The Influence of 3D Motions on the Efficiency of Children's Indoor Evacuations

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Abstract

During emergency evacuations, children sometimes adopt three-dimensional (3D) motions, such as crawling close to the ground or climbing up/down to obstacles, to pass through restricted spaces or in situations of heightened urgency. Examining how these motions affect children's evacuation performance is essential for designing effective behavioural instructions. The present study examines the influence of 3D motions on the efficiency of children's indoor evacuations. A simulation framework is applied, combining a voxel-based 3D indoor representation with an agent-based behavioural model. Detailed scenarios are elaborated to account for different agent numbers, urgency levels, and physical attributes. The work is presented as an exploratory case study, not as a validated replication of real-world evacuation drills. The results indicate: 1) The use of 3D motions is relatively low across all urgency levels and agent numbers. 2) The number of agents moving above or below indoor objects slightly increases with higher urgency and more agents. 3) 3D motions may not significantly influence children's evacuation efficiency due to minor congestion as well as limited use and lower speeds of 3D motions. We recommend refining behavioural instructions by: 1) restricting 3D motions in low-density conditions . 2) Conditional use of 3D motions when local congestion significantly hinders direct evacuation paths. 3) Conduct evacuation exercises tailored to children's physical and cognitive abilities under specific scenarios. The study contributes to short-term evacuation strategies as well as long-term preparedness and training programmes for children.

1. Introduction

During emergency evacuations in response to fires, earthquakes, or other hazards, children represent one of the most at-risk populations due to their limited physical capabilities, cognitive development, and reliance on adult instructions (Bahmani et al. 2023). Under low-urgency conditions, children typically evacuate by moving upright along floors, stairways, and ramps. However, when space is restricted or urgency increases, they may adopt 3D motions. For instance, documented school evacuations have shown children crawling under tables in schools (Xie et al. 2022a).

3D motions in evacuations involve both 3D movements and height-related 3D actions. 3D movements include walking upright on movable or dynamic objects (e.g., tables, chairs), bent-over walking, knee-and-hand crawling, and low crawling. 3D actions involve stepping up/down, jumping up/down, and climbing up/down (Xie et al., 2023). Analysing the impact of these motions on children's evacuation performance is important for designing practical behavioural instructions, especially in settings with dense furniture and intricate layouts like classrooms, dining halls, or canteens.

The body of research on children's evacuations has significantly expanded, encompassing both empirical data and simulation models. Regarding empirical data, some studies have investigated the differences in evacuation time and speed among children across various evacuation scenarios (Gu et al. 2016), thereby contributing to the development of comprehensive databases on children's evacuations (Najmanová and Ronchi 2017, Hamilton et al. 2017). These investigations primarily utilised video footage obtained from actual evacuations or controlled evacuation drills. Their main contribution has been the quantitative investigation of pre-evacuation delay, movement duration, and velocity, as well as the influence of demographic factors such as age and gender (Bahmani et al. 2023).

In terms of simulation models, the literature has mainly focused on three core areas: (1) the influence of indoor environments on children's evacuation efficiency (Zhu and Yang 2010); (2) the influence of individual characteristics and interactions on evacuation time and speed (Yao and Lu 2021); and (3) the interplay between indoor environments and individual behaviours (Liu et al. 2016). Among these studies, agent-based and cellular automata (CA) modelling have emerged as the most commonly adopted approaches (Bahmani et al. 2023). However, these studies primarily focus on walking upright, with limited attention given to more complex 3D motions.

To fill this gap, the present study examines how 3D motions affect children's evacuation performance through a simulation-based framework. Unlike empirical experiments with children or analogies drawn from animal behaviour, simulations provide a safer and more flexible means of evaluating evacuation conditions. Real-world trials involving children are constrained by cost, time, and ethical concerns, particularly when emergency scenarios must be replicated. Simulation techniques, by contrast, allow researchers to construct a wide range of "what-if" scenarios, making it possible to analyse evacuation processes systematically under different crowd densities, exit configurations, or hazard distributions (Chen et al. 2021, Xie et al. 2025a, Xie et al. 2025b).

This research employs a previously developed simulation framework that combines a voxel-based 3D indoor representation with an agent-based behavioural model. Through detailed scenarios that account for agent numbers, perceived urgency levels (PULs), and physical attributes, the study addresses three core questions: 1) In what ways do children perform 3D motions during evacuations? 2) How would 3D motions influence children's evacuation efficiency? 3) What behavioural instructions can be formulated for children's evacuations that incorporate 3D motions? The analysis should be regarded as an exploratory case study rather than a validated replication of real-world evacuation exercises. Ultimately, the work contributes to immediate response planning, long-term preparedness, and training initiatives tailored for children.

2. Related work

By reviewing prior studies on evacuation simulation and 3D indoor models, we highlight central concepts, methodological trends, and persisting research gaps. This review forms the basis for framing and justifying the present study.

2.1 Evacuation simulation models for 3D motions

A number of studies have integrated 3D motions into evacuation modelling, primarily using social force models, CA models, and agent-based approaches. For example, extensions of the social force model have been used to represent low crawling under fire and smoke (Guo et al. 2021) and to capture motions such as stepping over furniture or small barriers (Liu et al. 2022). Similarly, CA models have been utilised for walking upright, bent-over walking, and knee-and-hand crawling (Zheng et al. 2017). Wang et al. 2020a further developed CA formulations to examine human interactions with obstacles, including climbing over or pushing desks and chairs. In parallel, agent-based approaches have also been introduced. For instance, Tang and Ren 2012 proposed behavioural rules to govern crawling on hands and knees. Xie et al. 2022a further emphasised the capabilities of agent-based models to incorporate diverse 3D motions into individual agents' behavioural repertoires with relative ease.

Studies have identified key limitations in existing evacuation models incorporating 3D motions (Xie et al. 2022a, Xie et al. 2022b). These models have limited representation of the height dimension and navigable spaces above or below indoor objects such as desks or stairways. As a result, vertical movement and its impact on evacuation paths remain underrepresented, and interactions with indoor objects and the decision-making mechanisms behind 3D motions are only partially modelled. To fill these gaps, an enhanced agent-based behavioural model is being developed to capture all 3D motions and their associated behavioural logic within complex indoor environments (Xie et al. 2025a).

2.2 3D indoor models used for evacuation simulations

Effective evacuation simulations require 3D indoor models that integrate semantic, geometric, topological, and attribute information. These models need to capture navigable areas (rooms, corridors), physical structures (walls, slabs, furniture), and access points such as doors and windows (Aleksandrov et al. 2021, Boguslawski et al. 2022). Common data standards for this purpose include Industry Foundation Classes (IFC), CityGML, and IndoorGML. IFC, in particular, supplies core building elements—like spaces, slabs, and doors—that can be leveraged for navigation modelling. Deng et al. 2022 introduced a semantic framework that incorporates obstacle-specific attributes (e.g., footprint, height, material texture) to evaluate bypass potential. Special attention has been given on correct and appropriate representation of navigable spaces (Diakité and Zlatanova 2016, Zlatanova et al. 2020). However, these models do not yet fully account for navigable spaces above or below furniture and stairways, which restricts their applicability for 3D motion modelling.

The *navigable surface* concept has been applied to describe agent-accessible areas, typically represented through either mesh-based surfaces or discrete cell structures. Mesh-based methods, commonly employed in prior research (Kneidl et al. 2013, Kim and Han 2018), are derived from 2D/2.5D geometries (e.g., floor slabs, ramps, stairs) and consist of interconnected triangles, allowing movement in three directions. Yet, they omit regions occupied by physical elements like furniture or overhead structures, rendering such areas non-navigable for 3D motions (Xie et al. 2022b). Cell-based approaches, in contrast, partition interiors into discrete, non-overlapping units such as 2D cells or voxels. While 2D cells, commonly employed in CA and certain agent-based models, can represent elevation and slope (Xiong et al. 2017), but they cannot represent height, which limits their use in simulating 3D actions such as climbing up/down. In contrast, voxels extend cell representations into three dimensions, allowing more detailed modelling of environments, particularly staircases (Wei et al. 2015, Fichtner et al. 2018, Staats et al. 2019). Gorte et al. 2019 applied voxels to define navigable areas on floor slabs and stairs, and some researchers (Xie et al. 2022b, Xie et al. 2023) have showed that voxel models can effectively capture spaces above or beneath objects and describe their spatial connections.

A notable advancement is the automated generation of voxel-based 3D indoor models to support 3D motion simulation (Xie et al. 2024a). These methods classify space into P-spaces (freely navigable), C-spaces (navigable under conditions requiring specific 3D motions), and N-spaces (non-navigable). From these classifications, navigable surfaces are derived from P- and C-spaces, with vertical links introduced to connect surfaces across varying height levels.

3. Methods

Building on previous work (Xie et al. 2022b, Xie et al. 2024a, Xie et al. 2025a, Xie et al. 2025b), the present work applies a simulation framework that combines a voxel-based indoor representation with an agent-based model to reproduce 3D motions. Five assumptions are applied to isolate the specific effect of 3D motions. Subsequently, through a detailed evacuation scenario setup, we examine how such motions influence children's evacuation efficiency under varying conditions of crowd size, PUL, and physical characteristics.

3.1 Simulation models

The simulation of 3D motions is supported by two main elements (Xie et al. 2025a, Xie et al. 2025b):

- A voxel-based representation of the indoor environment, including indoor objects, navigable surfaces, and vertical links.
- An agent-based model governed by predefined rules that regulate each stage of 3D motions.

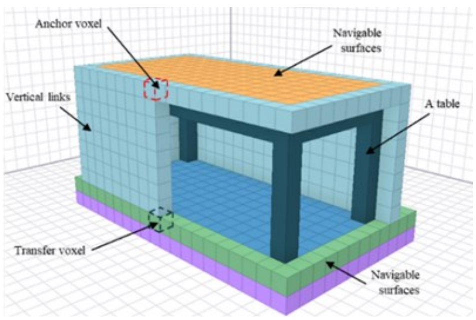


Figure 1. Conceptual illustration of navigable surfaces and connecting vertical links in relation to an M-object (table) (Xie et al. 2025b).

The 3D indoor model has been developed supported by a voxelisation algorithm (Aleksandrov et al. 2022), in which navigable surfaces allow agents to use 3D movements for moving above or below indoor objects (e.g., slabs, desks, stairways), while vertical links connect surfaces at different heights to enable 3D actions, such as jumping up/down (see Figure 1). This model enables the simulation of individuals evacuating from complex indoor environments. This approach overcomes a key drawback of conventional 2D and 2.5D mesh- or cell-based models, which have difficulty representing 3D spatial relationships. Further information on the automated generation process of the voxel-based indoor model is available in the study (Xie et al. 2024a).

Additionally, an agent-based model is developed to determine the conditions under which agents initiate, select locations for, and execute 3D motions. This model is organised into four categories of rules: 1) Initialisation rules – define critical parameters related to 3D motions. 2) Decision-making rules – determine agents' motivation and timing for performing 3D motions. 3) Indoor-agent interaction rules – specify the fine-scale interactions that occur between agents and surrounding objects within 3D space. 4) Agent motion rules – govern the execution and type of 3D motions performed (Xie et al. 2025a).

Because empirical datasets on 3D motions during emergencies are rare—largely due to ethical restrictions and the limited feasibility of involving children—this study relies on simulated scenarios. These scenarios are intended to explore how 3D motions may affect children's evacuation performance and should be regarded as exploratory demonstrations rather than empirical validations.

3.2 Assumptions made for simulations

To simplify the modelling and focus specifically on the role of 3D motions, five assumptions were adopted:

- Agents are considered to have complete awareness of the building design, including exit and corridor locations, thereby eliminating the requirement for exploration or spatial learning (Chen *et al*. 2021).
- No specific hazard scenarios (e.g., fire, earthquake, toxic smoke) are modelled, ensuring that agent behaviour is not altered by external disruptions such as reduced visibility or damaged passages (Lin *et al.* 2020).
- At the onset of the simulation, all agents begin evacuation instantly, with no delays from hesitation, decision processes, or external triggers. This ensures that evacuation times capture only the effects of motion strategies, especially 3D motions (Lin *et al*. 2020).
- Each agent operates independently, receiving no guidance from staff or automated systems, so that route selection reflects autonomous decision-making (Lin et al. 2020).
- All agents are constrained to take the shortest path to the closest exit. This condition ensures that any improvements in efficiency are linked to local 3D motion choices rather than global route reconfiguration (Ronchi 2021).

3.3 Evacuation scenario setup

The building scenario for this investigation is a hall within a teaching building. This hall features two exit doors and is furnished with a variety of movable objects, including tables, chairs, sofas, and boxes. We used the IFC model of the hall, which was created from architectural drawings. Figure 2 presents both the original IFC model and its voxel-based 3D indoor model. Informed by existing studies (Cesari et al. 2003, Taylor et al. 2010, Mououdi et al. 2018, Fryar et al. 2021), Parameters for children's body dimensions and vertical motion thresholds are summarised in Tables 1 and 2 and applied in generating the voxel-based model. A voxel resolution of 15 cm was selected, following an earlier evaluation (Xie et al. 2024b), as a compromise between computational load and spatial detail.

The simulation setup varied both the inclusion of 3D motions and the number of participating agents. Three experimental conditions were specified:

- 50 agents, with and without 3D motions: representing a low-density case akin to off-peak conditions.
- 90 agents, with and without 3D motions: corresponding to a typical moderate crowd level during regular hours.
- 130 agents, with and without 3D motions: describes a densely populated event, characterised by possible bottlenecks at exits.

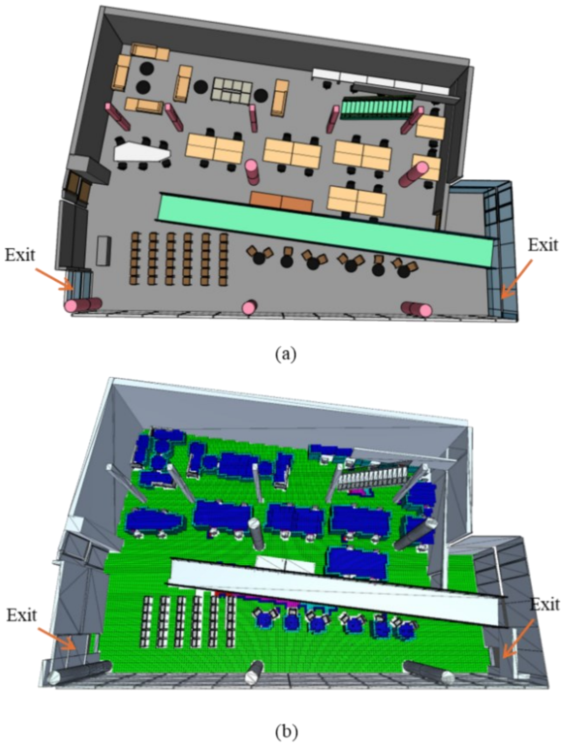


Figure 2. (a) IFC representation of the hall. (b) Corresponding voxel-based 3D indoor model. Colours indicate different navigable surfaces and vertical links: walking upright on floor slabs with step up/down links (green); walking upright on movable objects with jump up/down links (blue); bent-over walking with climb up/down links (cyan); knee-and-hand crawling (magenta); and low crawling (red).

Size of 3D cuboids (cm)	Height	Length	Width
Walking upright	135	30	15
Bent-over walking	90	30	45
Knee-and-hand crawling	45	30	105
Low crawling	30	30	135

Table 1. 3D body sizes for an assumed child.

Vertical motion thresholds (cm)	Stepping up/down	Jumping up/down	Climbing up/down
Maximum height	15	30	60

Table 2. Vertical motion thresholds for an assumed child.

To reflect different levels of urgency, three PUL values (0.3, 0.5, and 0.7) were applied across all sub-scenarios. The PUL scale spans from just above zero to one, with higher scores denoting stronger urgency and lower scores signifying calmer situations. A low PUL of 0.3 was interpreted as a calm response, where agents evacuate at a measured pace. A medium level (PUL = 0.5) reflects a more alert but still controlled evacuation behaviour. A high setting (PUL = 0.7) denotes stressful conditions, prompting agents to accelerate their movements. These distinctions make it possible to explore how the use of 3D motions varies with urgency and how such behaviours might be adapted to different evacuation contexts.

To reflect population diversity, physical variations were incorporated into the simulated agents, ensuring that different body characteristics were represented. The World Health Organisation defines anyone younger than 18 as a child (WHO 2014). Meanwhile, existing studies have categorised childhood specifically into newborns (0 days–1 month), infants (1 month–1 year), toddlers (1–3 years), preschool children (3–6 years), school-aged children (6–12 years), and adolescents (12–18 years) (Bahmani et al. 2023). In this study, we focused specifically on children aged 6–12 years, as they possess a certain independence to evacuate without direct assistance—unlike preschool children—and exhibit physical characteristics distinct from adolescents, whose body sizes may approximate those of adults. A balanced gender ratio was maintained, with equal proportions of boys and girls represented in the agent population.

In the hall scenario, initial agent positions were allocated randomly. Parameter values used in the agent-based model were informed by earlier studies (Helbing et al. 2000, Hamilton et al. 2017, Mououdi et al. 2018, Wang et al. 2020b, Fryar et al. 2021), the modelling assumptions, and iterative verification. Trial-and-error adjustments, supported by observations of 3D motion patterns and visual inspections, were applied to refine agent behaviours. The parameters govern decision-making, mobility limits and capabilities, as well as how agents interact during evacuation. Appendix A provides the full set of parameter values together with their sources and justifications. For instance, twelve parameters specify different walking or crawling speeds, while three govern the probability of undertaking 3D motions.

To reduce stochastic variability and improve statistical reliability, each scenario was simulated fifteen times. After each run, three performance indicators were collected: 1) number of agents engaging in 3D motions, 2) number of agents moving above/below movable objects, and 3) total evacuation time (TET), defined as the interval from the start of evacuation to the exit of the final agent.

4. Results

The prototype simulation system was implemented in Unity 3D, with development carried out in Microsoft Visual Studio 2022. Experiments were executed on a workstation equipped with an Intel® Core™ i7-12700K processor (5.00 GHz), an NVIDIA GeForce RTX 3080 graphics card, and 32 GB of memory.

4.1 Number of agents performing 3D motions

Figure 3 illustrates that engagement in 3D motions remains limited across all PULs and crowd sizes. At low urgency (PUL = 0.3), the large-group scenario recorded the highest involvement (three agents), while the medium and small groups reported only two participants each. At moderate urgency (PUL = 0.5), the large group increased slightly to four agents, but other groups showed no change. At high urgency (PUL = 0.7), participation in the large group stabilised at four agents. The medium group rose modestly to three, while the small group no longer engaged in 3D motions. Across the fifteen simulation repetitions, all 3D motions were performed exclusively by male agents, with no participation observed among female agents.

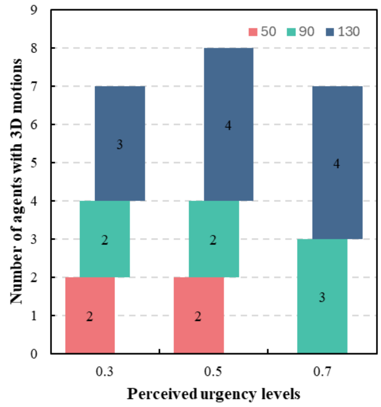
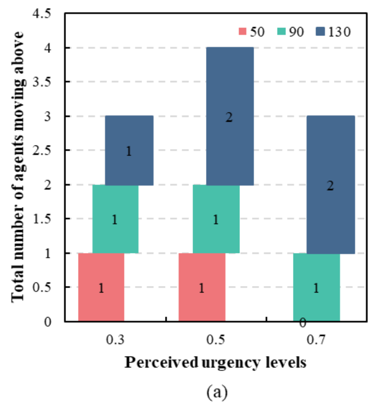


Figure 3. Number of agents engaging in 3D motions.

4.2 Number of agents moving above/below



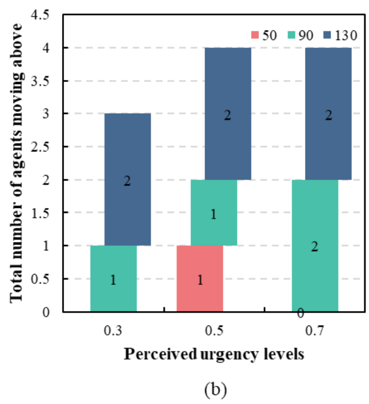


Figure 4. (a) Number of agents moving above movable objects. (b) Number of agents moving below movable objects.

Figure 4a illustrates the participation of agents moving above movable objects. When urgency was low (PUL = 0.3), a single agent in each group engaged in this motion type. At the medium level (PUL = 0.5), the large group showed an increase to two agents using these motions, while the small and medium groups maintained their previous values. Under high urgency (PUL = 0.7), the large group sustained two participants, the medium group dropped to one, and the small group no longer exhibited any moving above. The motions observed consisted primarily of climbing up/down and walking upright across elevated surfaces.

Figure 4b depicts how many agents chose to move below indoor objects at different urgency levels. In the low-urgency condition (PUL = 0.3), this motion was observed in only one agent within the medium-sized group, while the large group involved two agents. When urgency rose to 0.5, the large group again showed two participants, whereas the small and medium groups each had a single agent using this motion. At the highest urgency (PUL = 0.7), the large group maintained two participants, and the medium group increased slightly to two, while the small group exhibited no such motion. In all cases, the primary movement for moving below obstacles was knee-and-hand crawling.

4.3 Total evacuation time

We evaluated how the inclusion of 3D motions influenced the TET under varying crowd sizes and urgency levels. The only distinction between the two experimental settings lies in whether 3D motions were enabled; all other aspects of the evacuation model and parameter configuration were kept consistent across conditions.

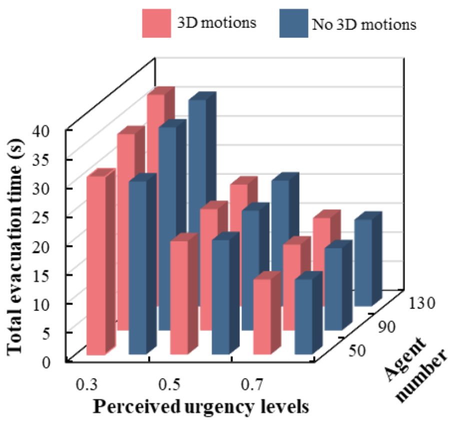


Figure 5. TET across different agent numbers and PUL levels.

As shown in Figure 5, only minor differences in TET were observed across conditions. For the small-group scenario, evacuation times were nearly identical at all urgency levels, with 3D motions providing no measurable benefit (e.g., at PUL = 0.3, 30.55 s with 3D motions versus 29.8 s without). In the medium group, a slight improvement appeared at low urgency, where enabling 3D motions reduced the average time from 34.96 s to 33.8 s, but this effect was not evident at medium or high urgency levels. Likewise, for the large group, the inclusion of 3D motions did not produce shorter TETs across any urgency setting. Overall, these findings suggest that under the present building configuration, 3D motions had little impact on the evacuation efficiency of children.

Given these findings, a critical question emerges: why did 3D motions not significantly influence children's evacuation efficiency under these scenarios? To explore this question, we compared speed variation maps for the scenario with 130 agents at a medium urgency level (PUL = 0.5), under both conditions: with only walking upright and 3D motions enabled (Figures 6a and 6b). We can compare the areas labelled with black circles. Three phenomena can be observed from this analysis. First, congestion around exits and narrow corridors with furniture was relatively minor. This lower congestion level can be attributed to the smaller body dimensions and reduced spatial occupancy of child-sized agents, facilitating smoother evacuation through constrained spaces. Second, only a small number of agents used 3D motions despite the availability of alternative routes provided by furniture in densely occupied areas. The limited use of these motions may stem from the lower speed variations or crowd density. Third, the observed speeds of 3D motions were not higher than that of walking upright despite occurring congestion. For example, walking upright above a table occurred at obviously reduced speeds compared to walking upright on floor slabs. Figures 6c further depicts a screenshot of a simulation where agents climbed up to a table, proceeded with walking upright, and climbed down and presents agent trajectories with speed variations around the table in 3D views.

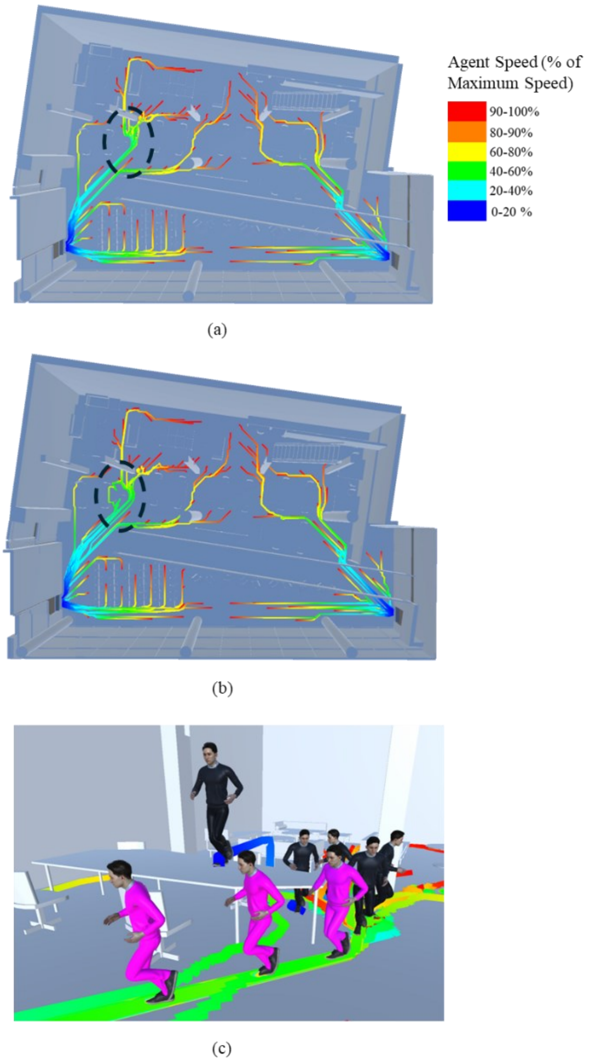


Figure 6. Speed variation maps for the 130-agent scenario at medium urgency (PUL = 0.5) under two conditions: (a) with only walking upright and (b) with 3D motions enabled. (c) Simulation snapshot showing one agent performing climbing up/down and walking upright around a table, together with its 3D trajectories (pink agents represent girls; black agents represent boys).

5. Discussion and conclusions

We investigated the potential influence of 3D motions on the efficiency of children's indoor evacuation. This study should be regarded as an exploratory demonstration, not as a validated replication of real-world evacuation experiments involving 3D motions. The findings are as follows: 1) The use of 3D motions is relatively low across all PULs and agent numbers. 2) The number of agents moving above or below movable objects (e.g., tables) slightly increases as higher PULs and larger agent numbers increase. 3) 3D motions may not significantly influence children's evacuation efficiency due to three possible reasons: a) Congestion around exits and narrow corridors is relatively minor due to child-sized agents' smaller body size and spatial occupancy. b) Few agents used 3D motions due to the lower speed variations or crowd density. c) lower speeds of 3D motions compared to walking upright under minor congestion may not facilitate evacuation efficiency.

Although the results highlight some promising patterns, they stem from specific simulated cases and should therefore be viewed as indicative rather than conclusive. Drawing on these case study outcomes, we recommend pursuing additional behavioural instructions, including: 1) Limit the use of 3D motions in low-density conditions. Children may be instructed to primarily follow conventional evacuation routes when congestion levels are low or moderate, as slower speeds associated with 3D motions may outweigh their potential benefits. 2) Conditional use near congestion points. Instructions may specify that children use 3D motions primarily when local congestion around furniture significantly hinders direct evacuation paths. 3) Conduct evacuation exercises targeted to specific scenarios. Evacuation exercises specifically tailored to children's physical and cognitive abilities may clarify when and how 3D motions should be utilised under specific scenarios, potentially enhancing decision-making during real emergencies.

By investigating how 3D motions influence children's evacuation efficiency, evacuation managers can potentially develop effective behavioural instructions tailored specifically for children. We recognize that some parameters within our simulation framework were established through assumptions and trial evaluations, largely because reliable empirical data on evacuation behaviours remain limited. Even when empirical data exist from specific scenarios, their direct applicability to future evacuations may be limited because each event varies considerably in aspects such as spatial layouts, furniture arrangements, and individual behavioural responses. Future research will address the scarcity of empirical data, such as actual evacuation experiments (Xie et al. 2020, Jiang et al. 2022). Even so, the proposed framework remains highly adaptable, allowing evacuation managers to modify parameters and test a wide range of evacuation scenarios. Consequently, this approach supports the development of adaptive behavioural instructions:

- Conduct controlled evacuation drills with children to generate empirical data on model parameters, strengthening both the validation and reliability of the simulation framework.
- Integrate this approach with dynamic models of exit and path selection and apply simulations within more intricate and diverse indoor spaces, including multi-storey primary schools.
- Explore how personal attributes, including factors like age, gender, affect children's likelihood of adopting 3D motions strategies in evacuation situations.

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Appendix A Parameter values in the agent-based models used for the simulations

Parameters	Quantity	Values for boys	Values for girls
$v_{max}^{i,u}$ (Hamilton et al. 2017)	Maximum speed of walking upright	4 m/s	3.5 m/s
$v_{min}^{i,u}$ (Hamilton et al. 2017)	Minimum speed of walking upright	1 m/s	0.5m/s
$v_{max}^{i,b}$	Maximum speed of bent-over walking	* 3 m/s	* 2 m/s
$v_{max}^{i,k}$ (Wang et al. 2020)	Maximum speed of knee-and-hand crawling	2.5 m/s	1.5m/s
$v_{max}^{i,l}$	Maximum speed of low crawling	* 1.5 m/s	* 1 m/s
v_s^i, v_j^i, v_c^i.(Hamilton et al. 2017)	Speeds of stepping up/down, jumping up/down and climbing up/down	2 m/s	1.5 m/s
α^i, β^i, γ^i, δ^i	Effect weights of PULs on the desired speeds of walking upright, bent-over walking, knee-and-hand crawling, low crawling	* 0.9	* 0.9
$[D_{min}, D_{max}]$	Local density range of other agents to affect if an agent performs 3D motions	* [2, 3.5] ped/m^2	* [3, 4] ped/m^2
R	Radius from an agent's footprint centre to detect other agents	* 0.8 m	* 0.6 m
D_a^i	Density threshold of other ahead agents to affect if an agent performs 3D motions	* 3.5 ped/m^2	* 4 ped/m^2
d_v^i, a_v^i, h_v^i	Distance, angle and eye height of an agent's visibility	* 2.5 m, 120°, 135 cm	* 2.5 m, 120°, 135 cm
$R_{i,m}$	Radius between an agent and an M-object to influence if perform 3D motions	* 1 m	* 0.7 m
w_{min}^i	Threshold of PULs to control if an agent is eligible to perform 3D motions	* 0.3	* 0.3
p_o^i	Probability of performing 3D motions, influenced by other agents around an agent	* 0.5	* 0.4
p_m^i.	Probability of performing 3D motions, influenced by other ahead agents through an agent's visibility	* 0.5	* 0.4
p_d^i	Probability of performing 3D motions, influenced by an agent's minimum desired speed	* 0.5	* 0.4
p_i	Probability of moving up	* 0.4	* 0.4
R_u^i	Radius within which an agent detects another agent moving up.	* 0.4	* 0.5 m
τ_i (Helbing et al. 2000)	Acceleration time of an agent	0.5 s	0.5 s
r_i (Mououdi et al. 2018)	Radius of an agent	0.15 m	0.15m
m_i (Fryar et al. 2021)	Mass of an agent	35 kg	35 kg
A_i (Helbing et al l. 2000)	Parameter for repulsive force of an agent	2000	2000
B_i (Helbing et al. 2000)	Parameter for repulsive force of an agent	0.08	0.08
K (Helbing et al. 2000)	Parameter for squeeze force of an agent	1.2×10^5	1.2×10^5
k (Helbing et al. 2000)	Parameter for squeeze force of an agent	2.4×10^5	2.4×10^5
K_{ih}	Parameter for horizontal attraction force of an agent	* 1.2×10^5	* 1.2×10^5
k_{iv}	Parameter for vertical interaction force of an agent	* 0.05	* 0.05

Note: * denotes that the value range is assigned based on assumptions and an extensive trial-and-error process.