/ social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods	built environment	community
	the influence/ impact/ effect of	on type of behaviour in fire (evacuation)														
1	cognitive functional limitations	on evacuation performance	Bukvić et al. [40] Hostetter and Naser [41]	✓											■	
2	functional limitations regarding smell	on evacuation performance	Bukvić et al. [40]	✓											■	
3	functional limitations regarding speech/ communication	on evacuation performance	Bukvić et al. [40]	✓							✓				■	

Table 2 (continued)

No.	Research gaps human behaviour in fires		References	Research themes											Fire contexts	
	More data needed on …			cognitive factors	behavioural responses	environmental factors	physical/physiological factors	group/social factors	aids/means of evacuation	cultural factors	communication/information	demographics	intoxication	data collection methods	built environment	community
	the influence/impact/effect of	on type of behaviour in fire (evacuation)														
4	multiple functional limitations combined	on evacuation performance	Bukvić et al. [40] Hostetter and Naser [41]	✓			✓								■	
5	cognitive factors and personal characteristics	on human responses in fire	Lin et al. [42] Tan and Moinuddin [43]	✓											■	
6	psychological factors	on evacuation behaviour	Ding et al. [44]	✓											■	

Table 2 (continued)

No.	Research gaps human behaviour in fires		References	Research themes											Fire contexts	
	More data needed on …			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/ social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods	built environment	community
	the influence/ impact/ effect of	on type of behaviour in fire (evacuation)														
7	psychological factors	on multiple stages of evacuation decision-making in wildfires	Kuligowski [45] Strahan and Gilbert [46] Strahan and Gilbert [47]	✓												■

Table 2 (continued)

No.	Research gaps human behaviour in fires		References	Research themes												Fire contexts	
	More data needed on …			cognitive factors	behavioural responses	environmental factors	physical/physiological factors	group/social factors	aids/means of evacuation	cultural factors	communication/information	demographics	intoxication	data collection methods	built environment	community
	the influence/impact/effect of	on type of behaviour in fire (evacuation)														
8	psychological and behavioural factors	on departure times and/or intermediate trips and final evacuation destination choices in wildfires	Kuligowski [45]	✓	✓											■	

Table 2 (continued)

No.	Research gaps human behaviour in fires		References	Research themes											Fire contexts	
	More data needed on …			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/ social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods	built environment	community
	the influence/ impact/ effect of	on type of behaviour in fire (evacuation)														
9	psychological, behavioural and social factors	on evacuation elevator usage	Ding et al. [44]	✓	✓			✓							■	
10	different building types/ layouts	on human behaviour in fire	Kobes et al. [36] Lin et al. [42] Thompson et al. [48]			✓									■	
11	(irritant/ non-irritant/hot) smoke	on movement, walking speed and way-finding during evacuation	Fridolf et al. [49]			✓									■	

Table 2 (continued)

No.	Research gaps human behaviour in fires		References	Research themes											Fire contexts	
	More data needed on …			cognitive factors	behavioural responses	environmental factors	physical/physiological factors	group/social factors	aids/means of evacuation	cultural factors	communication/information	demographics	intoxication	data collection methods	built environment	community
	the influence/impact/effect of	on type of behaviour in fire (evacuation)														
12	reduced visibility	on evacuation movement and on evacuation performance of populations with functional limitations	Agyemang and Kinateder [50] Fridolf et al. [49] Hostetter and Naser [41]			✓				✓					■	
13	physical exertion	on evacuation movement	Agyemang and Kinateder [50] Ding et al. [44]				✓								■	

Table 2 (continued)

No.	Research gaps human behaviour in fires		References	Research themes											Fire contexts	
	More data needed on …			cognitive factors	behavioural responses	environmental factors	physical/physiological factors	group/social factors	aids/means of evacuation	cultural factors	communication/information	demographics	intoxication	data collection methods	built environment	community
	the influence/impact/effect of	on type of behaviour in fire (evacuation)														
14	smoke inhalation or reduced oxygen	on evacuation movement	Agyemang and Kinateder [50] Fridolf et al. [49] Hostetter and Naser [41]				✓								■	
15	biomechanical factors	on evacuation movement	Agyemang and Kinateder [50] Bukvić et al. [40]				✓								■	
16	functional limitations in upper extremities	on evacuation way-finding	Bukvić et al. [40]				✓								■	
17	physical functional limitations	on evacuation behaviour	Ding et al. [44] Hostetter and Naser [41]				✓								■	

Table 2 (continued)

No.	Research gaps human behaviour in fires		References	Research themes											Fire contexts	
	More data needed on …			cognitive factors	behavioural responses	environmental factors	physical/physiological factors	group/social factors	aids/means of evacuation	cultural factors	communication/information	demographics	intoxication	data collection methods	built environment	community
	the influence/impact/effect of	on type of behaviour in fire (evacuation)														
18	physical position	on evacuation behaviour	Fridolf et al. [49] Kobes et al. [36]				✓								■	
19	demographic and information/communication variables	on human behaviour in wildfires	Fish et al. [51] McLennan et al. [32] Strahan and Gilbert [46]								✓	✓				■
20	substance/medication use	on evacuation performance	Bukvić et al. [40]										✓		■	
	the presence or emergence of phenomena in fire (evacuation)															
21	evacuees' perceptions, intentions and motivations in (wild)fires		Kobes et al. [36] Strahan and Gilbert [46]	✓											■	■

Table 2 (continued)

No.	Research gaps human behaviour in fires		References	Research themes												Fire contexts	
	More data needed on …			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/ social factors	aids/ means of evacuation	cultural factors	communication/ information		demographics	intoxication	data collection methods	built environment	community
	the influence/ impact/ effect of	on type of behaviour in fire (evacuation)															
22	evacuation timing and the types of activities performed in wildfires		Elhami-Khorasani et al. [52] Kuligowski [45]	✓	✓												■
23	route choice decisions and en route switching in wildfire evacuations		Kuligowski [45]	✓	✓												■
24	evacuation decision-making and behaviour in different cultures and populations in (wild)fires		Elhami-Khorasani et al. [52] Kuligowski [45] Lin et al. [42] McLennan et al. [32] Mytton et al. [53] Strahan and Gilbert [47]	✓	✓					✓						■	■

Table 2 (continued)

No.	Research gaps human behaviour in fires	References	Research themes											Fire contexts	
	More data needed on …		cognitive factors	behavioural responses	environmental factors	physical/physiological factors	group/social factors	aids/means of evacuation	cultural factors	communication/information	demographics	intoxication	data collection methods	built environment	community
	the influence/impact/effect of	on type of behaviour in fire (evacuation)													
25	decision-making, risk perception and behaviour in fire of young people (<18) and how these might change with age	Mytton et al. [53]	✓	✓					✓		✓			■	
26	merging behaviour in vertical evacuation	Ding et al. [44]	✓				✓							■	
27	the perception of warnings and alarms during wildfire events	Fish et al. [51] Kuligowski [45] Strahan and Gilbert [46]	✓							✓					■
28	the fire response performance (such as extinguishment of a fire) by building's occupants	Kobes et al. [36] Tan and Moinuddin [43]		✓										■	

Table 2 (continued)

No.	Research gaps human behaviour in fires	References	Research themes											Fire contexts	
	More data needed on …		cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/ social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods	built environment	community
	the influence/ impact/ effect of	on type of behaviour in fire (evacuation)													
29	the interaction between errors due to human and organizational factors during fire events	Tan and Moinuddin [43]		✓	✓									■	
30	wayfinding in fire evacuation	Fridolf et al. [49] Kobes et al. [36]			✓									■	
31	group evacuation behaviour in smoke	Fridolf et al. [49]			✓		✓							■	
32	group behaviour in evacuation	Ding et al. [44]					✓							■	
	other topics related to human behaviour in fire (evacuation)														

Table 2 (continued)

No.	Research gaps human behaviour in fires	References	Research themes											Fire contexts	
	More data needed on …		cognitive factors	behavioural responses	environmental factors	physical/physiological factors	group/social factors	aids/means of evacuation	cultural factors	communication/information	demographics	intoxication	data collection methods	built environment	community
	the influence/impact/effect of	on type of behaviour in fire (evacuation)													
33	the use of transportation modes by and driving behaviours of wildfire evacuees	Elhami-Khorasani et al. [52] Kuligowski [45]		✓				✓							■
34	the use of refuge floors/rooms in vertical evacuation	Ding et al. [44]			✓			✓						■	
35	the use of assistive devices for evacuation	Bukvić et al. [40] Ding et al. [44] Hostetter and Naser [41] Kobes et al. [36]						✓						■	
36	the use of sharing economy facilities in wildfire evacuations	Elhami-Khorasani et al. [52] Kuligowski [45]						✓							■

Table 2 (continued)

No.	Research gaps human behaviour in fires		References	Research themes										Fire contexts		
	More data needed on …			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/ social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods	built environment	community
	the influence/ impact/ effect of	on type of behaviour in fire (evacuation)														
37	the exploration of the link between controlled lab experiments and data observed from real world scenarios in evacuations		Agyemang and Kinateder [50] Zhang and Huang [54]											✓	■	

especially compared to physical functional limitations [40, 41]. Even though the ability to smell smoke is a cue in fire emergency scenarios, Bukvić et al. [40] did not find any studies on how functional limitations linked to the sense of smell might affect evacuation performance. Likewise, speech impairments could impact communications with rescue services or other occupants, but Bukvić et al. [40] also failed to find data connecting any kind of speech impairment to evacuation performance in fire scenarios. In addition, there is a limited understanding of how neurodiverse populations make decisions and find information during building evacuations compared to those without cognitive functional limitations [41]. Hostetter and Naser [41] concluded that it is, for instance, still unclear if neurodiverse populations are consistent in their evacuation behaviours or choose exit routes in the same way and/or evacuate in the same time frame as populations without functional limitations.

Our findings also show that further research is required on cognitive factors, such as personality characteristics, in relation to human responses in building fires [42, 43]. This requires an examination of how various occupant characteristics influence human responses and interactions during building emergencies and therefore Lin et al. [42] advocate for a comprehensive framework that covers all cognitive and behavioural processes. Additionally, Tan and Moinuddin [43] recommend further quantitative and qualitative research into human factors and personality traits that affect occupant behaviour in fire emergencies.

We also found that there are gaps in understanding decision-making processes during crowd merging in building evacuations, including the individual's concerns and psychological changes (e.g., tension, anxiety, stress) in the evacuation process [44].

For fires in the community context, our study also uncovered that more research is needed on which factors influence multiple stages of evacuation decision-making in wildfires, including threat and risk perception [45–47]. Kuligowski [45], for example, mentioned the lack of empirical data on departure time choice in wildfires. She also emphasizes the need to unpack departure time into multiple stages: decision time and mobilisation time, because her review highlighted that no data was available on distinguishing between these two time periods for wildfires [45].

Finally, our results on the cognitive factors for fires in the community context revealed a lack of data on which cognitive factors or processes influence the following choices in wildfire evacuations: intermediate trips, (final) destination choices and route selection [45]. There is almost no wildfire data available on intermediate trips and (final) evacuation destination choices or the types of destinations chosen (such as homes of friends and/or families or hotels/motels) [45]. Additional data is also required on how and when these destination decisions are made and what influences these choices. Furthermore, there is a knowledge gap in what routes evacuees will choose during wildfire evacuations, how they make route choice decisions and whether (and under what circumstances) they are willing to switch routes during travel [45].

3.3.2 Behavioural Responses

Most of the research gaps we found regarding the theme behavioural responses were about a lack of data on the specific fire response performance of occupants and/or residents in (wild)fire situations.

Regarding building fires, one of the selected reviews found that 78% of domestic fires reported to the fire department in Great Britain and 75.2% of those in Australia were not

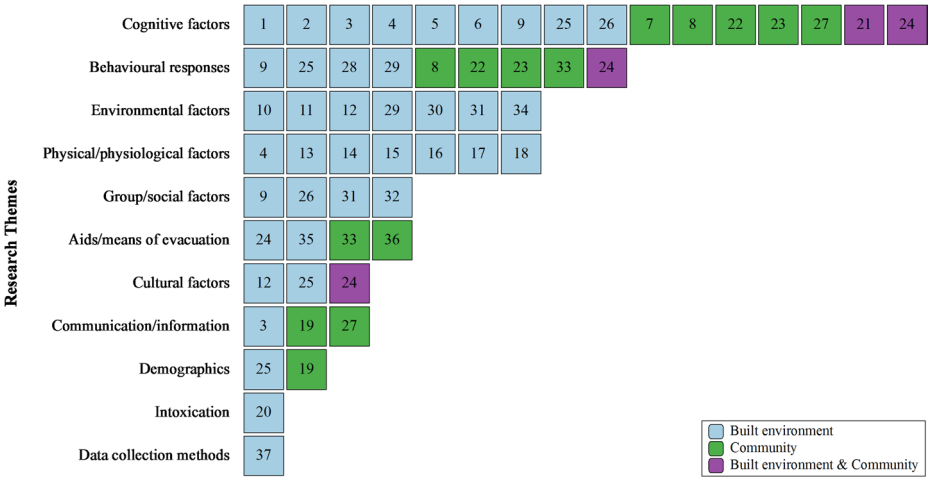

Fig. 4 Visualisation of the 37 identified research gaps per research theme among the fire contexts. The numbers in the squares refer to the specific research gaps listed in Table 2

extinguished by the fire service [36]. This suggests that in those studies most fires had either self-extinguished or were suppressed by occupants [36]. To understand occupant suppression actions and the circumstances under which these behaviours occur, Tan and Moinuddin [43] recommend to collect more qualitative data that provides more-detailed insights into occupant behaviours during fire emergencies. Mytton et al. [53] observed that there is limited information regarding the reasons behind children's behaviours, such as re-entering a burning room or building, as well as how the actions of children who survive accidental dwelling fires differ from those who do not.

For fires in the community context, our scoping review revealed research gaps in behavioural responses such as driving behaviours [45]. Kuligowski [45] noticed that there is a lack of data on driving behaviours (such as speeds and flows, car following, lane changing, gap acceptance, desired spacing and reaction times) under emergency conditions. Also, there is a lack of data on evacuee compliance with traffic control measures, such as contraflow, route closure, and route guidance [45].

3.3.3 Environmental Factors

Our scoping review also uncovered research gaps related to environmental factors, but only for the built environment. The absence of identified research gaps concerning environmental factors in the community context in our scoping review does not imply that such gaps do not exist. Rather, it simply indicates that our review did not uncover these potential gaps.

Most identified research gaps for the built environment are about evacuation in smoke. In general, there is a need for further research on the effects of smoke during evacuation on: walking speed, biomechanical factors, group behaviours and diverse populations, including those with functional limitations [41, 49, 50]. Fridolf et al. [49] also highlight the importance of studying how people adjust their walking speed at varying visibility levels during evacuation, and recommend investigating the effects of different types of smoke (irritant,

Table 3 Overview of main findings research gaps per research theme

Research theme	Main findings on topics that require more data
Cognitive factors	• Effects of cognitive functional limitations and personality characteristics on building evacuation performance • Factors that influence decision-making processes in (wild)fire scenarios
Behavioural responses	• Behaviours of occupants in building fires (e.g., re-entering burning rooms/buildings) • Actions of occupants/residents in (wild)fire scenarios (e.g., suppression actions) • Driving behaviours of residents in wildfire emergencies
Environmental factors	• Effects of (non-)irritant/hot smoke on walking speed, biomechanics, group behaviour and diverse populations (e.g., populations with functional limitations) in building (fire) evacuations • Effects of layout, size and type of building on human behaviour in fire
Physical/physiological factors	• Effects of different functional limitations (e.g., fatigue, sickness, pregnancy, chronic medical conditions) on building evacuation behaviour and movement • Effects of biomechanical factors on staircase and evacuation movement • Effects of physical position (standing, walking, sitting, crawling) on building evacuation behaviour
Group/social factors	• Social factors that affect group behaviour (e.g., cooperation, competition, following) • Social factors that affect merging behaviour
Aids/means of evacuation	• Evacuation elevator usage and chances of survival • Occupant behaviour on/in a refuge floor/room • Use/preference of transportation modes in wildfire scenarios • Use of Airbnb, Lyft, Uber, etc. as transportation and sheltering resources in wildfire scenarios
Cultural factors	• Behaviour and responses of children in dwelling fires • Impact of cultural background on cognitive and behavioural responses to building emergencies • Behaviours and responses of Indigenous peoples, migrants, tourists, individuals in secluded areas, populations in informal settlements, etc. in wildfire scenarios
Communication/information	• Perception, processing and monitoring of information and communications by building occupants and residents in fire emergencies • Effects of communication strategies and information dissemination on residents' information-seeking behaviour • Effects of smoke-related health messages for the general public or at-risk groups on their behaviours and responses
Demographics	• Effects of age, gender, socio-economic class, etc. on human behaviour and responses in fire scenarios
Intoxication	• Impact of substance/medication use on evacuation behaviour
Data collection methods	• Comparisons between data from controlled lab experiments and data observed from real world (fire) evacuations • Collect more datasets from field observations and experiments with diverse populations and setups

non-irritant, hot) on movement and wayfinding– beyond the commonly used artificial, cold, white smoke– while adhering to ethical standards.

Other environmental factors in the built environment that deserve more research, are how the layout [49], size [36, 42, 48] or type [42, 48] of building might affect human behaviour in fires. Most experimental studies have been conducted in fairly simple experimental set-

tings, such as straight corridors or tunnels, but studies into the process of wayfinding in smoke in more complex geometrical layouts are scarce [36, 49]. In this respect, Lin et al. [42] concluded that residential and office buildings were relatively well studied, while the majority of studies in their review (114 out of 164 studies) did not specify the building type. Therefore, it is necessary that researchers specify the building type in their reports because this information could be essential in enabling the applications of findings across multiple environments/contexts [42]. Consequently, the impact of varying environmental factors on human behaviour during fire emergencies in different building types remains uncertain, particularly regarding how similarities or differences in these factors might influence outcomes.

3.3.4 Physical/Physiological Factors

For physical/physiological factors our review only identified research gaps for the built environment. Again, the absence of identified research gaps concerning physical/physiological factors for the community context does not imply that such gaps do not exist.

The identified research gaps for the built environment concern the effects of different functional limitations on evacuation behaviour and movement. These limitations include fatigue [40, 41, 44, 50], sickness [40, 41, 44, 50], pregnancy [44], chronic medical conditions (e.g., asthma, cystic fibrosis, cancer) [41], and functional limitations linked to older age [44].

Our findings also reveal another physical/physiological topic that deserves more research, which is related to biomechanics. More data is required on the effects of biomechanical factors, such as compensatory strategies in the absence or reduction of visual information, on staircase and evacuation movement [50]. In this respect, a holistic research approach is recommended which includes also the impact of behaviours such as running, obstacle avoidance, and assisting others on the biomechanics of staircase and evacuation movement [50]. Following from this, our review also demonstrates that there is a lack of knowledge about the influence of the physical position (standing, walking, sitting, crawling) on evacuation behaviour [36, 49]. Earlier research suggests that those who are standing or walking are more likely to leave a room than people who are in a prone (i.e., lying on chest, with face looking down) or sitting position, but the researchers concluded that data on this topic is limited [36].

3.3.5 Group/Social Factors

Our scoping review also identified research gaps related to group and/or social factors, for the built environment only. Again, the absence of identified research gaps concerning group/social factors for the community context does not imply that such gaps do not exist.

The identified gaps for the built environment are about merging behaviour and group behaviour in (fire) evacuation [44]. Ding et al. [44] discuss the state-of-the-art on high-rise building emergency evacuation behaviour and they recommend more research on which social factors affect decision-making and behaviour in merging in vertical evacuation. They also concluded that more studies (especially field observations) are needed on which factors lead to small-group formation, cooperation and competition behaviour and how social relationships affect following behaviour in evacuation [44].

In addition, according to Fridolf et al. [49], the mutual relationship between visibility and group behaviours during evacuation should also be studied. This should include walking speeds and how evacuees behave towards other evacuees in dark and/or smoke-filled environments.

3.3.6 Aids/Means of Evacuation

For aids/means of evacuation, our scoping review found research gaps for both the built environment and the community context.

For the built environment, our review identified research gaps regarding evacuation elevator usage. For instance, it is still unclear how many people would choose to evacuate with elevators if told so, but also which factors affect the waiting behaviour of evacuees, such as how long and in what circumstances are they willing to wait for the elevators [44]. Furthermore, more data is required on the effect of elevator use on the chances of survival [36].

Other topics related to aids/means of evacuation in the built environment that deserve more research attention are the use of evacuation aids, such as evacuation slide systems [44] and the usage of refuge floor/rooms in vertical evacuation [44]. Especially, research on how occupants behave on/in a refuge floor/room needs further analysis [44].

For fires in the community context, the identified research gaps related to aids/means of evacuation are about the use of transportation modes and sharing economy facilities, such as Airbnb, Lyft and Uber in wildfires [45, 52]. There is a scarcity of data on whether or not evacuees prefer one transportation mode over another, which social and environmental factors influence modal choice, how many vehicles evacuees will use and in what instances they are likely to choose alternate modes, including how these factors differ by population type [45].

Regarding the research gap about the sharing economy facilities, Kuligowski [45] and Elhami-Khorasani et al. [52] concluded it is still unknown to what extent facilities such as Airbnb, Lyft, and Uber provide transportation and sheltering resources to evacuees.

3.3.7 Cultural Factors

The findings of this scoping review also revealed research gaps in both socio-cultural factors (i.e., related to different groups of people in society, such as children or older adults) and cross-cultural factors (i.e., related to differences between people of different cultures/countries) for the built environment as well as the community context.

We choose to address the gaps related to specific socio-cultural groups, such as children and older adults, in this particular section rather than in the demographics section. This decision stems from our view of these groups as distinct populations. In this context, we are not comparing them to other age groups. Conversely, the demographics section would be more appropriate for discussing comparisons between different consecutive age groups.

In the context of socio-cultural factors within the built environment, human behaviour in fire research including children or older adults is still scarce, especially in relation to their performance in smoke conditions [41, 49, 53]. Also, more research is needed on how children behave and make decisions in dwelling fires [53].

For cross-cultural factors, Lin et al. [42] recommend more research on the impact of cultural background on people's cognition, decision-making and behavioural responses to

building emergencies. Also, it is still unclear to what extent knowledge on human behaviour in building emergencies derived in one cultural context can be transferred to other cultural contexts, and how such knowledge transfer can be done [42].

Our scoping review also revealed that for fires in the community context more cross-cultural data on human behaviour in fire should be collected from other fire-prone countries outside the United States and Australia, and should also include Indigenous peoples, migrants, and comparisons between different countries/populations [32, 45, 47]. For instance, Strahan and Gilbert [47] noticed that migrants often do not appropriately respond to warnings in wildfires, possibly due to not knowing how to respond or misunderstanding warning information, and that there is limited literature on migrants in wildfire disasters.

Finally, for evacuation models and plans, it is also essential to collect more data on different populations in the wildland-urban interface, such as older aged or retired individuals, those with higher or lower socio-economic status, individuals who live in secluded areas, people with different cultures and religions, tourists and temporary visitors and populations in informal settlements [45, 52].

3.3.8 Communication/Information

This scoping review showed that research gaps on communication/information for both fire contexts are related to how information and communications (such as warnings via text messages, social media, the internet, etc.) are perceived, processed and monitored by building occupants and residents in case of fire emergencies [44–46, 51]. This includes communications between evacuees but also between evacuees and emergency responders or rescue services.

For fires in the community context, we found that it is necessary to do more comprehensive research into the ways communication strategies and information dissemination influence human behaviour and responses [32]. Specifically, we need to better understand the factors that contribute to residents' information-seeking behaviours after receiving wildfire warnings [46].

Our scoping review also found that there is only limited evidence available regarding the effectiveness of smoke-related health messages for the general public or at-risk groups [51]. Especially experimental research is necessary in this respect [51]. Further research should also assess the effectiveness of text message alerts, social media networks, and the internet in the context of public health messaging for fire events [51]. Research studies should also include culturally and linguistically diverse (CALD) communities [51].

3.3.9 Demographics

Our review also revealed research gaps related to demographic information such as age and gender for both fire contexts [32, 46, 53]. While research studies do gather demographic information like age and gender, these variables are not consistently incorporated in the final data analyses. Currently, if there is demographic data available, it is mostly data on gender [32]. More data on comparisons between different (consecutive) age groups is important because, for instance, behaviour, decision-making and risk perception might change with age [53].

Furthermore, other demographic information, besides age and gender, were rarely mentioned and/or investigated in the selected papers. Only in Kuligowski [45] and Mytton et al. [53] knowledge gaps on different socio-economic classes related to human behaviour and responses in fire are noticed. However, it should be mentioned here that Mytton et al. [53] themselves excluded studies from low and middle income countries in their review in order to identify evidence more likely to be relevant to the UK setting and the UK Fire and Rescue Service.

3.3.10 Intoxication

Our review identified only one research gap related to intoxication for the built environment. There is a lack of studies about the impact of substance/medication use on evacuation behaviour [40]. This is especially an important issue for (older) populations who use medication, since this group is considered as "high risk" in the context of fire scenarios [40].

3.3.11 Data Collection Methods

In this scoping review, only one research gap related to data collection methods for the built environment context was identified. According to Agyemang and Kinateder [50] more studies are needed to explore the link between controlled lab experiments and data observed from real world incidents in evacuations. However, it was often mentioned by several researchers that more field observations [44] and experiments [44, 51] with more diverse populations and setups [49] are necessary.

4 Discussion

The main goal of this scoping review was to identify gaps in human behaviour in fires research from a multidisciplinary perspective. Thirty-seven research gaps and eleven research themes for two fire contexts were identified. Initially, it was the intention to allocate the research gaps to three phases: preparedness phase, pre-evacuation (pre-travel) phase and evacuation (travel) phase. However, in general, most research gaps that were mentioned in the selected review papers were focused on the evacuation phase of a fire situation. Of course, evacuation is an important process in a fire emergency, but human behaviour and responses before evacuation could also be crucial to the survival of occupants and residents. Also, most review papers neglected to mention which phase(s) was/were investigated in their research. Therefore, it was decided to exclude these timeline phases in this scoping review.

Section 4.1 starts with a general discussion of the four main findings and will also include examples of recent studies that already addressed some of the identified research gaps. This section is followed by a discussion on strengths and limitations of this scoping review (Sect. 4.2), and concludes with a section on implications, next steps and future research (Sect. 4.3).

4.1 General Discussion

In Sect. 3.3.1–3.3.11, important findings for each research theme were discussed. However, as mentioned in Sect. 3.3, newer studies may have been published that address some of the research gaps identified in Sect. 3.3.1–3.3.11. Accordingly, besides a general discussion of the four main findings, Sect. 4.1.1–4.1.4 will also consider examples of these recent studies. This overview, while not exhaustive, highlights important developments in the human behaviour in fires research field.

4.1.1 First Main Finding: the Four Most Underrepresented Research themes

The first main finding is that, currently, the study of cognitive factors is underrepresented the most in human behaviour in fires research, followed by behavioural responses, environmental factors and physical/physiological factors.

Cognitive factors Of course, it is challenging to investigate cognitive factors because cognitive processes are not visually observable, nor are they easy to measure. For instance, exploring how the decision-making process operates during evacuations and how it is influenced by different factors is frequently identified as a research area requiring further study. Also, neurodiverse populations should be included in these studies, although it is likely that knowledge gaps exist because of the demanding design of experiments involving these type of populations due to safety and ethical issues [55]. Nonetheless, a recent study addressed this gap and investigated the evacuation performance of 18 students with a mild to moderate intellectual disability in a university fire drill [56]. Their results indicate that exit choice and pre-movement times for the students with intellectual disabilities diverge from the students without disabilities, but further investigation is required to fully understand these differences and their implications [56].

Our findings also highlight a need for more research on the factors that influence various stages of evacuation decision-making during wildfires, particularly regarding threat and risk perception. However, several recent studies have addressed some of these issues. For example, in a study of the 2021 Marshall wildfire in the United States, it was found that the decision to evacuate was influenced by factors such as observing fire cues and level of pre-fire risk perception [57]. Also, Grajdura et al. [58] investigated factors associated with initial wildfire awareness time, evacuation preparation time, and departure time in the evacuation for the 2018 Camp Fire in Northern California. They discovered, for instance, that faster awareness was linked to witnessing the fire directly, being familiar with local evacuation procedures, and owning a smartphone [58]. The earlier people became aware of the situation, the sooner they departed [58]. Hence, more and more studies appear in the literature that address the gap which factors affect the multiple stages of evacuation decision-making, but additional data on this topic is still welcome.

While studying the review papers, we observed that the impact of cognitive disorders such as dementia or amnesia on human behaviour, was rarely discussed. In the selected reviews, dementia is only mentioned briefly in Bukvić et al. [40] and amnesia is not mentioned at all. Nonetheless, this is a crucial area of research, as older adults (e.g., aged 60 and above) with dementia represent a high-risk group for fire incidents [59]. According to the World Health Organization [60], more than 55 million people worldwide have dementia and every year there are millions of new cases. Given these statistics, future research on

human behaviour in fire situations should prioritize the study of dementia and its associated cognitive impairments to better understand and mitigate risks for this vulnerable population.

Behavioural responses Most research gaps on behavioural responses were about a lack of data on the specific fire responses performance of occupants and/or residents in (wild) fire situations. More research is needed to understand occupant fire suppression actions and the circumstances under which these behaviours occur. However, in a recent experimental study, it was found that during the fire extinguishment of a burning pillow, which was placed on wooden pallets, most participants made a number of mistakes: they extinguished the flames but not the combustible material and they did not consider an escape route [61]. What the implications of these findings are for real fire incidents should be investigated further.

For fires in the community context research gaps regarding behavioural responses are beginning to be addressed in recent studies [62, 63]. These studies show that (1) evacuees mainly used major roads before getting onto the highway and used opposite lanes and drove outside of marked roads to avoid congestion [62] and (2) there was a reduction in speeds and flows on a highway during an evacuation scenario compared to normal conditions [63]. Nonetheless, more data on these topics is still necessary to improve pedestrian and traffic models for evacuation. Other behavioural responses in community fires identified by recent studies are: residents gather together [64], gather belongings and seek information [65], but they also protect property and life/health [65, 66]. However, data on if, how and how often residents defend their property/life/health and fight these fires is still required.

Environmental factors Uncovered research gaps related to environmental factors are mostly about evacuation in smoke. This is a challenging research topic, because in experimental studies it is not possible to use thick, black, hot and toxic smoke as might be the case in real fires. In the past, only a few studies in the building context investigated the effects of irritant and/or (hot) (black) smoke on visibility and/or walking speed [67–69]. In these experiments, the irritant effects were produced by burning wood cribs, hot smoke was produced using an electric heat radiator and black smoke was produced by burning kerosene. These studies show that signs in thick smoke may become not clearly visible [67] and smoke irritation affects thinking and walking speed [68, 69]. In more recent studies acetic acid was used to create a semi-irritant, but not unhealthy, environment in a tunnel [70, 71]. These researchers investigated the impact of smoke on movement strategies [70], exit choice [70] and walking speeds [70, 71]. It was found that reduced visibility conditions have a negative impact on walking speed [71] but that loudspeakers installed at emergency exits, path lighting installed into the walkway and handrails installed with a light strip would especially be helpful to increase moving speeds in smoke evacuations [70]. Finally, in another study, smoke bombs were used to simulate irritant smoke conditions in an evacuation experiment on an offshore platform in China [72]. These smoke bombs generated a smoke layer which had a slightly irritating smell, but was safe for people. This study found that walking speeds in the smoke scenario were 24% lower than in the control scenario without smoke and that following behaviour and small group formation were more common in smoke conditions than in normal conditions [72]. Nevertheless, especially studies into the effects of irritant smoke on other types of behaviour, besides walking speed, during building fire incidents seem to be scarce.

Physical/physiological factors Identified research gaps concerning physical/physiological factors primarily relate to how different functional limitations affect evacuation behaviour and movement. However, experimental studies with vulnerable populations are

challenging, but perhaps using data from evacuation drills is an option, as recently was done with children [73–76]. Also, a recent qualitative study conducted in Sweden involved interviews with 28 older adults with functional limitations [77]. This study revealed that visible impairments, such as the need for mobility aids, tended to elicit more attention and assistance from others. However, this well-intentioned help sometimes led to complications when people were unsure how to provide appropriate support [77]. Notably, the study found that in evacuation scenarios, these older adults predominantly depended on their own capabilities to overcome challenges posed by their functional limitations, rather than relying on external assistance [77].

Issues related to functional limitations will become more important, because the prevalence of functional limitations is increasing. For instance, according to the Centers for Disease Control and Prevention [39], in 2018 in the United States, 9.5% of the adults reported "a lot of difficulty or cannot do at all" in any functioning domain and 32.2% reported "some difficulty" in any functioning domain. Also, the World Health Organization estimates that worldwide an estimated 1.3 billion people experience significant disability [78]. These findings all indicate that more data on the impact of functional limitations on human behaviour in fires studies is needed.

4.1.2 Second Main Finding: More Heterogenous Populations Required in Studies

The second main finding is that for all research themes, more studies are required which include heterogenous populations (e.g., a combination of adults, older adults, children, etc.), different cultures and behavioural profiles (e.g., migrants, Indigenous peoples, tourists, comparisons between countries, etc.), and people with functional limitations. There are, however, various challenges associated with investigating different socio-cultures or conducting cross-cultural studies.

As mentioned earlier, there are some recent experimental studies into the evacuation behaviour and movement of children [73–76]. These datasets were collected during evacuation drills. In addition, a vulnerable group that is generally overrepresented in fatal fire statistics worldwide are older adults ($\geq$60 years) [59, 79]. For example, in the United States ages 65–74 years had 2.2 times, ages 75–84 years had 3.1 times and ages 85 and over had 3.5 times the risk of dying in a fire compared to the general population [80]. Insufficient understanding of risk behaviours that could lead to a fire, along with the belief that the likelihood of a fire at home is minimal, may be contributing factors [81]. Understanding these population-specific risks can help develop targeted fire safety strategies and prevention programs for these specific populations and, therefore, more data in this respect is needed.

Furthermore, for fires in the community context, more cross-cultural data on human behaviour in fire should be collected from other fire-prone countries outside the United States and Australia and should also include Indigenous peoples, migrants, tourists and comparisons between different countries/populations. For example, one study found that First Nations communities in Canada, accounted for 87% of evacuees in 41 smoke-related evacuations between 2000 and 2007 [82]. However, less is known about protective actions taken by Indigenous peoples in Canada during wildfires [83], how Indigenous peoples respond to evacuation orders and which factors influence their decisions and actions [66]. Although, it should be mentioned here that in 2021 a book was published that addressed some of these issues [84]. There are, nonetheless, various challenges associated with investigating differ-

ent cultures or conducting cross-cultural studies. Indigenous communities can be located in isolated areas and it takes time to build trust between residents and researchers [66]. In addition, in cross-cultural research several countries have to be involved, meaning logistical challenges. In this regard, a recent overview of the determinants (including logistical, ethical, legal challenges, etc.) leading to research gaps in the human behaviour in fire field has been discussed in Ronchi et al. [55].

4.1.3 Third Main Finding: Imbalance in Studies between Built Environment and Community Context

The third main finding is that there is an imbalance between studies into human behaviour in fires in the built environment and the community context. This aligns with the findings of the review by Haghani et al. [85]. Our scoping review identified almost three times as many research gaps about human behaviour in fires in the built environment than in the community context. This is likely influenced by the imbalanced number of articles in those fields, as the community context has been subject of less research compared to the building context [85]. As mentioned before, the absence of identified research gaps concerning specific factors in the community context does not imply that such gaps do not exist. Rather, it simply indicates that our review did not uncover these potential research gaps. Furthermore, it is notable that for the community context, the focus is mostly on wildfires with a lesser extent on other types of fire emergencies, e.g., informal settlements and urban fires [52]. This imbalance in research focus suggests a need for future studies on human behaviour in fires to expand their scope and include a broader range of fire contexts.

4.1.4 Fourth Main Finding: Two Scarcely Discussed and/or Investigated Research Themes

The fourth main finding is that for the research themes intoxication and data collection methods only one research gap was identified. This is probably due to the fact that these themes were scarcely discussed or investigated in the selected reviews. Therefore, it is likely that there are more research gaps for these two themes than those that are identified in this scoping review. Nevertheless, for intoxication there are of course challenges for studies into the effects of alcohol and (recreational or prescription) drugs on human behaviour in fires. Ethical constraints affect the possibility of performing experimental research with alcohol and drugs and investigate their effects on behaviour in fires. However, research on human behaviour in fire emergencies involving intoxicated participants can perhaps draw inspiration from previous studies in related fields (e.g., medical studies such as discussed in Nas et al. [86] and Nas et al. [87]). These examples can help to develop ethically sound protocols for investigating the behaviour of intoxicated individuals in fire scenarios. However, it might also be possible to investigate the effects of alcohol and drugs on human behaviour from real world fire investigations data [88].

For the research theme data collection method, we have some final observations. First, most of the discussed studies in the selected reviews, collected data from experiments, surveys or interviews. Second, although no specific gaps in data collection methods were mentioned in the other reviews, some authors did discuss this topic in their review. Zhang and Huang [54], for example, point to the fact that it is challenging to study human behaviour

in a real, full-scale tunnel. Nevertheless, they had the unique opportunity to conduct evacuation experiments in a large newly-built tunnel in China before it was open to public use [54]; however, this is rare. Elhami-Khorasani et al. [52] also highlight that collecting data on human behaviour in community fires is key to understanding human actions in those fires and that, until now, this primarily relies on subjective data, for example from surveys and interviews. This is of course valuable information, but it is also recommended to use technology-based location data (such as smartphone data) in future research [52], as recently was done in wildfire evacuation research [89, 90]. Furthermore, methods using new(er) technology, such as virtual reality, eye-tracking and artificial intelligence, have demonstrated to be useful tools and can be further applied in future research to collect additional data about human behaviour in fires [52, 54]. Furthermore, nowadays, there is an abundance of video footage or mobile phone recordings of fire incidents (online) available. These recordings can be used to observe and study actual behaviour in real incidents, as was done in Van der Wal et al. [91]. In this study, evacuation behaviours and emergency communications were analysed based on videos of real-world evacuation incidents. The same can be done for fire incidents specifically, although this will not be easy because smoke might obscures camera views. Also, observing videos does not necessarily help us with understanding the underlying cognitive factors involved in (evacuation) decision-making and behaviour. For future human behaviour in fire research, it is therefore recommended to adopt a wide variety of methods to collect data to compensate the strengths and weaknesses of each approach.

4.2 Strengths and Limitations

A strength of this scoping review is that the focus was on identifying research *gaps* instead of identifying important findings and results as usually is the case in reviews. It was a challenge to find an appropriate approach to identify missing data but a scoping review was deemed appropriate. Another strength of this scoping review is that different types of fire scenarios (building fires, bushfires/wildfires, WUI fires, informal settlement fires, urban fires, etc.) were included, thus improving its applicability to a wider range of topics. Also, databases from different disciplines were searched: Web of Science, PubMed and Scopus. Therefore, it was possible to identify research gaps from a multidisciplinary perspective. Likewise, this multidisciplinary approach resulted in another strength, namely the identification of various research themes. These themes highlight the key areas where additional research on human behaviour in fires is needed.

A limitation of this scoping review is that dissertations, conference papers, book chapters and grey literature were not included. For this reason, research gaps or available datasets might have been missed. However, in Sect. 4.1.1–4.1.4, we added some examples of (findings of) recent studies to point out that currently some research gaps are being addressed in the human behaviour in fires research field. Nevertheless, even though there are recent studies into certain research gaps, this does not mean that those research gaps have been fully resolved. More datasets from various data collection methods and populations are still required. Two final limitations are that (1) the selection of only English papers might have prevented finding relevant review papers with possible research gaps from other cultures and (2) it was not possible to match the gaps with the (evacuation) timeline phases preparedness, pre-warning, pre-travel and travel in this scoping review because most review papers neglected to mention which phase(s) was/were investigated in their research.

4.3 Implications, Next Steps and Future Research

Data about human behaviour in fires can support improvements in educating the general public, but fire safety managers responsible for building evacuations or community fire incident procedures could also benefit from this knowledge. In this context, a recent review on fire evacuation training has identified a variety of methods and approaches which are often based on different assumptions related to human behaviour in fires [92]. Furthermore, the availability of more data and knowledge on human behaviour in fires could also improve the development, calibration and validation of computational models for predictions on evacuation times and behaviour. In fact, one of the primary uses of human behaviour in fire knowledge is its translation into modelling assumptions that can be adopted for performance-based design in fire safety engineering.

The following natural step of this work has been the identification of the determinants of the research gaps in the field. This issue has been discussed in a recently published article [55].

Besides the suggestions for future research discussed earlier, another issue that should be addressed is arson. The question is whether arson should be considered as part of "human behaviour in fires" or not. While existing reviews (such as on the topic of juvenile fire setting behaviour) have identified patterns and motivation around human behaviour of arsonists, it may be argued that such a topic would better fit into a review related to fire investigations [93].

Furthermore, for future studies it is also important that the identified research gaps are not only investigated from a multidisciplinary perspective but it is also necessary to perform interdisciplinary studies. For example, engineers could partner with cognitive psychologists to explore the impact of architectural design on evacuee decision-making processes. Similarly, simulation model developers might team up with social psychologists to enhance the modelling of group dynamics during fire emergencies. These interdisciplinary approaches can provide more comprehensive and nuanced insights into complex evacuation scenarios, potentially leading to more effective safety strategies and building designs. Finally, this scoping review could be a precursor to a systematic review. Compared to scoping reviews, systematic reviews use more rigorous methods [28]. This approach is designed to reduce potential bias in the collected evidence, resulting in more dependable and robust findings [28].

5 Conclusions

Considering developing a research roadmap for human behaviour in fires, in this scoping review 37 research gaps within 11 research themes and two fire contexts were identified for future research. The main research gaps regarding human behaviour in fires are related to cognitive factors, behavioural responses, environmental factors and physical/physiological factors. Another main finding is that for all research themes more heterogenous studies are needed which include different populations (e.g., older adults, children, etc.), cultures (e.g., migrants, Indigenous peoples, tourists, etc.) and people with (multiple) functional limitations. Also, compared to the built environment, more studies are needed regarding human behaviour in fire in the community context. In addition, data on human behaviour in fires

should not only be collected through experiments, surveys and interviews, but also other data collection methods such as virtual and augmented reality and video footage observations should be included. Therefore, not only a multidisciplinary approach is needed, but also interdisciplinary research efforts in this respect are necessary. Simulation model developers/users, the general public and fire safety managers could all benefit from additional knowledge about human behaviour and responses in fires.

Appendix A

Used search terms in Web of Science on 5 July 2022.
Publication date: 1 January 2010 until 5 July 2022.
TI (=Title): Searches article titles.
TS (=Topic): Searches title, abstract, author keywords, and keywords plus.

1. TI=(fire* AND evacuation*).

   OR.

2. TS=("fire* evacuation" OR "fire* evacuations").

   OR.

3. TS=(("building*" OR "built environment*") AND fire* AND ("human behaviour*" OR "human response*" OR "evacuation behaviour*" OR "escape behaviour*" OR "evacuation* response*" OR "egress behaviour*")).

   OR.

4. TS=(("shopping mall" OR "shopping centre*" OR hotel OR hospital OR stadium OR theatre OR school) AND fire* AND ("evacuation behaviour*" OR "escape behaviour*" OR "evacuation* response*" OR "egress behaviour*")).

   OR.

5. TS=(("shopping mall" OR "shopping centre*" OR hotel OR hospital OR stadium OR theatre OR school) AND fire* AND (emergency OR evacuation OR escape) AND ("human behaviour*" OR "human response*")).

   OR.

6. TS=(("fire safety" OR "fire evacuation*") AND ("evacuation* behaviour*" OR "evacuee* behaviour*" OR "human behaviour*" OR "occupant* behaviour*" OR "egress behaviour*")).

   OR.

7. TS=((“evacuation time*” OR “pre-evacuation*” OR “pre-movement time” OR “evacuation efficiency” OR “evacuation delay”) AND (building* OR facility* OR “built environment*” OR occupant* OR “resident*” OR evacuee*)).

   OR.

8. TS=(“human* behaviour* in fire*” OR “building* fire evacuation*”).

   OR.

9. TS=(“evacuation procedure*” AND emergency* AND (occupant* OR resident*)).

   OR.

10. TS=((“evacuation drill*” OR “egress drill*” OR “fire emergency drill” OR “evacuation trial*” OR “evacuation exercise*”) AND (building* OR pedestrian* OR crowd* OR “built environment*” OR “confined space*” OR evacuee* OR occupant*)).

    OR.

11. TS=((“human behaviour*” OR “human response*” OR “evacuation* behaviour*” OR “escape behaviour*” OR “egress behaviour*”) AND “fire” AND (building* OR “built environment*” OR “ship” OR “tunnel*” OR “aircraft*” OR “vessel*” OR “subway station*” OR “metro station*” OR “train station*” OR airport*)).

    OR.

12. TS=((“aircraft evacuation*”) OR (“ship evacuation*”) OR (“vessel evacuation*”) OR (“tunnel evacuation*” AND fire*) OR ((“train evacuation*”) OR (“building emergency evacuation*”) OR (“building evacuation*”) OR (“indoor emergency evacuation*”) AND fire*) OR (“aircraft emergency evacuation*”) OR (“ship emergency evacuation*”) OR (“vessel emergency evacuation*”) OR (“tunnel emergency evacuation*”) OR (“train emergency evacuation*”)).

    OR.

13. TS=((“wildfire*” OR “bushfire*” OR “wildland fire*” OR “forest fire*” OR “mega fire*” OR “megafire*” OR “wildland-urban interface fire*” OR “WUI fire*”) AND (“evacuation behaviour*” OR “evacuee*” OR “evacuation response*” OR “evacuation*” OR “household* evacuation*” OR “household* response*” OR “household preparedness” OR “homeowner behaviour*” OR “human* behaviour*” OR “human* response*”)).

    OR.

14. TS=((“wildland-urban interface” OR “WUI” OR “urban-wildland” OR (“fire*” AND community*) OR “fire risk mitigation” OR “wildfire risk mitigation”) AND (“evacuation behaviour*” OR “evacuee*” OR “evacuation response*” OR “evacuation*” OR “household* evacuation*” OR “household* response” OR “household preparedness” OR “homeowner behaviour*” OR “human* behaviour*” OR “human* response*”)).

NOT.

15. TS=(earthquake OR tsunami OR cyclone OR flood OR storm OR hurricane OR estimation OR stochastic OR algorithm OR software OR model* OR simulat* OR optimisat* OR optimizat* OR “Bayesian” OR “social force” OR “agent-based” OR “cellular automata” OR “active shooter”).

Appendix B

See Table 4.

Table 4 Selected papers on human behaviour in fires, their research focus, important findings/results and the discussed research themes

References	Research focus	Important findings/results	Research themes discussed										
			cognitive factors	behavioural responses	environmental factors	physical/physiological factors	group/social factors	aids/means of evacuation	cultural factors	communication/information	demographics	intoxication	data collection methods
Agyemang and Kinateder [50]	Systematic review of the biomechanics of staircase descent evacuations	Review results include findings on the impact of walking speeds, gait, age, balance control, visual information processing, fatigue, smoke and grasping on downwards staircase evacuation movement	✓	✓	✓	✓		✓			✓		✓
Bukvić et al. [40]	Scoping review on the role of functional limitations on evacuation performance of adults in public buildings	Review results are presented in a tabular form linking predominant activities in terms of the International Classification of Functioning, Disability and Health (ICF) and six categories of functional limitations with the engineering evacuation timeline	✓	✓		✓		✓		✓		✓	

Table 4 (continued)

References	Research focus	Important findings/ results	Research themes discussed										
			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods
Ding et al. [44]	Review of (1) high-rise building evacuation experimental methods, (2) wayfinding and impact factors in horizontal evacuation and (3) individual and crowd behaviours in vertical evacuation	The review highlights the application of virtual technology in evacuation experiments and group behaviour effects in high-rise buildings	✓	✓	✓	✓	✓	✓		✓			✓

Table 4 (continued)

References	Research focus	Important findings/ results	Research themes discussed										
			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods
Elhami-Khorasani et al. [52]	Review of existing empirical research and modelling efforts on human behaviour in large community fires with a focus on: (1) methodologies on how information is collected, (2) summarization of available empirical literature and (3) how evacuation models have been developed to potentially predict human behaviour in large community fires	The review found that interviews and surveys have greatly advanced the understanding of human behaviour in large community fires. Also, past modelling efforts were mainly limited to traffic modelling approaches but the current research direction has shifted to the use of artificial intelligence and geographic information system methods to model evacuation behaviour in fires. Finally, informal settlement fires and urban fires are underexposed in fire disaster studies	✓	✓	✓			✓	✓		✓		✓

Table 4 (continued)

References	Research focus	Important findings/ results	Research themes discussed										
			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods
Fish et al. [51]	This rapid review investigated recent evidence regarding the effectiveness of public health messaging during smoke events with the following objectives: (1) determine the effectiveness of various communication channels used and public health messages disseminated during smoke events for general and at-risk populations	Important results were: (1) smoke-related public health messages are communicated via a variety of channels, but limited evidence is available about their effectiveness, (2) message that use simple language are more commonly recalled, understood and complied with, but compliance differs according to socio-demographic characteristics and (3) at-risk groups may be advised to stay indoors before the general population in order to protect the most vulnerable people in the community	✓	✓	✓				✓	✓	✓		

Table 4 (continued)

References	Research focus	Important findings/ results	Research themes discussed										
			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods
Fridolf et al. [49]	Systematic review of the behaviour and movement of people in fire evacuations in smoke-free and smoke-filled underground transportation systems	Walking speed reduction in smoke-filled situations is based on a combination of a universal reduction for all people, and individual changes based on factors such as visibility, walking speed in smoke-free conditions, the path of travel, group behaviour	✓	✓	✓	✓	✓			✓	✓		✓
Hostetter and Naser [41]	Comprehensive literature review of fire evacuation research focused on various forms of disability	A four-part *Disability Evacuation Framework* is presented, summarising the disability rights history, research gaps, significant accessibility legislation and key disasters. Based on these findings, a new definition of disability in relation to evacuation is defined for use by building professionals	✓	✓	✓	✓	✓	✓	✓	✓			✓

Table 4 (continued)

References	Research focus	Important findings/ results	Research themes discussed										
			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods
Kobes et al. [36]	Literature review on building safety and human behaviour in fire	Critical factors determining occupants' fire response performances are: characteristics of fire, human beings and buildings. The key finding is that psychonomics appear to have a significant influence on occupants' fire response performances	✓	✓	✓	✓	✓	✓		✓	✓		
Kuligowski [45]	Review of the literature and collected data on evacuation decision-making and behaviour in wildfires	Overview of past research, current challenges, research gaps, and a future research plan for further data collection of important wildfire evacuation topics to improve wildfire evacuation simulation models	✓	✓	✓		✓	✓	✓	✓	✓		✓

Table 4 (continued)

References	Research focus	Important findings/ results	Research themes discussed										
			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods
Lin et al. [42]	Systematic holistic review of behavioural characteristics and behavioural theories on how occupants respond to building emergencies	The review demonstrates that occupants' wayfinding behaviour has been the focus of prior research, usages of different research methods have evolved over time, different theories have been referenced ad hoc to explain different behaviours separately and a holistic framework that incorporates all human cognitive and behavioural processes in the entire building emergency response process could be valuable	✓	✓	✓		✓		✓	✓	✓		✓

Table 4 (continued)

References	Research focus	Important findings/ results	Research themes discussed										
			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods
McLennan et al. [32]	Review of behavioural factors in evacuation under wildfire threat in North America and Australia	Research from both regions indicates that following a wildfire evacuation warning some threatened residents will stay and protect their property, many will delay evacuation, and some residents who are not on their property at that moment may seek to return. Mandatory evacuation is likely to result in greater compliance and self-delayed evacuation is likely if warnings are not sufficiently informative. The wildfire warning and threat histories of a location may influence residents' decisions and actions	✓	✓	✓				✓	✓	✓		

Table 4 (continued)

References	Research focus	Important findings/ results	Research themes discussed										
			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods
Mytton et al. [53]	Systematic review of qualitative literature on children and young people's behaviour in accidental dwelling fires	The review indicates there is inadequate evidence of the current lived experience of children in accidental dwelling fires to support fire and rescue services in either their fire and rescue training or community fire safety education activities, particularly for non-US countries	✓	✓					✓		✓		
Strahan and Gilbert [46]	Systematic review of the "wait and see" literature on protective decision-making in bushfires	This review establishes the extent of wait and see behaviour, grounds for concern for such behaviour, reasons protective action is delayed, the influence of information and warnings, relevance of gender and other characteristics, delay by those who defend their property, and policy implications	✓	✓	✓		✓		✓	✓	✓		

Table 4 (continued)

References	Research focus	Important findings/ results	Research themes discussed										
			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods
Strahan and Gilbert [47]	Systematic review of the "leave early" literature on protective decision-making in bushfires	This review establishes the reasons people leave early, the influence of official and unofficial warnings, gender and other demographics, the influence of self-evacuation archetypes, planning and preparation, the influence of children and other dependents and pets, triggers initiating leaving, factors impeding and facilitating leaving, and policy issues around early leaving	✓	✓	✓	✓	✓		✓	✓	✓		

Table 4 (continued)

References	Research focus	Important findings/ results	Research themes discussed										
			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods
Tan and Moinuddin [43]	Systematic review of human and organizational risks for probabilistic risk analysis in high-rise buildings	The review identifies errors due to human and organizational factors that apply to and potentially affect risk estimates in fire safety modelling of high-rise buildings. Types of errors that occur in fire risk situations are described and a review is provided that categorizes and links human and organizational factors. Also, the review offers insights and recommendations to incorporate human and organizational risks into probabilistic risk analyses	✓	✓	✓		✓	✓		✓			✓

Table 4 (continued)

References	Research focus	Important findings/ results	Research themes discussed										
			cognitive factors	behavioural responses	environmental factors	physical/ physiological factors	group/social factors	aids/ means of evacuation	cultural factors	communication/ information	demographics	intoxication	data collection methods
Thompson et al. [48]	Review of the literature on human behaviour in dwelling fires	Research findings point towards fire risks as at least three separate forms: the risk of (1) a fire occurring, (2) fire injury and (3) fire fatality. This paper argues that those who survive dwelling fires cannot be considered as "near miss fatalities", but instead must be treated as a separate and distinct group	✓	✓	✓	✓	✓		✓	✓	✓	✓	
Zhang and Huang [54]	Review of the latest developments and studies in China on tunnel fire evacuation strategies and research of tunnel fires worldwide	The review outlined (1) differences between evacuation in tunnel fires worldwide and specific issues in China and (2) differences between China and other countries in evacuation strategies because of the design of structures	✓	✓	✓	✓	✓		✓				

Appendix C

See Table 5.

Table 5 Definitions and/or explanations of terminology

Terms	Definition/explanation
Biomechanics	The study of the mechanical aspects of living organisms, in this case the human body. The forces studied include both the internal forces produced by muscles and the external forces that act on the body [95]
Cognition	The collection of mental processes and activities used in perceiving, remembering, thinking, and understanding, as well as the act of using those processes [96]
Functional limitations	Limitations in performance at the level of the whole organism or person [97]
Informal settlements	Areas where multiple housing units have been constructed on land that the occupants have no legal claim to, or occupy illegally; and where housing does not comply with existing planning and building regulations [52]
Physiology	The study of biological function– of how the body works [98]
Psychology	The science of behaviour and the mind; behaviour refers to the observable actions of a person and mind refers to an individual's sensations, perceptions, memories, thoughts, dreams, motives, emotional feelings and other subjective experiences [99]
Refuge floor/room	A floor/room where evacuees can wait to be rescued or take a brief rest
Wayfinding	The cognitive, social and corporeal [=physical] process and experience of locating, following or discovering a route through and to a given space [100]

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