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Crowd dynamics research in the era of Covid-19 pandemic: Challenges and opportunities

Milad Haghani

School of Civil and Environmental Engineering, The University of New South Wales, UNSW Sydney, Australia

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ABSTRACT

With the issues of crowd control and physical distancing becoming central to disease prevention measures, one would expect that crowd research should become a focus of attention during the Covid-19 pandemic era. However, I will show, based on a variety of metrics, that not only has this not been the case, but also, the first two years of the pandemic have posed an undisputable setback to the development and growth of crowd science. Without intervention, this could potentially aggravate further and cause a long-lasting recession in this field. This article, in addition to documenting and highlighting this issue, aims to outline potential avenues through which crowd research can reshape itself in the era of Covid-19 pandemic, maintain its pre-pandemic momentum and even further expand the diversity of its topics. Despite significant changes that the pandemic has brought to human life, issues related to congregation and mobility of pedestrians, building fires, crowd incidents, rallying crowds and the like have not disappeared from societies and remain relevant. Moreover, the diversity of pandemic-related problems itself creates a rich ground for making novel scientific discoveries. This could provide grounds for establishing fresh dimensions in crowd dynamics research. These potential new dimensions extend to all areas of this field including numerical and experimental investigations, crowd psychology and applications of computer vision and artificial intelligence methods in crowd management. The Covid-19 pandemic may have posed challenges to crowd researchers but has also created ample potential opportunities. This is further evidenced by reviewing efforts taken thus far in pandemic-related crowd research.

1. Introduction

The body of research on the safety of human crowds, the domain that is often referred to as *pedestrian/crowd dynamics*, has been increasingly and consistently expanding during the current century. This was documented in previous work which showed how the field has been displaying a nearly exponential trend of expansion since 2000 (Haghani, 2021). The occurrence of the Covid-19 pandemic, however, seems to have exerted an unambiguous interruption to this trend and has affected the pre-pandemic momentum in knowledge production in this field. It was noted in the previous work that, during the last several years leading to the pandemic, the focus of the field had shifted markedly towards experimental research (Haghani, 2020a, b, 2021; Haghani and Sarvi, 2018), and understandably, the restrictions that came with the pandemic put that line of work to nearly a halt. This could be only one plausible explanation for this momentum loss. Alternatively, the issue may also be partly explained by the general research productivity loss that has been observed in many fields of research since the onset of the Covid-19 pandemic.

The current work is aimed to highlight and document the above-mentioned issue and discuss how the field of crowd dynamics can adapt itself to these new circumstances, noting that the pandemic itself has created a rich set of avenues to be explored by researchers of this field. The Covid-19 pandemic might have caused many changes (albeit temporary) in the way of life but is has certainly not made the issue of crowd safety any less relevant than before. Congregations of people in various contexts keep happening—some even driven by the pandemic itself such as political rallies and protests (see examples documented by Kowalewski (2021)). The need for evacuation of crowded venues has not disappeared and crowd incidents have not stopped during this time (Brzezińska et al., 2022). An example is the earthquake that happened on 22 March 2020 in Croatia during the peak of the pandemic in that

E-mail address: milad.haghani@unsw.edu.au.

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country, which required several hospitals to be evacuated (Markotić and Capak, 2020))[1]. Considering these events, one could argue that, if anything, the pandemic has created many new issues that are directly within the forte of crowd researchers to address; issues that were previously non-existent and have only been brought to human life by the pandemic. Guided and inspired by the efforts taken thus far in the pandemic-related crowd research, this paper unpacks a plethora of new issues in crowd dynamics that can offer potential new topics and research avenues in this domain.

The field of crowd dynamics is diverse and heterogenous and itself is composed of several subdomains. This work aims to outline potential avenues of pandemic-related crowd research in all major subdomains of the field. After documenting and demonstrating the effect that the Covid-19 pandemic has exerted on scholarly progress in crowd dynamics (Section 2), in Sections 3-7, I discuss how each subdivision of crowd dynamics research has encountered new research problems in the wake of the pandemic. I discuss how these recently opened research avenues can be explored to, perhaps, compensate for the suspension that was placed on many lines of research in this domain during the pandemic, particularly on experimental research. Such potential avenues are discussed within numerical simulation domain (Section 3), experimental domain (Section 4), crowd management (Section 5), crowd psychology (Section 6) as well as computer-vision crowd research (Section 7). It is hoped that these discussions can help this field maintain its relevance, regain its pre-pandemic momentum, and carry itself forward to a post-pandemic era as an even further expanded research field.

2. The pandemic-driven lost momentum in crowd dynamics research

This section revisits the trends in the growth of crowd dynamics as a research domain with a particular focus on investigating potential interruptions to this trend following the Covid-19 pandemic. In a previous publication (Haghani, 2021), a search query string was designed with the purpose of capturing the literature of crowd dynamics in its approximate entirety. The query string (accessible in Online Supplementary Material) is an extensive combination of key terms that characterise crowd dynamics research (and its different subdomains, components, and methods). The query was developed and optimised based on two criterial (1) to maximally encapsulate and reflect all aspects of crowd dynamics research (i.e., numerical, experimental, psychological, computer vision etc), (2) avoid false positives (articles that use language and terminologies similar to that of crowd dynamics research but are not crowd dynamics studies per se). One application of such query string, as discussed in the original article, is to keep track of the progression of the field on a unified and objective basis. Revisiting that search method two years after the onset of Covid-19 pandemic, now (at the end of 2021), seems to be a suitable time to examine whether the pandemic has had any effect on the progression of this field. This examination is based on three metrics: (i) number of articles published in the field of crowd dynamics, (ii) collective number of citations to the articles of crowd dynamics (collectively from within or outside the field) and (iii) number of citing articles of the field of crowd dynamics (collectively from within and outside the field). These are three typical metrics through which one can quantify the amount of scholarly research activities in a research domain. These quantities are extracted for each year since 1998 and the trend of 1998–2019 is contrasted with the manifested quantity of these metrics during 2020 and 2021, the first two years of the pandemic.

This set of data and the respective analyses are visualised in Fig. 1. The data shows that 2021 marks the first year where we observe a drop in the quantity of crowd dynamics publications since 2015. The momentum of publications appears to have slowed down notably in 2020 (with only a marginal increase compared to 2019 and well below the expected number) and in 2021, this translated to notable drop (from nearly 790 articles in 2019 and 2020 to only 680 articles in 2021, a 16% relative drop). It might be argued that since 1998 there have been three other transient drops in the number of crowd dynamics publications (2011, 2013 and 2015). However, firstly, it should be noted that this is the first instance since 1998 where we are observing two consecutive years of slowing down in activities. Secondly, the interruption of the trend is even less ambiguous when considering the number of citations and the number of citing articles of crowd dynamics[2]. Both these quantities have been exponentially on the rise since 1998 and now we observe a clear deviation from the trend since 2020. To quantify these effects, polynomial curves of degree 5 were fitted to both sets of data (i.e., number of citations and number of citing articles) for the period 1998–2019. These polynomial functions were then extrapolated to estimate the expected number of citations and citing articles in 2020 and in 2021. This analysis shows that, had the previous trend continued uninterrupted, we would have observed nearly 6,700 more citations to the field of crowd dynamics in 2021 compared to the manifested number. Similarly, nearly 1,200 potential citing articles seem to be missing in 2021. This clear deviation from an established trend gives an unambiguous indication that the occurrence of the pandemic has indeed had interruptive impacts on knowledge productivity in crowd dynamics[3].

The occurrence of the pandemic itself has, of course, created a new chapter in crowd dynamics field, albeit not a very substantial one. As mentioned in Haghani (2021), another use of a search query string that captures this field is that it allows us to subsequently source specific subsets of interest and isolate them from the rest of the field readily. In this case, one can simply place the query string within a pair of brackets and combine it with ("pandemic*" OR "COVID-19" OR "SARC-CoV-2" OR "Coronavirus") using the Boolean operator AND, and set the time-span to 2020 and onwards in the Web of Science search engine, in the Basic Search section and while specifying Topic as the search domain (this encompasses titles, abstracts and keywords of articles indexed by the Web of Science). This search query can be downloaded from the Online Supplementary Marial of this article and be simply copied into the Web of Science Core collection search engine, with the time-span specifications mentioned above. The size of the generated set of items will be such that the resultant items can be examined and filtered out individually. Using this method, it is estimated that nearly 40 pandemic-related studies were published in the field of crowd dynamics during the first two years of the pandemic, and this will be the estimate for the size of this new chapter in crowd dynamics research at the end of 2021. This makes up about 2.7% of the articles published in this field during 2020 and 2021. This can be contrasted with the field of Transportation, for example, where out of nearly 12,000 articles during 2020 and 2021, about 500 items were pandemic related research (4.2%), a considerably higher percentage compared to the field of crowd dynamics. This is an indication that crowd researchers were less inclined to shift their attention to pandemic-related topics compared to an associate field like transportation.

[1] Another example is the tragic death of eight people at rapper Travis Scott's Astroworld concert in Texas which also happened during the pandemic and showed that fatalities at major events like festivals and football matches have not ceased during pandemic, and thus, highlighting that the need for crowd safety research does still exist, just as much as the pre-pandemic era.

[2] Understandably, the decline in the citations to crowd dynamics could itself be a side-effect of the decline in publications and a reflection of a general reduction in research productivity in this field.

[3] As a reviewer rightly pointed out, the effect of these pandemic-related disruptions on crowd research productivity may even manifest in a more pronounced way in the coming year(s), considering the lag that often exists between research being conducted and disseminated.

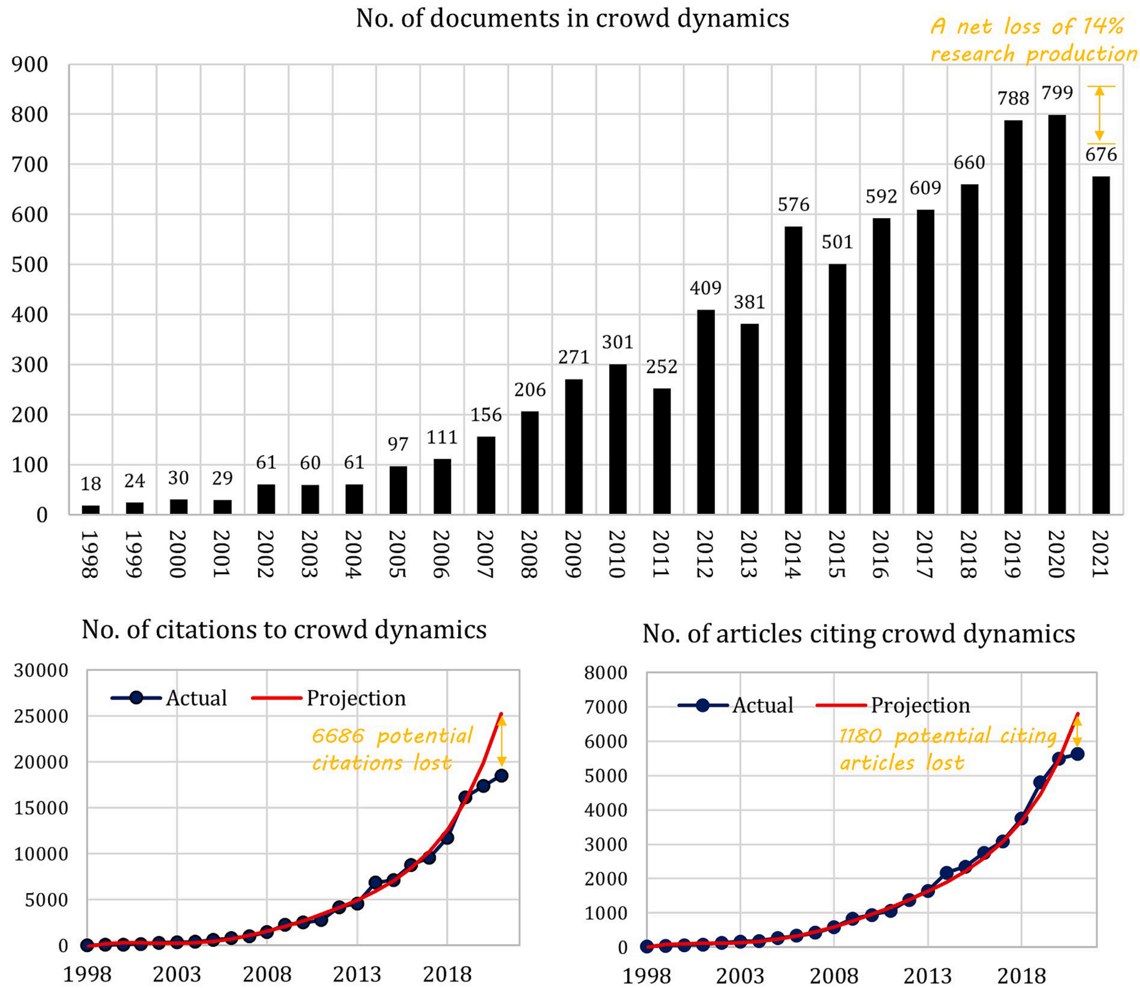

Fig. 1. Lost momentum in crowd dynamics research caused by the Covid-19 pandemic, quantified in terms of (a) total number of annual publications (top), total number of citations to crowd papers (bottom left), total number of citing articles to crowd papers (bottom right).

3. Potential pandemic-related crowd research avenues in the numerical simulation domain

With the emergence of the disease prevention measures following the Covid-19 pandemic, the most evident issue that crowd researchers with specialty in numerical modelling could address is the simulation of physical distancing in crowds (Alam et al., 2022; Espitia et al., 2022; Ronchi et al., 2020a; Ronchi et al., 2020b). This can provide practitioners with tools to evaluate effectiveness of different policies in relation to distancing and could also enable them to have estimates of the risk of transmission in facilities that have considerable foot traffic in order to decide whether the risk is below acceptable thresholds (Du et al., 2021; Lahijani et al., 2021). This, however, will create a multitude of issues, each of which could constitute a research topic for numerical researchers of this domain. Some of the most critical matters that may particularly need attention from crowd researchers include (i) how the inputs and outputs of simulation models (whether commercial or research based) need to be modified in order to accommodate all characteristics required for physical distancing simulation, (ii) whether the focus should be on embedding additional risk models customised for specific pedestrian simulation modelling types or on developing generic secondary models that can be integrated with standard outputs of any simulation model, regardless of the simulation kernel, (iii) whether the focus of these efforts should be levelled at estimation absolute risk of disease transmission or the relative risk, and in the former case, how the additional challenges that come with absolute risk calculation can be dealt with.

Regarding issue (i), the need for simulation of foot traffic with consideration of physical distancing has created a range of new user input and output measures that did not used to be a matter of concern prior to the pandemic. The extent to which simulated agents[4] get close to each other during the simulation process did not used to be a user-specified input in most simulation platforms. Modellers often set up some relevant parameters, such as that of the repulsive force within a social-force-based paradigm (Bouchnita and Jebrane, 2020), at a default value that produces reasonable amounts of inter-agent distances. Now, there appears to be a need for accommodating methods through which users of crowd simulation models can control this feature more explicitly. The existing evidence shows that the dominant tendency is still to resort to the coefficients of repulsive force in order to control this feature, i.e., inter-agent distances. However, the extent to which this parameter guarantees that agents maintain the distance dictated to them is questionable (Si and Fang, 2021). Researchers that have worked with social force models are aware that depending on the size of the crowd and a range of other input parameters such as the desired velocity, agents may still get very close to each other and have body contact even when we magnify the coefficient of repulsive force to extreme degrees. Therefore, more research is required to establish best possible ways of

[4] These discussions are all exclusively confined to the context of agent-based simulation models and may not have any bearing to macroscopic style of pedestrian modelling.

enforcing desired inter-agent distances during simulation processes in a controllable and intuitive manner. How many parameters, for example, would be needed to enforce such feature and how can a naïve user enforce the desired amount of distancing without knowing about the underlying mechanism in the simulation engine (Mayr and Köster, 2020). This could particularly be a matter importance to commercial pedestrian software developers who wish to modify their programs in light of the new features that the pandemic has demanded. Also, considering that not every pedestrian simulation model has a social-force-based core for its locomotion layer, further research is also going to be needed to determine how inter-agent distances can be controlled without non-social-force frameworks and how many additional parameters would be needed to enforce the desired distancing during the simulation process. For example, further research could investigate whether grid-based models are better capable of making agents avoid cells which are within a certain distance of another agent, using more straightforward parameter alterations. In flow-type models, this could potentially be made possible through adjustment of the capacity attributes but is yet to be investigated and reported. The problem is not, per se, making the agents maintain a distance. The issue is rather around the human behavioural side related to how and when the model allows variation in distances, especially in contra-flow situations, to avoid "locking" and represent the "give or take" side of human behaviour.

Continuing on issue (i), another line of question is the range of new outputs that pedestrian simulation models need to produce in order to quantify physical exposure in ways that matter to the calculation of disease transmission risk. It is clear that the classic metric of average/maximum pedestrian density that used to be the standard output for most crowd models is no longer detailed enough when it comes to the calculation of virus transmission risk, as it cannot capture individual exposures. Transmission of airborne viruses is about the exposure of individual pairs of people and the duration of such exposures (Parisi et al., 2022) (also referred to as "contact time" (Abdul Salam et al., 2021)), and in that sense, density would not be a perfect reflection of exposures (although, it can still be used as a coarse indirect indicator). One can accommodate, for example, four individuals within a square of a certain dimension in such a way that they maintain an acceptable level of physical distancing or in a way that they are in extreme violation of distancing (Mohammadi et al., 2021). In both case, density as a metric would be the same, and as such, one will be unable to tell these two scenarios apart based on this conventional metric. Therefore, the pandemic has made it necessary for pedestrian model developers to measure interpersonal distance of pairs of individuals, instances of breach in physical distancing and the duration of each breach. However, from the modelling and scenario testing perspective, no user will be interested in individual instances of breaching, and as such, these individual-level calculations should also be eventually summed up in the form of aggregate metrics. These also require research innovation to determine how these aggregations should take place. For example, the trajectories of pedestrian movements are never perfect straight lines. If one desires to calculate the *distance* between pedestrian trajectories, for example, that may require borrowing, from other fields, concepts that did not used to be within the attention of crowd researchers. This could include measures such as Fréchet distance (Su et al., 2021) as a measure of similarity between curves that could be utilised and combined with raw outputs of pedestrian simulation models to reflect physical distancing at aggregate levels. Also, further on the calculation of exposures, is the matter of body/head orientation of simulated pedestrians. Conventionally, standard raw simulation outputs only included motion trajectory of simulated pedestrians. However, if such simulation output are to be integrated with virus transmission models (Garcia et al., 2021), then for a detailed transmission model, it may be necessary to record body/head orientation of agents at every time step, in addition to their spatial coordinates. This feature may necessitate heavy modifications of the existing crowd motion models, including within the social-force modelling paradigm.

An important question with respect to the calculation of virus transmission risk for applications in crowded spaces (e.g., shopping centres, university campuses, busy streets) based on outcomes of pedestrian simulation models, is whether the best approach is to integrate the layer of virus transmission with each pedestrian model and customise it to its features, or to develop universal transmission models that can rely on standard (or modified) output of any pedestrian model (Ronchi and Lovreglio, 2020) (issue (ii)). It should be noted that calculation of metrics such as instances of exposures (i.e., breaches of physical distancing) as well as duration of such exposures and translating them to risk estimation can be done as a secondary calculation on outputs of simulation models. From this perspective, a model of transmission does not need to be linked to specific pedestrian models. Rather, an independent universal model, such as that of Ronchi and Lovreglio (2020), can essentially work based on output of any standard pedestrian model, whether commercial (Mohammadi et al., 2021) or research-based. As mentioned earlier, however, depending on the sophistication level of the transmission modelling layer, certain modifications to the standard pedestrian simulation output may be required. For most models, all calculations can be conducted on the trajectory of agents' movement, but more detailed transmission models may demand more information such as the head orientation of agents at every time step of the simulation process.

One of the most critical questions with respect to the application of pedestrian models for disease transmission risk purposes is whether such models should be designed for estimation of absolute risk or relative risk of transmission (issue (iii)). These two purposes demand vastly different modelling requirements. In the case of relative risk estimation, the aim is to compare different policies and infrastructure designs (e.g., one-way versus two-way foot traffic, or different shopping mechanisms (Harweg et al., 2021; Li and Yin, 2021; Romero et al., 2020; Tong et al., 2021; Xu and Chraibi, 2020). Such comparisons of risk are made based on the amount of individual-to-individual exposure that each intervention causes and will allow users to choose interventions with minimum risk. This exempts crowd modellers from getting into the epidemiological aspects of virus transmission and an epidemiological modelling layer may even not be required after all for such estimations. Such modelling has of course limited applications, as it only serves comparison of scenarios (e.g., two forms of architectural interventions in a pedestrian facility, with all other things equal). This form of modelling cannot produce absolute risk estimates and determine if a given design meets minimum requirements of disease transmission risk. If the aim of modelling is to produce absolute risk of disease transmission and to determine whether the risk of a given policy or intervention fall below acceptable thresholds, then adopting an epidemiological modelling payer will become inevitable (Bouchnita and Jebrane, 2020; Xiao et al., 2021). It is worth noting that introduction of such additional layer (i.e., a hybrid between pedestrian and virus transmission simulation) will make the task of modelling exceedingly more complex. A whole array of new inputs will be required that will otherwise not matter for relative risk calculation. This includes elements such as whether we are simulating an indoor or outdoor space, the level of ventilation in the venue, the distribution of ventilation points across the space, the level of immunity of the crowd (vaccination rate), percentage of people wearing face mask, whether the crowd is stationary or on the move, whether the crowd is singing, talking or silent, and the demographic of the crowd, to name only a few. These additional complexities are all avoided when calculating relative risk of transmission, on the assumption that these factors are all the same across the scenarios that we are comparing. How these elements can all be plausibly accommodated within simulation models that aim for absolute risk estimation warrants considerable research and modelling innovation.

So far, applications of modified crowd models have been extended to pandemic-related investigations in the contexts such as boarding and alighting of passengers in train stations (Sun et al., 2021), boarding and alighting policies of airlines (Islam et al., 2021b), pedestrian traffic on university campuses and in academic buildings (Castro and Ford, 2021; Romero et al., 2020), foot traffic in shopping centres and supermarkets (Tong et al., 2021; Xiao et al., 2021; Xu and Chraibi, 2020), and religious gatherings (Al-Shaery et al., 2021). These applications have predominantly employed variations of social force pedestrian model (Bouchnita and Jebrane, 2020; Derjany et al., 2021; Harweg et al., 2021; Islam et al., 2021a; Si and Fang, 2021; Tong et al., 2021; Xiao et al., 2022; Xiao et al., 2021), although this has not been a universal feature of pandemic-related simulation studies in crowd dynamics and other agent-based modelling paradigms such as those of cellular automata have been reported too (Li and Yin, 2021).

Also, while the issue of hospital evacuation has been particularly of the focus of attention of crowd researchers within both numerical and experimental realms in the years prior to pandemic, it may be worth noting that with hospitals around the world working at capacities treating Covid-19 patients, there may be further complications with respect to hospital evacuation that may require specific attention (Haghpanah et al., 2021; Yazdani et al., 2021). Development of specific strategies for the evacuation of hospital in which a mixture of Covid-19 patients and other patients are treated may require simulation testing and optimisation methods. Especially considering the highly contagious nature of the variants of coronaviruses that are spreading around the world, strategies need to be in place as to how best Covid-infected and other vulnerable patients can be kept apart while being evacuated safely in a case of emergency. Effectiveness of such strategies need to be tested using suitable simulation models and that can itself be a new dimension of investigation in crowd dynamics. Similarly, the problem of occupant evacuations from built environments, in general, is confronted by the issue of minimising exposures. Whereas, previously, the focus of such analyses on building evacuations was mainly on minimising evacuation times. It should be noted that even for buildings that are under-occupied, a case of an emergency evacuation may create crowding at points of interest (e.g., evacuation lifts, staircases, exit doors). Evacuation of buildings under physical distancing guidelines now presents a trade-off between the risk of disease transmission and the risk of the danger for which evacuation is taking place (e.g., a building fire). This trade-off and the possible ways to address it has, thus far, not been addressed in the scientific literature. Perhaps this issue warrants revisiting of the notion of staged evacuations as a potential way to strike a balance between the two types of risks mentioned above. Such investigation will fall nicely within the realm of numerical modelling in crowd dynamics research.

4. Potential pandemic-related crowd research avenues in the experimental domain

Understandably, pandemic-related experimental research in crowd dynamics has been highly scarce thus far (Echeverría-Huarte et al., 2021a). While crowd experiments are generally difficult to conduct for logistical purposes even during normal times, the pandemic itself has become a major hinderance in many areas of the world for researchers to conduct such experiments. While certain research groups have managed to conduct their experiments during the pandemic under strict conditions of testing and recruiting vaccinated-only participants and mask wearing, not many have reported on experiments related to pandemic topics per se. In that sense, the experimental front in crowd dynamics research has not adopted much to the notion of the pandemic other than being largely abandoned. Continuation of this line of work, that has in fact been the most dynamic stream of research in this field since 2015 (Haghani, 2021), may require innovations and logistical compromises such as experimenting in outdoor venues (Lu et al., 2021) and/or experimenting under sparse crowd conditions (Bartolucci et al., 2022).

Similar to the pre-pandemic research, experimental work can be the most important support for numerical research in crowd dynamics, allowing us to ensure that our assumptions are kept in check and the outputs that our numerical models produce are accurate enough. For example, in the previous section and when discussing the new requirements for inputs of pedestrian models, the notion of enforcing physical distancing was raised. It is understandable that there is always going to be a difference between the distance dictated as a policy and the distance that people can actually maintain from one another under different movement conditions (e.g., corridors, exits etc) (Bartolucci et al., 2022). This discrepancy is a valuable piece of information that can be obtained from experimentation (e.g., to determine high-risk locations). Experimental insight into this question can also inform our numerical models and influence how we represent physical distancing within the simulated realm. It would be also interesting to determine how social groups reshape themselves and how their dynamics change in crowded conditions when trying to adhere to the requirements of physical distancing. There is a rich literature on the behaviour of social groups based on field and experimental observations collected prior to the pandemic which could serve as a valuable benchmark of comparison, should post-pandemic data also be made available.

Another critical aspect on which experimental crowd researchers focused during the years prior to the pandemic is the notion of fundamental diagram (Echeverría-Huarte et al., 2021b), i.e., the relationship between flow and density of moving crowds. This is a critical concept both from the perspective of crowd management and finetuning of numerical models. Models are often deemed inaccurate when their output fail to reproduce realistic flow-density relationships, consistent with observations in experimental settings. The problem is that none of the previous experiments of fundamental diagram were conducted under conditions of physical distancing or anything of that nature, and now, there could be a suitable time to revisit these notions based on new sets of experiments (Lu et al., 2021). In fact, the rich line of experimentation and the associated set of findings that accumulated over the years prior to the pandemic in relation to topics of stepping behaviour, single-file movement, unidirectional and bidirectional flows, overtaking behaviour and body rotation can all be revisited under the distancing conditions. The wealth of pre-pandemic experimental research that exist could again serve as a valuable benchmark of comparison.

5. Potential pandemic-related crowd research avenues in the crowd management domain

Living for sustained amounts of time under conditions of disease prevention measures has certainly affected people's perception of crowd and comfort (Aghabayk et al., 2021). This may call for a revisiting of the definitions and thresholds related to the pedestrians level of comfort and level of service (Mohammadi et al., 2021; Talavera-Garcia and Perez-Campana, 2021) at crowded facilities and infrastructure, such as trains, train stations and other crowded venues. Quantifying thresholds for various levels of pedestrian perceived safety/comfort could constitute a pandemic-specific line of research in crowd dynamics that can directly inform practitioners, event organisers and crowd managers.

Another realm that feeds directly into the notion of crowd management is determining the minimum amount of space that patrons or shoppers require in order to be able to maintain certain levels of physical distancing. This is particularly relevant for the management of pedestrian flow into dynamic spaces such as retails and shopping centres where individuals move freely within the space rather than having an allocated spot (Ntounis et al., 2020). The question can essentially be formulated as follows: what the level of occupancy should be kept at a given venue in order for physical distancing (of a certain level) to become feasible for every occupant (Echeverría-Huarte et al., 2021a). As simple as the question may sound on the surface, the answer is not very intuitive and requires mathematical methodologies. Developing methods that can produce such lower bounds for the amount of required space in consideration of the relevant nuance such as the nature of space, nature of activities and the nature of the occupants could become a new line of crowd research (Yang et al., 2021).

Another potential avenue in pandemic-related crowd management research could be development of knowledge-based user recommendation (or, user guidance) systems that can facilitate adherence to physical distancing at certain points of interest in places such as shopping centres. Clearly, developments of such systems, in addition to their requirements for optimisation algorithms on the management side, introduces issues such as end-user acceptance and experience. This may itself require behavioural research as well as behavioural models that can replicate acceptance level and interaction of end-users with such systems (Durán-Polanco and Siller, 2021; Yang et al., 2021).

6. Potential pandemic-related crowd research avenues in the psychology domain

The psychology domain of crowd dynamics research is perhaps being presented with one of the richest and most diverse sets of unexplored pandemic-related research avenues compared to other subdomains of this field. The issue of crowd members' adherence to physical distancing policies as well as their engagement in risk taking behaviour in crowded settings is a prime example of these areas. Clearly, the success of policies related to physical distancing in pedestrian facilities rests on the adherence rate of the crowd members. Therefore, it is important to determine factors that increase or decrease the adherence rate (Drury et al., 2021a). For example, does the adherence vary depending on the nature of the crowd, i.e., whether the crowd has gathered for a common purpose such as supporting a sport team or watching a concert or participating at a political rally? There is evidence suggesting that the extent to which crowd members act safely may depend on the group definition and social norms (Stott et al., 2001; Templeton, 2021), which highlights the importance of group processes in understanding risky behaviour. Research has shown that group processes at crowd events are core to the understanding of safe behaviour, such as how perceived risk is attenuated by ingroup relations (Cruwys et al., 2021). In fact, there exists much useful social psychology knowledge pertinent to crowd management to be adopted and further pursued by crowd researchers with respect to pandemic research and risk avoidance in crowded spaces. For example, social psychology experiments have shown that members of a group who share a social identity often perceived attenuated feeling of disgust towards one another's smell of sweat compared to outgroup members (Reicher et al., 2016). This has relevance to how or why group members may engage in more instances of risky behaviour within their group and may perceive lesser risk of catching diseases from members of their social group than from outsiders. As such, the differentiation between the nature of the crowd and their associated level of adherence to physical distancing and other disease prevention measures is an important one. It is a distinction that simulation models also need to make and a factor to be taken into consideration for risk estimation purposes using such models. Interested readers may also refer to the work of Drury et al. (2021b) on how perceived crowdedness is mediated by social identities. Topics of this nature could potentially be investigated using both survey methods (i.e., self-reported questionnaires) as well as field observations and constitutes an important area where crowd psychology can enrich numerical modelling research subdomain of crowd dynamics.

Equally important is also investigating interventional methods that can increase adherence of crowd members to disease prevention measures (Neville et al., 2021). In a previous article (Haghani, 2020c), when discussing potential avenues of crowd optimisation during emergency evacuations, I elaborated on the method of 'behavioural intervention' or 'behavioural optimisation' and the necessity that the crowd research focuses more on such prescriptive/normative approaches as opposed to pure descriptive approaches in scholarly investigations. Now, in the face of the current pandemic, the same concept has become even more applicable to the optimisation and management of crowds.

For years, crowd researchers have also focused on the role of social influence in emergency evacuation behaviour. As a result of that line of research a rich literature has accumulated on how 'peer behaviour' (Prentice et al., 2020) influences evacuation decision-making of individuals. The global pandemic could be a good reason to salvage the theories, data collection methods and modelling methods in those areas and adopt them for this new problem at hand, i.e., peer influence on crowd behaviour under physical distance measures and its effect on individual adherence.

While on the topic of psychological theories and their applications in pandemic-related crowd research, we may also note the fact that the misuse of certain theories that had become prevalent in pre-pandemic crowd research (Haghani et al., 2019) has also continued to pandemic-related research too (i.e., the so-called notions of crowd 'panic' and 'irrational' behaviour) (Malebary and Basori, 2021; Zhao et al., 2021). This is evidenced by statements and conclusions such as "Panic situations increase disease transmission in crowded areas despite social distancing" (Bouchnita and Jebrane, 2020) (p. 6) or, "keeping a distance from everyone becomes hard when an individual is moving inside a crowd of panicking people" (Bouchnita and Jebrane, 2020) (p. 7). Therefore, another potential line of research could be investigating and dissecting these misconceptions within pandemic-related crowd literature (Bavel et al., 2020). A new dimension that has been introduced by the pandemic itself to this domain is the notion of so-called 'panic-buying' behaviour (Prentice et al., 2020). Crowd researchers have conventionally taken great interest in the behaviour of crowds during emergencies. However, and rather surprisingly, no investigation has thus far been conducted on behaviour of shoppers during those so-called 'panic-buying' episodes[5]. It can be argued that this is just an example of crowd behaviour under emergency, though not an acute form of emergency. Acquisition of field data from supermarkets can shed light on the behaviour of crowd during such episodes and could become a rare opportunity to examine these controversial crowd theories using objective evidence provided by real-world behavioural data. Did the behaviour of shoppers reflect any characteristics of what a lay person often describes as 'panic' behaviour?[6] Was such behaviour prevalent or rare? Were there more instances of risky behaviour detectable by shoppers during such episodes? In general, how can the state of mind, behaviour and decision-making of shoppers be described during such episodes? These and many more questions of this nature could all constitute unexplored grounds for crowd researchers.

7. Potential pandemic-related crowd research avenues in the computer-vision and AI domain

In a previous article (Haghani, 2021), it was determined that the computer vision subdomain of crowd research is a highly active and dynamics subdomain of this field, and yet, one that is conceptually isolated from the mainstream of this research. It was pointed out that one of the potential ways for avoiding topic stagnation and making meaningful paradigm shifts in crowd research lies within collaborations of modellers and experimenters with computer vision researchers of crowd dynamics. The Covid-19 pandemic has also further highlighted the importance of this domain in furthering the state of knowledge in crowd dynamics and broadening horizons of this research.

Researchers of this subdomain predominantly apply Artificial Intelligence (AI) and Machine Learning (ML) methods (Durr et al., 2022; Elbishlawi et al., 2021; Jarraya et al., 2021; Zuo et al., 2021) to crowd field observations obtained from optical cameras, optical sensors and occasionally Wifi sensors (Zakaria et al., 2020). The most evident

[5] As a reviewer rightly pointed out, this could be largely because shopping crowds are considered by most crowd psychologists to be physical crowds (i.e., unrelated people or small groups who happens to be there are the same time) in comparison to psychological crowds (i.e., people who share a feeling of being part of the same group).

[6] Or, is it even justified to describe rush of demand to purchase essential goods as 'panic buying'?

pandemic-related research ground that can be within the purview of this particular domain is the problem of Visual Physical Distancing, defined as automatic estimation of inter-individual distances (as well as the characteristics of the detected individuals) from video cameras and other imaging sensors (Cristani et al., 2020; Shao et al., 2021; Su et al., 2021). This can provide a largely non-invasive method for determining compliance of people within crowds with physical distancing restrictions, whereby determining potential hotspots for distancing breaches. However, it has to be noted that this constitutes a problem beyond merely estimating geometrical distances (Su et al., 2021). Such image processing task will entail inferring complex social aspects from the scene including distinctions between social groups (e.g., family members) and unaffiliated individuals (Cristani et al., 2020; Pouw et al., 2020). Visual Physical Distancing research may itself require investigations on ethical and privacy policies. Such methods can also potentially be used for crowd management purposes in the form of automatic real-time surveillance and warning systems, i.e., systems that can produce auditory or visual signals to crowd members when violations of distancing are detected (Cong et al., 2020; Elbishlawi et al., 2021; Yang et al., 2021). Applications of computer vision methods in this area could also extend to the detection of unmasked faces within crowds and that can also provide further automatic real-time systems for crowd management (Amin et al., 2021). A particular advantage that computer vision methods can offer to crowd researchers is the possibility of making before and after crowd behaviour analyses in relation to Covid-19 (Szczepanek, 2020). In many circumstances, CCTV footage do exist in comparable settings for both before and after the onset of the pandemic and that can provide a rich ground for investigating crowd movement and the behavioural changes that have occurred over time as a result of the pandemic. So far, only a few studies have reported on such before-after analyses (Almutairi et al., 2022; Li and Xu, 2021; Lu et al., 2021; Pouw et al., 2020).

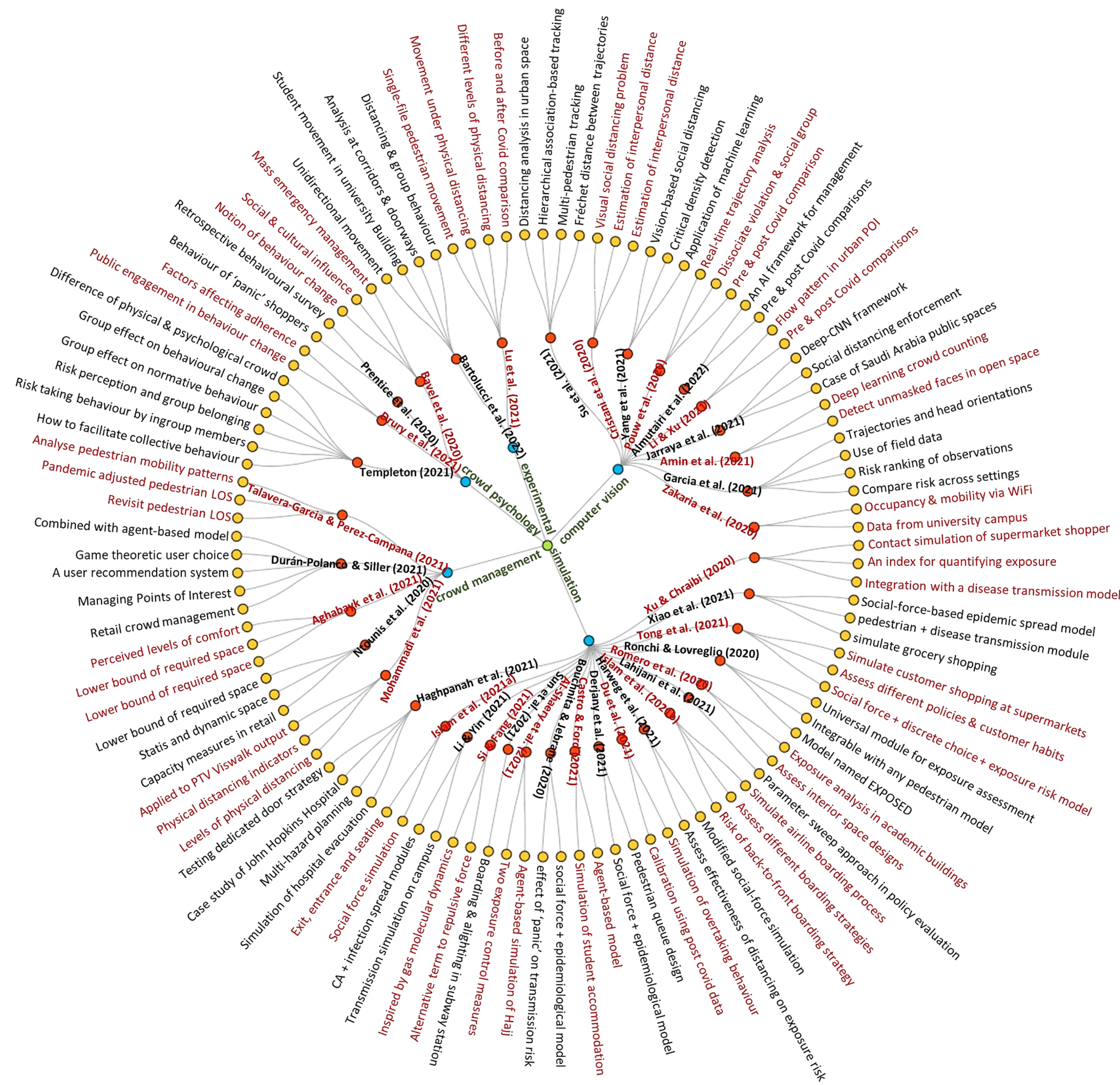

Fig. 2. Crowd dynamics research in the era of pandemic.

Fig. 2 summarises and categorises studies that have emerged in relation to the pandemic in the crowd dynamics literature during 2020 and 2021. For each study, two to four dot points have been extracted as highlights to summarise its content. Alteration of the font colours in the outer layer is merely meant to increase readability and facilitate the distinction between highlights related to adjacent papers on the plot.

8. Discussions and conclusions

With the movement of people in public spaces and buildings being at the centre of attention since the onset of the Covid-19 pandemic, it would have been expected that the pandemic would make the field of crowd dynamics an even more relevant domain than before (Haghani et al., 2020a). However, several indicators point to the contrary, suggesting that the pandemic has caused a notable loss of momentum to this field. At this stage, one can only speculate about why activities of this field might have slowed down during 2020 and 2021. One particular reason could be the shutting down of university campuses and in-person activities that would have naturally put an obstacle on the way of experimental work. As demonstrated in a previous work, experimental research of crowd dynamics has been the one of the most active research streams of this field during the pre-pandemic years and an interruption to this line of research would have naturally reflected as a notable decline in the activities of the field, in general. Although this cannot be the sole reason for this problem and there may be other factors involved too.

What is clear, however, is that this loss of momentum cannot be because crowd research is becoming any less relevant as a result of the pandemic. Despite efforts in mitigation of crowding during periods of restriction, mass gatherings have continued, crowd incidents have not stopped and building fires and other forms of emergencies have kept happening. In fact, the pandemic itself has added new types of congregations in the form of 'anti-lockdown' protests. Therefore, traditional topics of crowd dynamics have all retained their importance. Also, while this may sound like wishful thinking at this stage, there will be a post pandemic time and it is important that the conventional topics of crowd dynamics are not completely abandoned during this transitional time.

The far-reaching impacts of the pandemic, however, have opened new problems that can be addressed by crowd researchers. In a previous publication, it was noted that although this field has been increasingly active and expanding at least in terms of the quantity of publications, there were signs of stagnation in the state of the knowledge. This was caused mainly by the fact that a great portion of studies were becoming repetitive and major innovations were becoming scarce (Haghani, 2021). Now, one can argue that the myriad of issues that have been the creation of the Covid-19 pandemic could offer ways out of such state of stagnation in this field. There seems to be a need for revisiting many of our numerical simulation models and their assumptions and structures and for expanding their applications to issues such as disease prevention risk in public places. This could indeed be a new chapter in this field. Prior to the Covid pandemic, to the best of my knowledge, there has only been a single study in crowd dynamics that had considered this dimension (Johansson and Goscè, 2014)[7]. Perhaps this also could be an opportunity for some forward thinking in our modellings to lay out even more generic foundations in our models that can make them usable for future potential pandemics too. This, in fact, can become a standard feature for the new generation of commercial crowd modelling software, i.e., to offer disease transmission risk estimation modules. It would, however, be important to parametrise all aspects of these modules in such a way that makes them versatile and flexible enough for other future diseases and not restrictively specific to characteristics of the current pandemic.

[7] Note that this paper, having been published since 2014, had never been cited until 2020.

In the previous publication (Haghani, 2021), it was also suggested that another potential way out of stagnation in crowd dynamics lies within more collaborations between computer vision scientists and mainstream researchers of this field (modellers and experimenters). The pandemic has further highlighted this need. While experiments are hard to undertake at the moment, quasi-experiments and field data could be an opportune alternative. In gathering such data, the role of computer vision methods will be more important than ever. Efforts of computer vision scientists are often focused on developing methods that can enhance and maximise information extracted from video images. Their investigations may not necessarily extend to behavioural aspects of crowds. The behavioural researchers of crowd dynamics, on the other hand, are equipped with expertise of inferring crowd behaviour and modelling it, but their capabilities in image processing may be limited. The field of crowd dynamics can majorly benefit from and be enriched by joint utilisation of the expertise of these two groups, particularly during the pandemic era where the role of field data has become crucial.

As mentioned in the previous sections, the pandemic and post-pandemic environment provide a testing ground for re-evaluating established theories. In that sense and in light of the existing published research efforts, I found that a major element that has not been embraced considerably by pandemic-related studies (except a few) is making before and after comparisons of pedestrian motion and decision-making behaviour in reference to the onset of the pandemic or the periods of peaks and troughs in the prevalence of the disease. There is an abundance of experimental data on various aspects of pedestrian motion collected prior to the pandemic that can be used as comparison benchmark (Boltes et al., 2020; Haghani et al., 2020b). Similarly, certain research groups have been gathering field data archives of pedestrian motion that continuing from pre to post-Covid-19 onset (Pouw et al., 2020). These data gathering efforts could all open opportunities for investigating how the motion and behaviour of pedestrians have changed, if any, during the pandemic era, while this also feeds directly into the assumptions that we need to revisit for developing new generations of crowd simulation models. In undertaking such lines of enquiries, the expertise of computer vision scientists can considerably enrich the amount of information that can be extracted from field or quasi-experimental data.

The presented analyses of the trends in crowd dynamics in this work highlights the fact that ethical issues about possible exposing people to covid are preventing much potential research at the time of pandemic. For the field to progress, it needs to overcome additional constraints placed on human trials such as physical distancing and emerging ethical issues associated with performing physical trials. However, and despite these obstacles, the extent of research problems that have been created by the current pandemic is such that, regardless of the subdomain that crowd researchers identify with, there are a broad range of novel and unexplored research questions to tackle. Embracing these opportunities will help the field resume its activities and regain its momentum while also adding new dimensions to the field and expanding its horizons.

CRediT authorship contribution statement

Milad Haghani: Writing – original draft, Writing – review & editing, Visualization, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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References

Abdul Salam, P.S., Bock, W., Klar, A., Tiwari, S., 2021. Disease contagion models coupled to crowd motion and mesh-free simulation. Math. Models Methods Appl. Sci. 31, 1277–1295.

Aghabayk, K., Esmailpour, J., Shiwakoti, N., 2021. Effects of COVID-19 on rail passengers' crowding perceptions. Transportation Research Part A: Policy and Practice 154, 186–202.

Al-Shaery, A.M., Hejase, B., Tridane, A., Farooqi, N.S., Al Jassmi, H., 2021. Agent-Based Modeling of the Hajj Rituals with the Possible Spread of COVID-19. Sustainability 13.

Alam, M.J., Habib, M.A., Holmes, D., 2022. Pedestrian movement simulation for an airport considering social distancing strategy. Transp. Res. Interdiscip. Perspect. 13, 100527.

Almutairi, M.M., Yamin, M., Halikias, G., Sen, A., Ahmed, A., 2022. A Framework for Crowd Management during COVID-19 with Artificial Intelligence. Sustainability 14, 303.

Amin, P.N., Moghe, S.S., Prabhakar, S.N., Nehete, C.M., Ieee, 2021. Deep Learning Based Face Mask Detection and Crowd Counting, 6th International Conference for Convergence in Technology (I2CT), Electr Network.

Bartolucci, A., Templeton, A., Bernardini, G., 2022. How distant? An experimental analysis of students' COVID-19 exposure and physical distancing in university buildings. Int. J. Disaster Risk Reduct. 70, 102752.

Bavel, J.J.V., Baicker, K., Boggio, P.S., Capraro, V., Cichocka, A., Cikara, M., Crockett, M. J., Crum, A.J., Douglas, K.M., Druckman, J.N., Drury, J., Dube, O., Ellemers, N., Finkel, E.J., Fowler, J.H., Gelfand, M., Han, S., Haslam, S.A., Jetten, J., Kitayama, S., Mobbs, D., Napper, L.E., Packer, D.J., Pennycook, G., Peters, E., Petty, R.E., Rand, D. G., Reicher, S.D., Schnall, S., Shariff, A., Skitka, L.J., Smith, S.S., Sunstein, C.R., Tabri, N., Tucker, J.A., Linden, S.v.d., Lange, P.v., Weeden, K.A., Wohl, M.J.A., Zaki, J., Zion, S.R., Willer, R., 2020. Using social and behavioural science to support COVID-19 pandemic response. Nature Human Behaviour 4, 460-471.

Boltes, M., Holl, S., Seyfried, A., 2020. Data archive for exploring pedestrian dynamics and its application in dimensioning of facilities for multidirectional streams. Collective dynamics 5, 17–24.

Bouchnita, A., Jebrane, A., 2020. A hybrid multi-scale model of COVID-19 transmission dynamics to assess the potential of non-pharmaceutical interventions. Chaos, Solitons Fractals 138.

Brzezińska, D., Barański, M., Bryant, P., Haznar-Barańska, A., 2022. The safe evacuation of persons from a building operating within COVID-19 restrictions. Build. Serv. Eng. Res. Technol. 01436244221074542.

Castro, D.A., Ford, A., 2021. 3D Agent-Based Model of Pedestrian Movements for Simulating COVID-19 Transmission in University Students. ISPRS Int. J. Geo-Inf. 10.

Cong, C., Yang, Z., Song, Y., Pagnucco, M., 2020. Towards Enforcing Social Distancing Regulations with Occlusion-Aware Crowd Detection, 2020 16th International Conference on Control, Automation, Robotics and Vision (ICARCV). IEEE, pp. 297-302.

Cristani, M., Del Bue, A., Murino, V., Setti, F., Vinciarelli, A., 2020. The visual social distancing problem. IEEE Access 8, 126876–126886.

Cruwys, T., Stevens, M., Donaldson, J.L., Cárdenas, D., Platow, M.J., Reynolds, K.J., Fong, P., 2021. Perceived COVID-19 risk is attenuated by ingroup trust: evidence from three empirical studies. Bmc Public Health 21, 869.

Derjany, P., Namilae, S., Srinivasan, A., 2021. Parameter Space Exploration in Pedestrian Queue Design to Mitigate Infectious Disease Spread. J. Indian Inst. Sci. 101, 329–339.

Drury, J., Carter, H., Ntontis, E., Guven, S.T., 2021a. Public behaviour in response to the COVID-19 pandemic: understanding the role of group processes. BJPsych open 7.

Drury, J., Rogers, M.B., Marteau, T.M., Yardley, L., Reicher, S., Stott, C., 2021. Re-opening live events and large venues after Covid-19 'lockdown': Behavioural risks and their mitigations. Saf. Sci. 139, 105243.

Du, B., Zhang, C., Shen, J., Zheng, Z.D., 2021. A Dynamic Sensitivity Model for Unidirectional Pedestrian Flow With Overtaking Behaviour and Its Application on Social Distancing's Impact During COVID-19. Ieee Transactions on Intelligent Transportation Systems.

Durán-Polanco, L., Siller, M., 2021. Crowd management COVID-19. Annual Reviews in Control 52, 465–478.

Durr, E.N., Qamar, A.M., Khan, R.U., Albattah, W., Khan, K., Habib, S., Islam, M., 2022. Sparse Crowd Flow Analysis of Tawaaf of Kaaba During the COVID-19 Pandemic. Computers Materials and Continua, pp. 5581–5601.

Echeverría-Huarte, I., Garcimartín, A., Hidalgo, R., Martín-Gómez, C., Zuriguel, I., 2021a. Estimating density limits for walking pedestrians keeping a safe interpersonal distancing. Sci. Rep. 11, 1–8.

Echeverría-Huarte, I., Garcimartín, A., Parisi, D., Hidalgo, R., Martín-Gómez, C., Zuriguel, I., 2021b. Effect of physical distancing on the speed–density relation in pedestrian dynamics. J. Stat. Mech: Theory Exp. 2021, 043401.

Elbishlawi, S., Abdelpakey, M.H., Shehata, M.S., 2021. SocialNet: Detecting Social Distancing Violations in Crowd Scene on IoT devices, 2021 IEEE 7th World Forum on Internet of Things (WF-IoT). IEEE 801–806.

Espitia, E., Gorrini, A., Vacca, A., Deponte, D., Sarvi, M., 2022. How COVID-19 is Affecting Pedestrian Modeling and Simulation: The Case of Venice. Transp. Res. Rec. https://doi.org/10.1177/03611981221088224.

Garcia, W., Mendez, S., Fray, B., Nicolas, A., 2021. Model-based assessment of the risks of viral transmission in non-confined crowds. Saf. Sci. 144.

Haghani, M., 2020a. Empirical methods in pedestrian, crowd and evacuation dynamics: Part I. Experimental methods and emerging topics. Saf. Sci. 129, 104743.

Haghani, M., 2020b. Empirical methods in pedestrian, crowd and evacuation dynamics: Part II. Field methods and controversial topics. Saf. Sci. 129, 104760.

Haghani, M., 2020c. Optimising crowd evacuations: Mathematical, architectural and behavioural approaches. Saf. Sci. 128, 104745.

Haghani, M., 2021. The knowledge domain of crowd dynamics: Anatomy of the field, pioneering studies, temporal trends, influential entities and outside-domain impact. Physica A 580, 126145.

Haghani, M., Bliemer, M.C., Goerlandt, F., Li, J., 2020a. The scientific literature on Coronaviruses, COVID-19 and its associated safety-related research dimensions: A scientometric analysis and scoping review. Saf. Sci. 129, 104806.

Haghani, M., Cristiani, E., Bode, N.W., Boltes, M., Corbetta, A., 2019. Panic, irrationality, and herding: three ambiguous terms in crowd dynamics research. J. Adv. Transp. https://doi.org/10.1155/2019/9267643.

Haghani, M., Sarvi, M., 2018. Crowd behaviour and motion: Empirical methods. Transportation research part B: methodological 107, 253–294.

Haghani, M., Sarvi, M., Shahhoseini, Z., 2020b. Evacuation behaviour of crowds under high and low levels of urgency: Experiments of reaction time, exit choice and exit-choice adaptation. Saf. Sci. 126, 104679.

Haghpanah, F., Ghobadi, K., Schafer, B.W., 2021. Multi-hazard hospital evacuation planning during disease outbreaks using agent-based modeling. Int. J. Disaster Risk Reduct. 66.

Harweg, T., Bachman, D., Weichert, F., 2021. Agent-based simulation of pedestrian dynamics for exposure time estimation in epidemic risk assessment. Journal of Public. Health-Heidelberg.

Islam, M.T., Jain, S., Chen, Y.J., Chowdhury, B.D.B., Son, Y.J., 2021a. An Agent-Based Simulation Model to Evaluate Contacts, Layout, and Policies in Entrance, Exit, and Seating in Indoor Activities Under a Pandemic Situation. Ieee Transactions on Automation Science and Engineering.

Islam, T., Lahijani, M.S., Srinivasan, A., Namilae, S., Mubayi, A., Scotch, M., 2021b. From bad to worse: airline boarding changes in response to COVID-19. Royal Society Open Science 8.

Jarraya, S.K., Alotibi, M.H., Ali, M.S., 2021. A Deep-CNN Crowd Counting Model for Enforcing Social Distancing during COVID19 Pandemic: Application to Saudi Arabia's Public Places. Cmc-Computers Materials & Continua 66, 1315–1328.

Johansson, A., Goscè, L., 2014. Utilizing crowd insights to refine disease-spreading models, Pedestrian and Evacuation Dynamics 2012. Springer 1395–1403.

Kowalewski, M., 2021. Street protests in times of COVID-19: adjusting tactics and marching 'as usual'. Social Movement Studies 20, 758–765.

Lahijani, M.S., Gayatri, R., Islam, T., Srinivasan, A., Namilae, S., 2021. Architecture-Aware Modeling of Pedestrian Dynamics. J. Indian Inst. Sci. 101, 341–356.

Li, C.Y., Yin, J., 2021. A pedestrian-based model for simulating COVID-19 transmission on college campus. Transportmetrica a-Transport. Science.

Li, Y.H., Xu, L.Y., 2021. The Impact of COVID-19 on Pedestrian Flow Patterns in Urban POIs-An Example from Beijing. ISPRS Int. J. Geo-Inf. 10.

Lu, T.T., Zhao, Y.X., Wu, P., Zhu, P.F., 2021. Dynamic analysis of single-file pedestrian movement with maintaining social distancing in times of pandemic. Journal of Statistical Mechanics-Theory and Experiment 2021.

Malebary, S.J., Basori, A.H., 2021. Reinforcement learning for Pedestrian evacuation Simulation and Optimization during Pandemic and Panic situation. J. Physics: Conference Series. IOP Publishing, 012008.

Markotić, A., Capak, K., 2020. Earthquake in the time of COVID-19: The story from Croatia (CroVID-20). J. Global Health 10.

Mayr, C.M., Köster, G., 2020. Social distancing with the optimal steps model. arXiv preprint arXiv:2007.01634.

Mohammadi, A., Chowdhury, M.T.U., Yang, S., Park, P.Y., 2021. Developing levels of pedestrian physical distancing during a pandemic. Saf. Sci. 134, 105066.

Neville, F.G., Templeton, A., Smith, J.R., Louis, W.R., 2021. Social norms, social identities and the COVID-19 pandemic: Theory and recommendations. Soc. Pers. Psychol. Compass 15, e12596.

Ntounis, N., Mumford, C., Lorono-Leturiondo, M., Parker, C., Still, K., 2020. How safe is it to shop? Estimating the amount of space needed to safely social distance in various retail environments. Safety science 132.

Parisi, D.R., Patterson, G.A., Pagni, L., Osimani, A., Bacigalupo, T., Godfrid, J., Bergagna, F.M., Brizi, M.R., Momesso, P., Gomez, F.L., 2022. Physical distance characterization using pedestrian dynamics simulation. Papers in Physics 14, 140001-140001.

Pouw, C.A.S., Toschi, F., van Schadewijk, F., Corbetta, A., 2020. Monitoring physical distancing for crowd management: Real-time trajectory and group analysis. PLoS ONE 15.

Prentice, C., Quach, S., Thaichon, P., 2020. Antecedents and consequences of panic buying: The case of COVID-19. Int. J. Consumer Studies.

Reicher, S.D., Templeton, A., Neville, F., Ferrari, L., Drury, J., 2016. Core disgust is attenuated by ingroup relations. Proc. Natl. Acad. Sci. 113, 2631–2635.
Romero, V., Stone, W.D., Ford, J.D., 2020. COVID-19 indoor exposure levels: An analysis of foot traffic scenarios within an academic building. Transportation Res. Interdisciplinary Perspectives 7, 100185.
Ronchi, E., Lovreglio, R., 2020. EXPOSED: An occupant exposure model for confined spaces to retrofit crowd models during a pandemic. Safety science 130.
Ronchi, E., Lovreglio, R., Scozzari, R., Fronterrè, M., 2020a. Use of Crowd Evacuation Models in Times of Pandemic. SFPE Europe.
Ronchi, E., Scozzari, R., Fronterrè, M., 2020b. A risk analysis methodology for the use of crowd models during the covid-19 pandemic. LUTVDG/TVBB.
Shao, Z., Cheng, G., Ma, J., Wang, Z., Wang, J., Li, D., 2021. Real-time and accurate UAV pedestrian detection for social distancing monitoring in COVID-19 pandemic. IEEE Trans. Multimedia.
Si, X.Y., Fang, L., 2021. A novel social distance model reveals the sidewall effect at bottlenecks. Sci. Rep. 11.
Stott, C., Hutchison, P., Drury, J., 2001. 'Hooligans' abroad? Inter-group dynamics, social identity and participation in collective 'disorder'at the 1998 World Cup Finals. Br. J. Soc. Psychol. 40, 359–384.
Su, J., He, X.H., Qing, L.B., Niu, T., Cheng, Y.Q., Peng, Y.H., 2021. A novel social distancing analysis in urban public space: A new online spatio-temporal trajectory approach. Sustainable Cities Society 68.
Sun, L.S., Yuan, G., Yao, L.Y., Cui, L., Kong, D.W., 2021. Study on strategies for alighting and boarding in subway stations. Physica a-Statistical Mechanics Its Applications 583.
Szczepanek, R., 2020. Analysis of pedestrian activity before and during COVID-19 lockdown, using webcam time-lapse from Cracow and machine learning. PeerJ 8, e10132.
Talavera-Garcia, R., Perez-Campana, R., 2021. Applying a Pedestrian Level of Service in the Context of Social Distancing: The Case of the City of Madrid. Int. J. Environ. Res. Public Health 18.
Templeton, A., 2021. Future research avenues to facilitate social connectedness and safe collective behavior at organized crowd events. Group Processes & Intergroup Relations 24, 216–222.
Tong, Y.H., King, C., Hu, Y.H., 2021. Using agent-based simulation to assess disease prevention measures during pandemics*. Chin. Phys. B 30.
Xiao, T., Mu, T., Shen, S., Song, Y., Yang, S., He, J., 2022. A dynamic physical-distancing model to evaluate spatial measures for prevention of Covid-19 spread. Physica A 592, 126734.
Xiao, Y., Yang, M.F., Zhu, Z., Yang, H., Zhang, L., Ghader, S., 2021. Modeling indoor-level non-pharmaceutical interventions during the COVID-19 pandemic: A pedestrian dynamics-based microscopic simulation approach. Transp. Policy 109, 12–23.
Xu, Q.C., Chraibi, M., 2020. On the Effectiveness of the Measures in Supermarkets for Reducing Contact among Customers during COVID-19 Period. Sustainability 12.
Yang, D., Yurtsever, E., Renganathan, V., Redmill, K.A., Özgüner, Ü., 2021. A vision-based social distancing and critical density detection system for COVID-19. Sensors 21, 4608.
Yazdani, M., Mojtahedi, M., Loosemore, M., Sanderson, D., Dixit, V., 2021. Hospital evacuation modelling: A critical literature review on current knowledge and research gaps. Int. J. Disaster Risk Reduct. 66, 102627.
Zakaria, C., Trivedi, A., Cecchet, E., Chee, M., Shenoy, P., Balan, R., 2020. Analyzing the impact of covid-19 control policies on campus occupancy and mobility via passive wifi sensing. arXiv preprint arXiv:2005.12050.
Zhao, R., Jia, P., Wang, Y., Li, C., Ma, Y., Zhang, Z., 2021. Dynamic propagation model of crowd panic based on Shanoon's entropy theory under COVID-19 epidemic situation, 2021 IEEE 5th Advanced Information Technology, Electronic and Automation Control Conference (IAEAC). IEEE 1720–1724.
Zuo, F., Gao, J., Kurkcu, A., Yang, H., Ozbay, K., Ma, Q., 2021. Reference-free video-to-real distance approximation-based urban social distancing analytics amid COVID-19 pandemic. J. Transp. Health 21, 101032.