Sound Guidance on Evacuation under Limited Visibility: an Experimental Study

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Abstract. In an emergency, like fire or terroristic attack, visibility reduces due to the power failure or smoke, and the sound guidance could be an effective method to improve the pedestrian evacuation. Thus, in this study, we experimentally investigated the evacuation efficiency under conditions of various sound guidance, with different limited visibility. By the extracted trajectories of pedestrians, we analyzed the temporal-spatial features of the density. The main findings include: (1) With the exit width of 1.2 m and the 20% visibility, the sound guidance improves the evacuation efficiency by 12.6%, and the mean time lapse between two successive evacuees passing through the exit reduces by 22.3%; (2) Under limited visibility conditions the power-law index of the complementary cumulative distribution function (*CCDF*) for the exit under the sound guidance is always higher than that without sound guidance, implying a more fluent bottleneck flow under sound guidance; (3) The sound guidance has limited effect on the crowd temporal-spatial distribution, while the visibility plays a dominant role.

Keywords: sound guidance, different visibility, pedestrian evacuation.

1 Introduction

Pedestrian evacuation, as a big concern in the design of pedestrian facilities and a common strategy in emergency management, has become a hotspot in transportation research [1]. In different environments, pedestrians could easily be affected by the surrounding environment and show a variety of behaviors. In particular, pedestrians' movements would be quite different in limited visibility, which is caused by smog, broken power supply, or other situations [2]. Previous studies [3] have proved that limited visual field may be an important factor hindering evacuation.

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In the upstairs [4], downstairs [5], and horizontal plane evacuation [6] scenarios, the limited visual field hinders pedestrian evacuation is mainly reflected in the movement mode, movement speed, and evacuation time of pedestrians [7]. When the view is limited, the most common mode of movement for pedestrians is along walls once find the wall. Cao et al. [8] observed the pedestrians have the preference of choosing the left-hand side direction when they find the wall, while Isobe et al. [9] observed pedestrians randomly choose the right-hand or left-hand direction if a wall was found. In the work of Chen et al. [3], individual upward evacuation experiments on stairs shown the influence of visibility on average evacuation speed was more significant for the female than the male. Guo et al. [10] studied route choice in pedestrian evacuation under conditions of good and zero visibility, their found pedestrian evacuation time under zero visibility condition is longer than that under the condition of good visibility.

It can be seen that many studies on evacuation limited visibility are a critical factor affecting evacuation efficiency. When the field of view is limited, pedestrians can guide their movements by hearing, and using sound to guide the pedestrians' evacuation may affect the evacuation efficiency. However, most of the current research on the impact of sound on pedestrian movement focuses on the normal field of view. For example, the pioneering study by Styns et al. [11] the effect of music on individual pedestrians has been studied experimentally. Inspired by them, Yanagisawa et al. [12] analyze the effect of rhythm on crowded pedestrians, showed that pedestrian flow can be improved by instructing pedestrians to follow a metronome rhythm below the normal pedestrian step frequency, and similar experiments were also carried out by Ikeda et al. [13]. Regarding the influence of different music on pedestrian movement, Franek et al. [14] found that the fast and energetic motivational music seems to induce people to walk faster, while non-motivational, slower, relaxing music makes people walk slower.

Although sound rhythms can affect pedestrian's movement state, the effect of sound guidance on pedestrian evacuation under limited visibility is still unclear. To eliminate the impact of visibility, it is necessary to use sound to guide pedestrians to evacuate. However, there are little researches on the effect of sound on evacuation under restricted visual field conditions. Hence, this work focuses on research the influence of sound guidance on evacuation efficiency with different visibility. We hope to improve the evacuation ability of pedestrians when the field of view is limited through sound guidance.

2 Experimental set-up

The experiment was carried out in Chengdu, China on June 11th and 12th, 2019. The experiment included 35 college students, aged between 18 and 25, with an average height of 1.7 m. Fig.1(a) and (b) shows the geometry of the experiment room and experiment snapshot. The length, width, and height are 8 m, 4 m, and 2 m, respectively. The exit is located in the upper left corner of room, and the exit width includes two cases: 0.6 m and 1.2 m. Table 1 shows the details of the experiment. All participants were randomly distributed in the shadow waiting area before the experiment started.

Plastic transparent soft film artificially manufactured eye masks with different transmittances were used in the experiment. As shown in Fig.2, the evacuees wear eye-patch with different visibility. The transmittance optical detector [3] (measurement accuracy ≤ 2%) was used to detect the eye-patch transmittance. In this paper, we consider average light transmittance as approximate visibility, thus, visibility (i.e., average light transmittance) includes 20%, 10% and 0. During the evacuation drill, loudspeaker is used to guide the evacuation under different visibility. When the experiment start instruction is given, the loudspeaker will repeatedly play the slogan of ‘Here's exit’ with a rate of recurrence every 2 s/time. To reduce the familiarity of the participants when the field of vision is limited, all participants put on eye masks outside the room before entering the waiting area inside the room. In the process, each participant lost their orientation. Simultaneously, participants wore a red hat with a white dot mark at the top is used for later trajectory extraction. Everyone was asked to remain silent and not allowed to talk to each other. The trajectory of the evacuees obtained by the PeTrack is shown in Fig.1. (c), and (d).

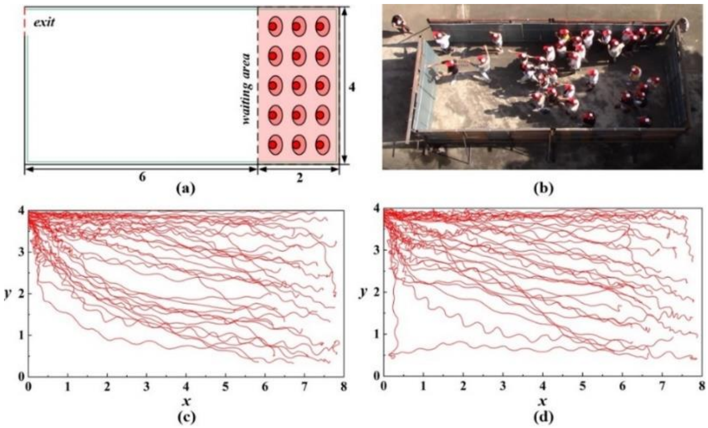

Fig. 1. Experimental set-ups (units: m), (a) and (b) are the room geometry and snapshot of the experiment at 0 visibility, (c) and (d) are the trajectories of 35 evacuees with and without sound guidance when the exit width is 0.6 m under the condition of 0 visibility.

Table 1. Details of the experiments.

Visibility	Exit width (m)	Sound guidance	Number of subjects	Number of repetitions
20%,10% and 0	0.6	with	35	3
		without	35	3
	1.2	with	35	2
		without	35	2

Fig. 2. A participant wearing eye-patch with different visibility, and the visibility from left to right is 20%, 10%, and 0 respectively.

3 Results

3.1 Density temporal-spatial distribution

To study the density change in the room during the entire evacuation process, the Voronoi method can be used to calculate the density in the room because it can accurately estimate the density for minimal scatter. It can refer to our previous research for the density specific calculation details [15].

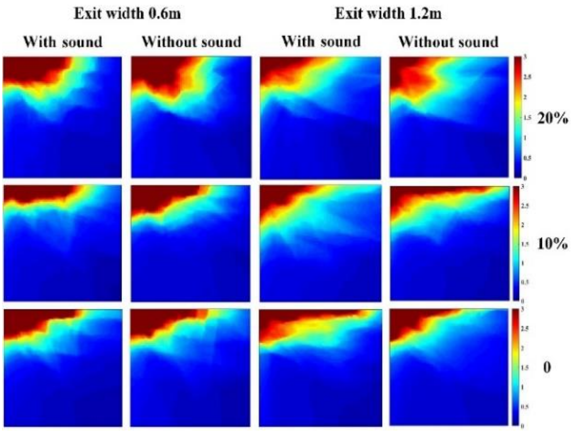

Fig. 3. Temporal-spatial distribution of density. The visibility from top to bottom is 20%, 10% and 0, respectively. The exit width of the first (with sound guidance) and second (without sound guidance) columns is 0.6m. The exit width of the third (with sound guidance) and fourth (without sound guidance) columns is 1.2m.

We quantified the density temporal-spatial distribution with and without sound guidance for different visibility in a $4 \times 4m^2$ area with $x \in [0.0m, 4.0m]$ and $y \in [0.0m, 4.0m]$ for exit widths of 0.6m and 1.2m, and shown in Fig.3. It can be seen that pedestrians are concentrated near the exit, with the decrease of visibility, pedestrian movement tends from regular diamond to irregular strip. This is because with the decrease of visibility, most pedestrians will move along the upper left wall. When visibility is

20%, the shape of exit width 0.6m is more regular than that of exit width 1.2m, while when visibility is 10% and 0, there is no significant difference in their shapes. Pedestrian distributions with and without sound guidance are similar under the different visibility. It shows that exit width and sound guidance are hardly affects pedestrian distribution when visibility restricted, while the visibility plays a dominant role in pedestrian distribution.

3.2 Evacuation time and time interval

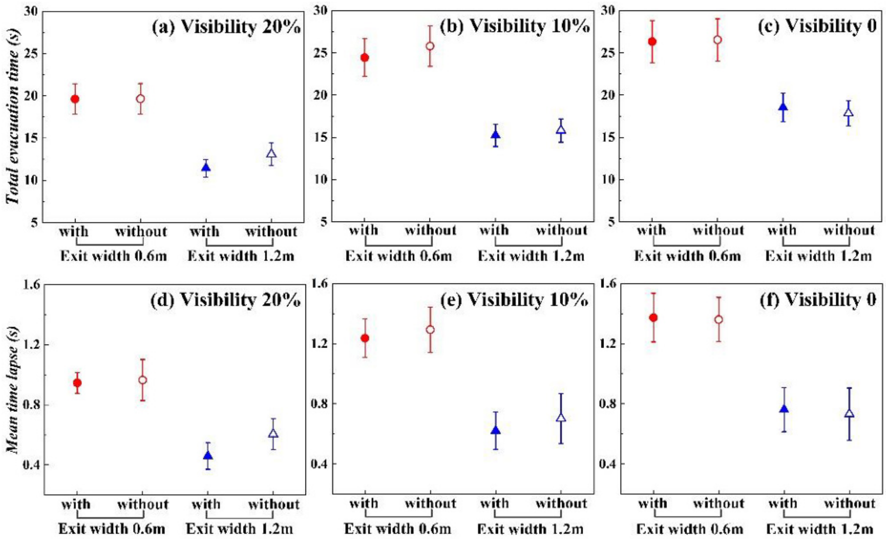

Fig. 4. Total evacuation time (a, b and c) and error bars show standard deviation, mean time lapse (d, e and f) and error bars show a 95% confidence interval. The visibility of (a, d), (b, e) and (c, f) are 20%, 10% and 0, respectively. The exit width of red solid circle (with sound guidance) and red hollow circle (without sound guidance) are 0.6m. The exit width of blue solid triangle (with sound guidance) and blue hollow triangle (without sound guidance) are 1.2m.

The total evacuation time (*TET*) is the time from the beginning of the evacuation to the time when the last pedestrian moves out. It is an essential indicator of evacuation efficiency. However, the *TET* leaves out significant information on the exit process [16]. Moreover, investigating the nature of the flow fluctuations may provide information concerning clogs, and understanding the variations from one individual to another may also have deep significance [17]. Hence, we analyzed the *TET* and the time interval between two consecutive individuals. Fig.4 (a), (b) and (c) gives the *TET* with and without sound guidance under different visibility, and (d), (e) and (f) shows that the mean time lapse with and without sound guidance for different visibility.

The *TET* whose exit width is 1.2m is obviously lower than that of 0.6m, consistent with the mean time lapse. Both the *TET* and the mean time lapse increase with the decrease in visibility when the exit width is the same. When the visibility is 20% and the exit width is 1.2m, the *TET* and the mean time lapse with sound guidance is 12.6% (1.65*s*) and 22.3% (0.15*s*) shorter than without sound guidance, respectively. When the visibility is 10% with the 0.6m exit width, the *TET* and the mean time lapse with sound guidance is 5.2% (1.35*s*) and 3.9% (0.05*s*) shorter than that without sound guidance, respectively; meanwhile, the *TET* and the mean time lapse with sound guidance is 3.6% (0.57*s*) and 11.6% (0.08*s*) shorter than that without sound guidance for 1.2m exit width, respectively.

At the same time, the *P* value of the mean time lapse by *t*-test, which shows that there is a significant difference (df=126, $P=0.04<0.05$) when the visibility is 20% and the exit width is 1.2m, while *P* values are all greater than 0.05 in the other case, indicating that the sound guidance has a significant effect on the mean time lapse only in 20% visibility and the exit width is 1.2m situation.

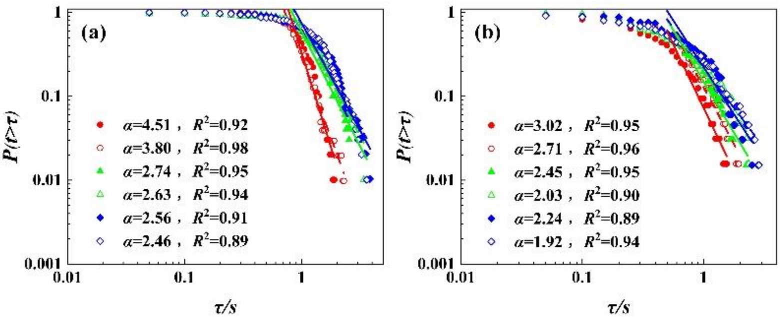

Fig. 5. Complementary cumulative distribution function (*CCDF*) of the time interval at exit with and without sound guidance. The circles, triangles, and diamonds represent 20%, 10% and 0 visibility, respectively, and solid and hollow represent at exit with and without sound guidance in figures (a) (Exit width 0.6m) and (b) (Exit width 1.2m).

Fig.5. gives the complementary cumulative distribution function (*CCDF*) (also known as the survival function) [17] of the time interval at exit with and without sound guidance under different visibility. The *CCDF* gives the probability of the time interval of two successive individuals leaving room higher than a specific time τ. After $\tau \geq 0.7s$ and $\tau \geq 0.5s$, the survival functions for the exit width 0.6m and 1.2m satisfy a power-law tail distribution. With the reduced visibility, the decay of the probability seems to come late. Meanwhile, we linear fitted the 'tails' and obtained the power-law index α, i.e., the slope of the linear fitted line. A lower index means longer interference between escaping pedestrians [18], and congestion is more likely to happen. In the exit width 0.6m and 1.2m scenarios, the α index of exit with sound guidance is always higher than that of exit without sound guidance when the visibility are 20% (0.6m: $\alpha=4.51 > \alpha=3.80$, 1.2m: $\alpha=3.02 > \alpha=2.71$), 10% (0.6m: $\alpha=2.74 > \alpha=2.63$, 1.2m: $\alpha=2.45 > \alpha=2.03$) and 0 (0.6m: $\alpha=2.56 > \alpha=2.46$, 1.2m: $\alpha=2.24 > \alpha=1.92$), indicating that congestion level of exit with sound guidance always lower than that of exit without sound guidance in front of the exit bottleneck.

4 Conclusions

In this study, the effect of sound guidance on the pedestrian evacuation was investigated under different visibility by controlled experiments. The main results are as follows.

From the temporal-spatial characteristic perspective, pedestrian density temporal-spatial distribution tends from regular diamond to irregular strip with the decrease of visibility. Setting the sound guidance at the exit has no significant effect on density temporal-spatial distribution under different visibility, while the visibility plays a dominant role in pedestrian density temporal-spatial distribution.

From the evacuation time standpoint, The *TET* and mean time lapse whose exit width is 1.2m is obviously lower than that of 0.6m. The *TET* and mean time lapse increase with the decrease in visibility when the exit width is the same. When exit width 1.2m with 20% visibility, the *TET* and mean time lapse with sound guidance is 12.6% (1.65*s*) and 22.3% (0.15*s*) shorter than without sound guidance, respectively. Proved by *t* test that the sound guidance has a significant effect on the mean time lapse in 20% visibility and the exit width is 1.2m situation. The *CCDF* indicating that the α index of exit with sound guidance is always higher than that of exit without sound guidance when the visibility is 20%, 10% and 0, and explained congestion level of exit with sound guidance always lower than that of exit without sound guidance in front of the exit bottleneck.

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References

1. Fu, Z., Jia, Q., Chen, J., Ma, J., Han, K., & Luo, L. (2018). A fine discrete field cellular automaton for pedestrian dynamics integrating pedestrian heterogeneity, anisotropy, and time-dependent characteristics. *Transportation research part C: emerging technologies*, *91*, 37-61.
2. Cao, S., Wang, P., Yao, M., & Song, W. (2019). Dynamic analysis of pedestrian movement in single-file experiment under limited visibility. *Communications in Nonlinear Science and Numerical Simulation*, *69*, 329-342.
3. Chen, J., Wang, J., Wang, B., Liu, R., & Wang, Q. (2018). An experimental study of visibility effect on evacuation speed on stairs. *Fire safety journal*, *96*, 189-202
4. Liu, R., Fu, Z., Schadschneider, A., Wen, Q., Chen, J., & Liu, S. (2019). Modeling the effect of visibility on upstairs crowd evacuation by a stochastic FFCA model with finer discretization. *Physica A: Statistical Mechanics and its Applications*, *531*, 121723.
5. Zeng, Y., Song, W., Huo, F., Fang, Z., Cao, S., & Vizzari, G. (2018). Effects of initial distribution ratio and illumination on merging behaviors during high-rise stair descent process. *Fire technology*, *54*(5), 1095-1112.
6. Xue, S., Shi, X., Jiang, R., Feliciani, C., Liu, Y., Shiwakoti, N., & Li, D. (2021). Incentive-based experiments to characterize pedestrians' evacuation behaviors under limited visibility. *Safety Science*, *133*, 105013.

7. Cao, S., Liu, X., Chraibi, M., Zhang, P., & Song, W. (2019). Characteristics of pedestrian's evacuation in a room under invisible conditions. *International journal of disaster risk reduction*, *41*, 101295.
8. Cao, S., Song, W., Lv, W., & Fang, Z. (2015). A multi-grid model for pedestrian evacuation in a room without visibility. *Physica A: Statistical Mechanics and its Applications*, *436*, 45-61.
9. Isobe, M., Helbing, D., & Nagatani, T. (2004). Experiment, theory, and simulation of the evacuation of a room without visibility. *Physical Review E*, *69*(6), 066132.
10. Guo, R. Y., Huang, H. J., & Wong, S. C. (2012). Route choice in pedestrian evacuation under conditions of good and zero visibility: Experimental and simulation results. *Transportation research part B: methodological*, *46*(6), 669-686.
11. Styns, F., van Noorden, L., Moelants, D., & Leman, M. (2007). Walking on music. *Human movement science*, *26*(5), 769-785.
12. Yanagisawa, D., Tomoeda, A., & Nishinari, K. (2012). Improvement of pedestrian flow by slow rhythm. *Physical Review E*, *85*(1), 016111.
13. Ikeda, S., Nozawa, T., Yokoyama, R., Miyazaki, A., Sasaki, Y., Sakaki, K., & Kawashima, R. (2017). Steady beat sound facilitates both coordinated group walking and inter-subject neural synchrony. *Frontiers in human neuroscience*, *11*, 147.
14. Franěk, M., van Noorden, L., & Režný, L. (2014). Tempo and walking speed with music in the urban context. *Frontiers in psychology*, *5*, 1361.
15. Deng, Q., Fu, Z., Li, T., Ma, J., & Luo, L. (2021). Effect of luggage-carrying on pedestrian flow through bottleneck: an experimental study. *Transportmetrica A: transport science*, 1-20.
16. Garcimartín, A., Pastor, J. M., Ferrer, L. M., Ramos, J. J., Martín-Gómez, C., & Zuriguel, I. (2015). Flow and clogging of a sheep herd passing through a bottleneck. *Physical Review E, 91*(2), 022808.
17. Garcimartín, A., Parisi, D. R., Pastor, J. M., Martín-Gómez, C., & Zuriguel, I. (2016). Flow of pedestrians through narrow doors with different competitiveness. *Journal of Statistical Mechanics: Theory and Experiment*, *2016*(4), 043402.
18. Jianyu, W., Jian, M., Peng, L., Juan, C., Zhijian, F., Tao, L., & Sarvi, M. (2019). Experimental study of architectural adjustments on pedestrian flow features at bottlenecks. *Journal of Statistical Mechanics: Theory and Experiment*, *2019*(8), 083402.