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Experimental investigation on the evacuation performance of pedestrians in a three-lane urban tunnel with natural ventilation in a fire scenario

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Abstract: This paper presents a field experimental study of several participants' evacuation behaviour in fire-induced smoke in a bidirectional six-lane, urban tunnel with natural ventilation. Ceiling openings with vertical shafts are equipped as natural ventilation and provide a large amount of sunlight into the tunnel in the daytime, increasing the illuminance in the tunnel and assisting evacuation in fire emergency. In this study, route choice, movement time, physical condition and reaction to technical installations were recorded and discussed to evaluate evacuees' performance. Human factors including pedestrians' gender, age and emotional state were taken into consideration. Besides, the characteristic of ceiling openings and its impact on human evacuation and technical systems settings are analysed. The results of the experiment and analysis suggest natural ventilation has a positive impact on evacuation. This study also leads to guidance on evacuation strategies in tunnels with natural ventilation and puts forward suggestions regarding to technical installations in the tunnel, such as way-finding signs and continuous light.

Keywords：Tunnel fire; ceiling openings; natural ventilation; evacuation performance; human behaviour

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1. Introduction

The consequence of a fire in a road tunnel can be far more serious than a fire in the open air, and lessons have already been learned from several tragedies (Amundsen, 1994; Amundsen and Ranes, 2000). Fires, and the high temperature, toxic smoke they produce, have catastrophic consequences for the safety of the occupants trapped in the tunnel, for example the subway tunnel fire in Daegu, Korea resulted in 198 deaths; and the Jinji high-way road tunnel fire in Shanxi, China caused 31 deaths (Hong, 2004, Cui, 2014). During a fire incident, escaping passengers must choose the direction and route of their evacuation. Wrong direction or route may lead people towards the fire or into smoke, which will have negative consequences on their health, due to the presence of toxic gases, heat and radiation (Yan, 2018; Zhang, 2019). Several scientific methods have applied to study fire and risk assessment has been used to evaluate fire and its potential harm to occupants and structure like FAHP (Lyu et.al., 2019 a, b; 2020a). Lyu (2020) and his team have done improved risk assessment towards fire and it has a much wider application to mega-tunnel systems in modern cities.

To minimize exposure to smoke for escaping people in a tunnel, various smoke control systems are used to extract the smoke out of the tunnel or keep the smoke in the tunnel above head height. These may be either mechanical or natural ventilation systems. Forced ventilation systems use fans to extract or blow smoke out of the tunnel, and this use considerable energy during operation. In contrast with mechanical ventilation, natural ventilation with vertical shafts takes advantage of the buoyancy of smoke, as shown in **Fig. 1**. Natural ventilation uses natural forces such as the stack

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effect and piston effect to exhaust smoke through shafts. This approach generally does not need mechanical fans, which results in space savings in the upper parts of the tunnel and is appropriate for shallow tunnels in urban areas. With no mechanical parts, natural ventilation entails less maintenance and is more economical. For these reasons, making efficient use of natural ventilation for underground space ventilation is attracting increasing attention in more and more shallow urban tunnels, such as the Chiba section of the Tokyo Outer Ring Road in Japan, Xi'anmen Tunnel in Nanjing, China, Hongxing Tunnel in Chengdu, China, Xinjian Tunnel and Kunming Tunnel in Shanghai, China (Yan, 2009; Baek, 2017; Jin, Jin, 2017; Takeuchi, 2018).

Recent investigations of natural ventilation have been conducted to investigate the efficiency of these systems for smoke control (Ji, 2012; Cong, 2017; Zhang, 2016; Jin 2017). However, limited research has been conducted to investigate the influence of such tunnel designs on human behaviour in case of fire emergency. Vertical shafts and openings on the ceiling permit sunlight directly into the tunnel and may be perceived as a connection between the tunnel and the outside world, although these do not provide an exit route. It is therefore necessary to investigate the effects of these on route selection and their impact on human egress behaviour.

The detailed study of human behaviour in fire situations is relatively new, although there have been sporadic studies into this issue in building fires from the start of the 20th century, and studies are still ongoing (Latane and Darley, 1968; Fischer et al., 2011). Our understanding of human behaviour during egress from tunnels is largely based on studies of human behaviour in other environments like stairs, high rise

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buildings, etc. (Huo et al., 2016). In 1985, Sime reported that vehicle drivers were most likely to return to the tunnel portal, and generally would not use emergency exits, or other efficient ways for evacuation, even if these were closer. This may be regarded as the start of research into human behaviour during tunnel fires, and most studies in this field have been carried out in the 21st century (Boer, 2002; Boer and van Zanten, 2007). Previous research has been largely based on a traditional enclosed tunnel and has focused on people's performance, including pre-movement behaviour, finding the exits, movement towards the exits (Ronchi, 2013; Kuklane, 2016), some social characteristics (Drury, 2009; Moussaid, 2010; Templeton, 2015), and comparing technical installations for wayfinding (Nilsson, 2009; Ronchi, 2016a; Kinateder, 2019). Most experiments have been conducted in model tunnels with no smoke control systems or in a virtual reality (VR) environment with no consideration of the ventilation system (Kinateder and Warren, 2016, Ronchi, 2016b). Fridolf et. al (2013) observed that the average movement speed in tunnels was generally higher than that in buildings, due to fewer stairs and obstacles. Kinateder (2014 and 2016) investigated the social influence during egress from tunnels by providing a virtual agent and found that social influence on behaviour, pre-movement time, and route choice during evacuation in VR experiments. Ronchi (2016c) did a VR experiment with 96 participants to provide recommendations on the design of flashing lights at emergency exit portals for road tunnel emergency evacuation. Fridolf and Ronchi (2016) carried out a full-scale tunnel evacuation experiment in a road tunnel in Stockholm to evaluate the effectiveness of different emergency exit portal designs. Templeton (2015) did research about collective

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behaviour in case of emergency and suggested that social influence plays a positive role among people. Some studies related to technical installations have shown that a pre-recorded alarm is beneficial in encouraging people to evacuate from their cars in a tunnel (Seiko, 2017; Jiang, 2020). It has been shown that white and green lights are more effective for wayfinding than other colours (Nilsson, 2008; Ronchi, 2016b). Those studies have investigated several human characteristics in tunnel egress scenarios.

In contrast, few experiments investigating the influence of ventilation on egress behaviour have been carried out. Such tunnels with natural ventilation are usually located in urban areas and carry high traffic flow and many people, thus understanding of egress behaviour in these tunnels is important. It is essential to study the behaviour, physical condition, mental condition, and egress speed for occupants in such large-long urban tunnel with natural ventilation and natural light openings on the ceiling.

This paper presents the results of an experiment concerning pedestrian behaviours during egress in an urban tunnel with natural ventilation. The evacuation performance, as well as pedestrians' awareness and use of technical installations during the evacuation process are analysed and discussed.

2. Experiment configuration

2.1. Urban tunnel with natural ventilation

Shanghai has one of the largest traffic volumes in the world and therefore has severe traffic congestion in urban area. Tunnels are being built to relieve the traffic congestion since these provide alternative routes for vehicles and commuters underground. Tunnels

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with mechanical ventilation systems require larger excavations than tunnels with natural ventilation, so are economically undesirable. Also, the geology of the Shanghai area dictates that shallow tunnels are preferred. Combining these constraints with the fact that tunnels are comparatively limited in length in the urban area, means that natural ventilation is a feasible choice in these situations.

The Beidi Tunnel in Shanghai is a new urban road tunnel with natural ventilation, it opened to traffic in 2019. It connects the Middle Ring and the Outer Ring in Shanghai, which are two of the busiest transport routes in Shanghai, and it carries a huge amount of traffic with a great number of occupants. The Beidi Tunnel is designed with natural ventilation provided through large openings on the ceilings. Those openings allow natural light into the tunnel and change the enclosed environment to a semi-enclosed one. People's response to this natural light leads to a change in their behaviour, and this is investigated in the experiments described.

2.2. Tunnel condition

The experiment was conducted in the Beidi Tunnel (hereafter referred to simply as "the tunnel"), which is located in Changning District, Shanghai, China. The experiment was carried out during construction of the tunnel, before the tunnel opened to the public. The tunnel is bidirectional, with three lanes in one direction, as shown in **Fig. 2**. It has a length of 1780 m in total. The section used in this experiment was a standard section, as shown in **Fig. 3** (Section 2, Zone 6). The slope of the tunnel is less than 1° and any influence of slope is disregarded in this experiment. The experimental section covered a total length of 258 m, and contained two evacuation gates with 100

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m separation distance. The egress distance from the experimental zone starting point to Gate A is 60 m and from Gate B to the other end of the zone is 98 m. The sizes of the two evacuation gates are indicated on **Fig. 3**. Both Gate A and Gate B had two doors, each the same size with a height of 2 m and a width of 1 m. Two gates allow people to evacuate from one side of the tunnel to the other side to escape from fire and smoke on either side. The vertical shafts supplying natural ventilation to the tunnel are 4 m × 10 m, allowing large amounts of sunlight into the tunnel in the daytime; these are positioned 50 m apart, as shown in Fig. 3.

2.3. Experiment

2.3.1. The participants

30 volunteers participated in this experiment in total from universities and design companies. They were unfamiliar with the tunnel and they did not know the layout or the position of the exits. The participants were numbered randomly from 1 to 30. Each participant had their number displayed on a card on their back and their front. The card was 0.21 m × 0.3 m, clear enough for cameras to record even in the presence of some smoke. The 30 participants' basic information was recorded prior to the experiment and is listed in Table 1; including gender, age, occupation and physical condition.

The participants ranged in age from 20 to 59, with an average of 32.74 (standard deviation: 9.86). Among the 30 people, 19 were male and 11 were female. The average ages for males and females was similar; 33.5 for the males, 31.6 for the females. The age variation for males was relatively larger than that for the females, with standard deviations of 12.02 and 6.43 respectively. The males, with an average height of 1.73 m

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and weight of 68.2 kg, were generally taller and heavier than the females, who were on average 1.62 m and 53.8 kg. Their baseline pulse and blood pressure were recorded in advance and all participants appeared normal, both physically and mentally. All participants stated that they were in good physical condition without hypertension, heart disease and did not have any mental health considerations that would have been affected by the experiments.

2.3.2. Recording methods

Video recordings, health monitoring equipment, post-experiment questionnaires and interviews were used in this experiment to record the data; including movement, physical condition, and participants' emotional state.

The experiment was recorded using eight fixed-location video cameras covering the tunnel section, the evacuation gates and all the participants. Videos recorded the whole process from the time the participants entered the tunnel until all were through the gates and reached the designated place of safety in the other tunnel. The video recordings were used only for data collection, and the participants cannot be identified from the processed data.

Three questionnaires were applied after this experiment to obtain participants' perception of their physical change and emotional state after the evacuation experiment. The first questionnaire evaluated people's physical condition using a four-grading rating including headache, sweating, dizziness etc. The questionnaire was written based on the Simulator Sickness Questionnaire (Kennedy et al., 1993). The second questionnaire was filled out after they had finished the evacuation experiment, aiming

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to assess participants' anxiety levels in the tunnel. The third questionnaire ranked participants' approval or otherwise of the utility of the technical installations in the tunnel; namely lighting, way-finding signs, and loudspeakers. This questionnaire contained different types of questions, as follows:

a) Questions that required the participants to indicate if they had noticed technical installations like way-finding signs, fire alarm, and lighting in the tunnel.

b) Questions that ranked those technical installations in the tunnel physically and mentally using four-grade rating scales.

c) Questions that reflected their perception of those technical installations in the tunnel before the evacuation began and after the evacuation.

2.3.3. Technical installations in tunnel

Three types of technical installations were provided in the experimental section of the tunnel; way-finding signs, pre-recorded broadcasts, and lighting. Two different kinds of way-finding signs (pointing towards the nearest exit and indicating distance to the exits) were installed on both sides of the tunnel, at 20 m spacings, as shown **Fig. 4**. Exit signs were positioned over the entrance of the evacuation doors. Way-finding signs and exit signs were all 0.23 m × 0.14 m and were back-lit, in accordance with the construction code in China.

The pre-recorded broadcast was played using the tunnel public address system. The message played in the tunnel included an alert, which rang for 10s, followed by a statement informing people that there was a fire in the tunnel, and instructing people to leave their vehicles and escape through the nearest exit. The voice was recorded in

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Chinese by a woman who was a native speaker. The loudspeaker equipment was installed every 100 m in the tunnel.

The experiment was carried out on a sunny day. Sunlight came through the vertical ventilation shafts, positioned every 50 m along the ceiling of the tunnel. On sunny days, visibility is at least 100 m, generally better.

2.4. Experiment process

2.4.1. Preparations

A project group consisting of employees of Tongji University prepared the experiment with the assistance of the workers from the tunnel. Experimental preparation included clearing the tunnel section, laying out the accident scenario, installation of the related signs, etc., and preparing the questionnaires and checklists for the interviews.

Since large-scale trucks with chemicals and oil are forbidden in most urban tunnels during the daytime, the potential fire scenario is small to medium, and the biggest threat to occupants is smoke rather than high temperature. Given the strict restrictions on open fires in the urban area in Shanghai, smoke cakes were used as the smoke source instead of an open fire, as shown in **Fig. 5**. Common practice assumes a visibility of 10 m or more at head height is required for evacuation (Purser, D. A， et., al, 2016). To ensure the experiment was representative of a relatively adverse scenario for evacuation, the tunnel's visibility was maintained between 5 m and 10 m.

In a real fire scenario, vehicles will be stopped on the roadway and escaping occupants will need to navigate around these. It was not possible to use real vehicles in these experiments, so rectangular parts of the tunnel were cordoned-off using traffic cones and traffic tape to represent stopped cars, as shown in **Fig. 4**. 200 traffic cones were used in groups of four, to represent 50 vehicles distributed across the three traffic lanes in the experimental section. Participants were instructed that the cordoned-off areas were representing cars in the tunnel and they should evacuate through the spaces between these.

We strove to ensure the security of the participants in the evacuation. The whole area was clean, dry, with no visible or potential obstacles. Professional medical staff joined in the experiment and provided proper help if needed. Corresponding health care, both physically and mentally, were prepared to avoid participants experiencing possible short and/or long-term damage. Professional caring teams from Tongji Hospital, Shanghai stayed in site and kept a close eye during the whole experiment with complete aid kits in case of any emergency. Besides, all participants learned the real aim of the evacuation and got instruction on how to evacuate after the experiment.

2.4.2. The experiment

The experiments were conducted on 14th Sep. 2018 from 09:00 to 17:30 in the tunnel. 30 experiments were carried out in total with one participant each time. Participants were kept in the nearby rest room, on the ground, near the tunnel before their evacuation began. Participants read instructions about the study and were informed that the purpose of the experiment was to study ‘human behaviour in road tunnels’ and gave their informed consent. Their basic information like height, weight, age, baseline pulse rate and blood pressure were recorded in advance.

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In each experiment, the participants had bracelets recording their pulse and blood pressure fluctuations. Initially wearing blinders and earplugs, they were led downstairs by assistance staff and into the adjacent tunnel, before being led to their starting location in the experimental tunnel. Prior to the first experiment, smoke cakes were ignited in the experiment tunnel and a member of staff took charge of the smoke throughout the experiment, to make sure the tunnel was filled with smoke. Participants were guided into experimental tunnel by a randomly selected evacuation gate and were led to a random location near the middle of the tunnel (midway between the two exit gates). At the start of the evacuation experiment, the participant was instructed to turn around three times, then they were instructed to take off the blinders and earplugs. At this time, the pre-recorded alarm and voice message started playing. The participants evacuated themselves from the tunnel and they were regarded as “having escaped successfully” when they passed through one of the gates and reached the adjacent tunnel.

Immediately after they reached the adjacent tunnel, their pulse and blood pressure were recorded, and then they were asked to complete the questionnaires. All the questions were printed in advance in Chinese, including all the questions and options. The participants were free to ask questions, and staff were around them to help them. The results of the experiments are presented in the following section.

2.4.3. Data processing

The video recordings were examined to evaluate pre-movement time, the route each participant took, and their movement during the evacuation. The data from the questionnaires were analysed statistically and all the data were studied using frequency

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analysis. In order to identify any influence on people's behaviour due to gender and age, the data were analysed by ANOVA and ANCOVA. A significance level of five per cent was used in all statistical tests(Nilsson, Johansson et al. 2009). For instance, a 2x2 ANOVA was conducted that examined the effect of age on movement speed in the tunnel. There was a statistically significant interaction between the effects of age and movement speed, $F(2, 30) = 4.643$, $p = .014$.

Some interviews were carried out after the questionnaires, asking about technical installations like the lighting, alarms and way finding signs. The participants' emotional state, their perception of the technical installations and their opinions of the evacuation were analysed and are presented in the next section.

3. Results

The whole experimental campaign consisted of 30 individual evacuation experiments. These may be broken down into four main stages: (a) participant takes off the blinders and earplugs and prepares to escape; (b) participant searches for an evacuation gate in the tunnel; (c) participant identifies an evacuation gate and moves towards it; (d) participant passes through a gate and escapes successfully. These stages are shown in the photos in **Fig. 6**. No participants were injured, and no accidents happened during the experiments. All participants evacuated from the gates and reached the adjacent tunnel within 4 minutes.

3.1. Exit choice

Participants were initially positioned near the halfway point between the two available exits. Participants initially closer to Exit A were designated as starting in Zone

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1 (grey), while participants who started nearer Exit B were designated as starting in Zone 2 (green), as shown in **Fig. 3**. There was no intended correlation between which gate participants were led in through and the zone in which they started. Participants' entrance gates, their original starting zones and their exit choices are listed in **Table 2**. 15 participants were led to enter the tunnel from Exit A and 15 from Exit B.

Regarding the entrance location and exit choice, 13 participants of the 15 who entered into the tunnel from Exit A evacuated through A and 14 of the 15 who entered into the tunnel from Exit B evacuated through B. This shows a strong relationship between exit choice and original entrance and people tend to choose original entrance as their exits ($p = .001; < 0.025$), even though measures were taken to disorientate the participants. Besides, this preference to the original exit has no significant difference on Gate A or Gate B ($p = 0.58; > 0.05$). Sime (1985) was the first to point out similar phenomena, where drivers tend to return towards to the tunnel portal they entered by, and did not emergency exits or other efficient ways for evacuation, which were closer.

Regarding starting point and exit choice, for 15 participants starting in Zone 1 (near Exit A), seven of them chose A and eight of them chose Exit B. For the other 15 participants starting in Zone 2 (near Exit B), they made similar choice as those in Zone 1. With the statistical analysis, the null hypothesis could not be rejected ($p = 0.81; > 0.05$) and could conclude that, in this experiment, at least, there was a weak connection between starting point and exit choice.

Some participants expressed similar exit choices in the interview, and they tried to explain the reasons of their choices.

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One participant said "*I felt unsafe when I entered the tunnel, so I paid extra attention to my route. I tried to remember my entrance direction.*"

Another said, "*I have strong sense of direction and I could figure out the relative location between the entrance and my position.*"

Some participants stated that although they were "blind" and "deaf" on the way to the tunnel, and they experienced some small disturbance like circling three times, they could still tell their location relative to their entrance to some extent.

In contrast, though participants' telling their direction of travelling, it was hard for occupants to estimate the distance to the exits in a strange environment. They did not know how long they walked from the entrance to their starting point.

One said "*I did know that I walked some distance, but I have no idea how long it is. I think it may be 100m? or 200m?*"

Another said *"I could not locate myself in the tunnel and I could not tell which exit was nearer. It is impossible to find the nearest exit in a strange environment with smoke."*

From occupants' performance and their statement, they expressed they were confused the distance to the exits. Since they did not know how far they travelled and they could not locate themselves, it was difficult for them to distinguish a nearer exit.

3.2. Time and speed

This experiment was designed to investigate human behaviour in the naturally ventilated tunnel. Therefore, the focus is on the period when the occupants are exposed in the tunnel, rather than the whole evacuation process including stopping the vehicles and getting out of the cars. The average recorded time of evacuation movement in the tunnel was 45 s for all participants; for the male participants it was 47 s and for the females it was 41 s. The max/min times were 116 s/17 s for the males and 94 s/18 s for the females. Based on averages, the females evacuated about 15％ faster than the males, but the averages may be skewed by three males who took over 100 s, while no female took over 100 s. From the conducted interviews, it was found that two of these men claimed that they were curious about the inner structure, since they had previously had little opportunity to walk in a tunnel. The third explained that he had tried to run to the end of the tunnel but was stopped by warning lines and had to return to an exit gate.

The egress time consists of two parts: adaptation time and movement time. The adaption time in this experiment started from the point at which the participants took off the earplugs and blinders until the participants moved. It is different from common pre-movement, which also contains people deciding to evacuate and getting out of their vehicles. In this experiment, this process was simplified to concentrate on evacuees' performance and their movements in the tunnel. The movement time was determined starting from their initial movement until their arrival through the exit gates.

In this experiment, males and females showed some difference in evacuation time. The main reason observed here is that men have a broader curiosity in their surroundings, leading to more observation around and a longer time. Based on this experiment, it cannot be determined if this will be a factor in a real emergency situation. Another reason contributing to this result is that the total evacuation distance was short and physical ability was not a key influence. Since it is more likely that people would

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focus on their target more in real accidents than in drills, more investigations should be conducted in the future about different genders and their focus during evacuation.

The correlation of age with total time was calculated for the tunnel experiments. The results show that age influenced the evacuation time considerably ($p < 0.05$). The younger occupants finished their escape process significantly faster than the old. This is in accordance with conclusions from research and experiments by Spearpoint (2012).

3.3. Physical condition

Physical condition was evaluated in this evacuation experiment using heart rate and blood pressure measurements; both Systolic blood pressure (SBP) and Diastolic blood pressure (DBP). Heart rate and blood pressure were measured before participants entered the tunnel and as soon as they finished their evacuation in the safety zone.

The heart rate before the experiment varied from 64 to 113 beats per minute (bpm), with no significant variation and all within the normal range. The average initial heart rate was 76.4 bpm (SD: 11.8), with the average for females being 78.2 bpm (SD: 9.8), a little faster than the average for the males of 74.9 bpm (SD: 10.5). After the experiment, the heart rate ranged from 97 to 140 bpm with an average of 112.5 bpm (SD: 13.9) for the females and 106.2 bpm (SD: 13.2) for the males. The females' heart rates were generally a little faster than the males, both before and after the experiment. The participants' heart rate fluctuations were a little larger after the experiment.

In order to access the blood pressure, mean arterial pressure (MAP) was calculated for in this study, as follows (Maron, 1995):

$$MAP = DBP + (SBP - DBP) / 3 \quad (1)$$

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The average MAP was 94.6 mmHg before the experiment and 103.5 mmHg after the experiment. The males and females exhibited similar values of MAP both before and after the experiment; there was no obvious correlation between blood pressure and gender from this experiment.

Hypertension heart disease was not a factor for any participants in the experiments. They were all found to be in normal physical condition after the experiment, with a little rise both in heart rate and blood pressure.

Apart from physical data, a questionnaire valuing people's abnormal reactions and physical problems like headache, sweating, and dizziness was applied in this experiment. The questionnaire was based on the Simulator Sickness Questionnaire (SSQ) (Kennedy et, al, 1993). From the 18 questions posed, palpitation, shortness of breath, sweating and disorientation were the four symptoms most commonly reported by participants. In the interviews later, it was determined that those four symptoms were triggered by their running in evacuation and their unfamiliarity with being underground. The data from physical condition was not only required for investigation of the gender variations, it was also required for ethical considerations, to make sure participants were not traumatised by the experiment.

3.4. Emotional state

Participants answered several questions after their evacuation experiment, to quantify their anxiety level in the tunnel. The questionnaire was based on the Tunnel Anxiety Questionnaire (Mühlberger and Pauli, 2000) for participants recording their anxiety levels after evacuation.

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The anxiety level of average values for each question during the evacuation process in the tunnel are compared in **Fig. 7** (Questions are organized with the process of participants completing the experiment, available in Appendix A). Participants exhibited a high anxiety level before the evacuation (Q1), and it decreased a little when they took off the blinders and earplugs and started the evacuation (Q2 to Q4). Their anxiety level rose again when they were searching their way in the smoke (Q5-Q7) and it decreased a lot when they finally found an evacuation gate and ran out of it (Q8 – Q9). The anxiety level kept steady between seeing the gate and escaping through it (Q10 to Q11).

Focusing on individuals' anxiety level, the average value from all questions was adapted as the overall anxiety level for each participant. Analysis shows a clear correlation between that the anxiety level exhibited and egress time, as shown in **Fig. 8**. The participants with shorter evacuation times claimed less anxiety. It is unclear which factor is the cause and which is the effect; does lower anxiety lead to faster egress, or does faster egress result in lower anxiety? Perhaps people with low levels of anxiety tend to keep calm and behave better in evacuation situations. The three participants with egress times over 100 s do not fit this trend. They were curious and noticed more about surroundings, but they also showed a low level of anxiety in the questionnaire.

Though females showed a slightly higher score in anxiety than males, no strong relationship could be obtained in this experiment between gender and the anxiety level. More research needs to be conducted concerning anxiety levels and people's performance in tunnel evacuation.

4. Evacuation analysis

This study provides valuable information regarding people's evacuation performance in urban tunnels with large ceiling openings. The emergency i.e. fire breaks the original coordination of the tunnel from traffic and occupants need to evacuate from the tunnel before it is regarded as incapacitation. The occupants will evacuate from the fire and the tunnel systems will help them during the process. The key to the evacuation is the decrease of the tunnel's capacity is slower than the remaining occupants' need so that it makes sure the occupants in the tunnel are safe. The ability to maintain the safety of the environment before occupants' successful evacuation is defined as "emergency resilience" and various methods are applied to increase the emergency resilience. This unique natural ventilation system is supposed to increase the tunnel's emergency resilience since it changes the original enclosed environment into semi-enclosed, which does not only bring about an increase in lighting, but also appears to provide a connection between the tunnel and the external environment. The occupants' performance in the experiments and feedback after the experiments are analysed as followed regarding route preference, suggestions for technical installations and evaluation of the natural ventilation design on human behaviour.

4.1. Participants' route and track

Participants' egress track was recorded using intelligent bracelets and was calibrated by comparison with the video footage. **Fig. 9** and **Fig. 10** show the routes followed by the participants who entered the tunnel through Exit A and Exit B, respectively. The entrance gate, starting location and exit gate choices of the participants are listed in **Table 1**.

Almost 80% of participants egressed with the tunnel wall to their right, about 10% of people escaped with the wall to their left, and about 10% of people walked in the middle of the road. People's gender, age, and their original location have little influence on their route choice in this experiment. People preferred to escape along the right side of the tunnel irrespective of their movement direction, toward Exit A or B. The results verify the simulation results of Yang in 2008, which found that right-preference is effective when the density is below critical (Yang, 2008; Muramatsu, 1999). In interviews, the participants explained that their right-handed route choice was based on their habitual and cultural driving, and walking habits; traffic drives on the right in China. This was in accordance with the findings of Zhang et al. (2018).

When exits are located on the right side from people's movement direction, it is easier for them to find the exit. However, when on the left side, people may overlook the exit on the other side of the tunnel since they escape along the right side. To address this problem, it is necessary to add information signs showing the exit location on both sides of a tunnel to guide egress in an emergency.

As well as the cultural preference to walk with the wall on their right side, people also liked to approach the natural ventilation openings in the tunnel. As illustrated in **Fig. 9**, some people left the right-hand wall and crossed the tunnel to reach the point where a ceiling vent is directly overhead. A few participants claimed that they walked towards the bright place because of the sunlight shining through openings. Some other

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participants did not mention the illuminance's influence on their route choice, while some who did walk towards the natural light, denied their getting close to openings. The effect is also seen in **Fig. 10**, although for those travelling towards Exit B, the zone of natural light was on the right-hand side of the tunnel, so the effect is not as marked. This tendency to go toward the natural light may result from people's phototropism in their subconsciousness, or may be due to their desire to go back to the surface, since these openings represent a connection between the tunnel and the outside. It may be helpful to take advantage of this orienting response to natural light, for example, arranging the evacuation gate with higher illuminance near the openings in large urban tunnels with such vertical shafts. The effects of increasing illuminance and people's tendency towards the light it needs further investigation.

People's route choice reflects their preference in two ways: escaping along the right side of the tunnel and being attracted towards bright places (or places with natural light). More research should be conducted to establish the correlations and take advantage of people's natural preferences when designing evacuation systems for tunnels.

4.2. Suggestions for technical installations

Trajectories of occupants' in the tunnel suggest they would like to approach or make a turn at the openings with more sunlight. Enns (1997), Vilar (2013) and Pakkert' (2018) did related investigation separately and suggested people tend to approach bright place than darkness. Sunlight through ceiling openings increases the illuminance and visibility in the tunnel and saves energy for lightings. Sunlight is stable and soft,

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therefore is easy to attract occupants (Dijkstra, 2014). However, the sunlight in the tunnel is uneven with different illuminance and would provide photopic vision and scotopic vision (Pelz, 1993; Marc, 2014). Photopic vision exists when the illuminance exceeds 3 cd/m^2, usually in the daytime with sunlight. When people are with photopic vision, their cone cells work to sense the size and colour of objects (Kandel, 2000; Trepel, 2015). In contrast, when the illuminance reduces from 3 cd/m^2, the rod cells start to work with cone cells. Rod cells are more than 1000 times sensitive to illuminance than cone cells, and they could work in the darkness to sense the shape of objects, called scotopic vision. However, the rod cells could not tell the colours but just the shape. Besides, people could adapt the bright space within 3mins from the darker, but the opposite adaptation would sometimes need 30 mins or more.

From the above analysis, the vertical shafts supplying natural ventilation also provides large amounts of sunlight into the tunnel in the daytime. People's subconsciousness benefited from brightness to make positive decision. Hence the technical installations of tunnels with natural ventilation should be optimized and rearranged. According to the experiment results, all the technical installations, i.e. lighting, information signs and alarms demonstrated qualified performances during experiments. Way-finding signs only point towards the nearest exit. The signs are installed on both sides of the tunnel, at 25 m spacing adapting with the 50m spacing of vertical shafts. The location of each shaft should be set one pair of signs. Hence certain supplementary light in the dark place will be placed to decrease the illuminance difference. Since eyes are difficult to distinguish color in dark places, all the signs,

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especially ones in dark place, should be designed to illustrate with shape, e.g. diamond, ellipse etc. Besides, signs could be designed with backlit or with reflective material to catch attention and to be noticed. The time interval of the alarm is suggested to be lengthened to 20 s to reduce the echo effect with a proper pace.

Three technical installations were constructed in the tunnel, namely lighting, alarms and information signs. To evaluate the installations' utility and influence on people's evacuation, evacuees filled out questionnaires and answered interview questions, similar to the work of Ronchi et al. (2018) and Nilsson et al. (2009). Using three types of questions, attitudes towards the technical installations were recorded, categorized and analysed. Regarding awareness of the three technical installations, the results are listed in **Table 3**. More than 60% of participants noticed the alarms and information signs during their evacuation, and about half of them noticed the lighting. Participants in the later interviews claimed that they did not regard the sunlight as lighting even though large openings on the ceiling provided a large amount of sunlight into the tunnel.

Though a relatively smaller number of people reported their awareness of the lighting in the above questionnaire, they showed their preferences in terms of the function and importance of the technical installations. Participants expressed preferences for those technical installations in the tunnel, using a four-grade rating scale. Participants regarded lighting as the most helpful installation with an average score of 3.27. Next was information signs with an average of 3.07 and alarms with 2.57, as listed in **Table 3**. Some participants claimed that they could not hear the words from the

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loudspeakers during the evacuation and were annoyed by the echo. Besides, some people mentioned that they were confused with the numbers on the signs indicating the distances to the exits. It will be helpful to normalize information signs for all occupants to make full use of them.

4.3. **Natural ventilation and human behaviour**

The tunnel in this experiment is the largest and longest tunnel with natural ventilation in the Shanghai urban area. Large natural ventilation shafts have been shown to provide positive influence on people's evacuation behaviour in fire in this experiment.

(1) Natural ventilation provides an instant smoke extraction system in the tunnel. If there is a fire, it functions immediately, maintaining smoke stratification and exhausting it out of the tunnel. This is an obvious advantage over mechanical methods since these may take a longer time to operate, hence people may be exposed to smoke in the crucial initial moments of an evacuation.

(2) As it has no active fans, this natural ventilation method is quieter than mechanical ventilation. Lower noise levels in the tunnel will assist occupants in hearing useful information during the evacuation process like alarms, broadcast messages, and shouts from companions. Also, it avoids distraction from focusing on important information like information signs and exits. People in lower noise situations tend to be in a calmer condition and have a lower level of stress. (Okokon, Yli-Tuomi et al. 2018)

(3) As seen in Section 3.1, people tend to evacuate towards their original entrance for an exit. This kind of behaviour may result in trouble for tunnels with longitudinal

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ventilation in case of fire, people's natural inclination may be to egress in the same direction as the smoke is being directed. In contrast, natural ventilation provides a good control of smoke in two adjacent vertical shafts and would not bring threat to people due to supplementary airflow.

(4) The tunnel has applied natural ventilation system with vertical shafts, as shown in **Fig. 2**. Those vertical shafts are composed of large openings on tunnel ceiling with the size of 4 m × 10 m. The openings with large cross-sections bring natural light into the tunnel. On one hand, this provides enough light and maintains good visibility in the tunnel. The system takes advantage of sunlight outside, saves large amount of energy and gives assistance for people's evacuation, On the other hand, sunlight offers a (perhaps false) sense of security, which was expressed by some participants in the later interview. They described like: *"I feel comfortable when running in this tunnel with sunlight coming through the openings. It is different from previous tunnels I have ever driven through."* Though this statement needs further research, it shows occupants' positive attitude towards ceiling openings in the tunnel.

The advantage of natural ventilation has been demonstrated in this experiment with good sunlight in the daytime. The advantage will weaken with less sunshine levels on rainy days and at night, and supplementary light will need to be facilitated to solve this problem in bad weather. Overall, natural ventilation provides a better evacuation environment for people during the daytime and is suitable especially for regions with much sunshine.

(5) Natural ventilation changes a tunnel structure from an enclosed space to semi-

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enclosed. Apart from little noise, immediate operation and sunlight, it enhances the connection between the tunnel inside and the open. Those openings become new outlets besides the exits of both ends of the tunnel. The enhanced connection relieves people's stress and related terrible feeling in a confined space underground, especially in an emergency. Apart from this, it could be used as a fast evacuation route for firefighters. They could climb down through the vertical shafts to the tunnel and aid.

5. Conclusions

This paper describes the performance of participants in an evacuation experiment with smoke in a three-lane urban tunnel with large natural ventilation shafts. These vertical shafts affect people's behaviour and route choice during evacuation. People's behaviour in the urban tunnel has been recorded and described, including route choices, evacuation time, physical condition and their emotional state. Based on people's performance, some analysis concerning tunnel structure's impact and technical installation has been presented. The experiment applied various methods including video recording of participants' whole process of evacuation, some tests concerning their physical condition and some questionnaires and interview after the evacuation. The main conclusions are as follows:

(1) The experiment results showed that natural ventilation in a large urban tunnel, like the Beidi tunnel can provide a positive influence and a safe environment for people to evacuate in a fire emergency because great amount of smoke is exhausted, and sunlight is introduced.

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(2) People tend to evacuate using their original entrance as an exit instead of a nearer one. In addition, they are more likely to approach bright places like ceiling openings in a natural ventilated tunnel. Considering people's preference for brightness, setting information signs in bright places could attract more attention in evacuation.

(3) Ceiling openings have a positive impact on people's evacuation. On one hand, it brings enough sunshine and high visibility. It helps people in finding correct exits and evacuate quickly to exits. On the other hand, natural ventilation enhances the connection between inside and outside, which increases sense of security for occupants.

(4) Light is regarded as the most influential factor assisting evacuation in technical systems compared to information and fire alarm. Instead of increasing the illuminance during tunnel fires, lighting should be set as stable and even since sunlight via natural ventilation is of uneven distribution in the tunnel.

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Figures

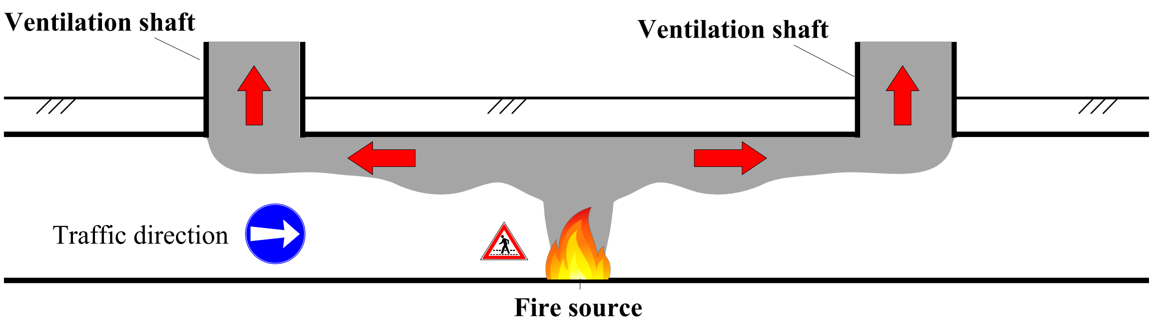

Fig.1 Natural ventilation with vertical shafts

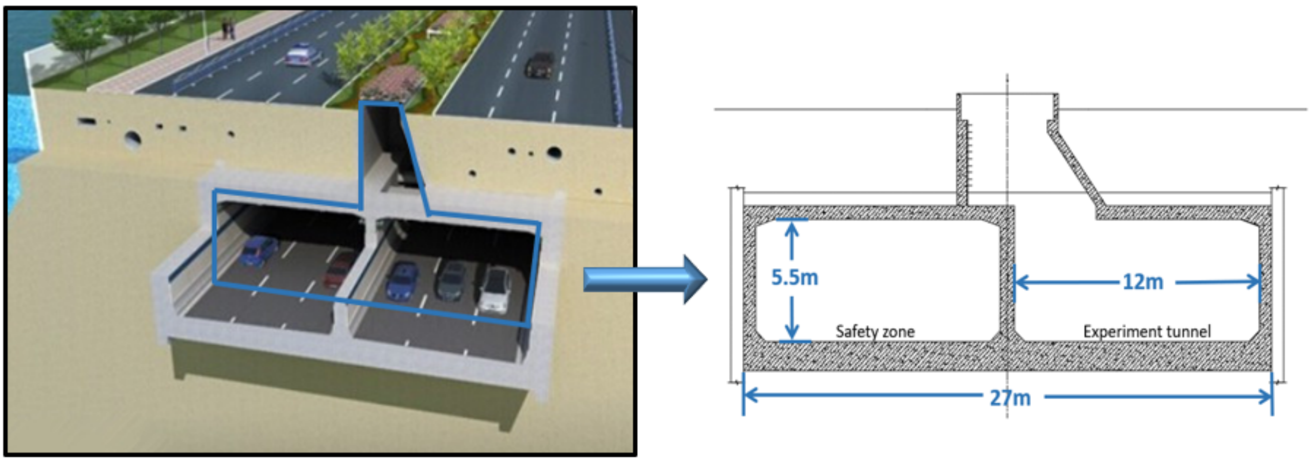

Fig. 2 The dimensions of the experimental tunnel

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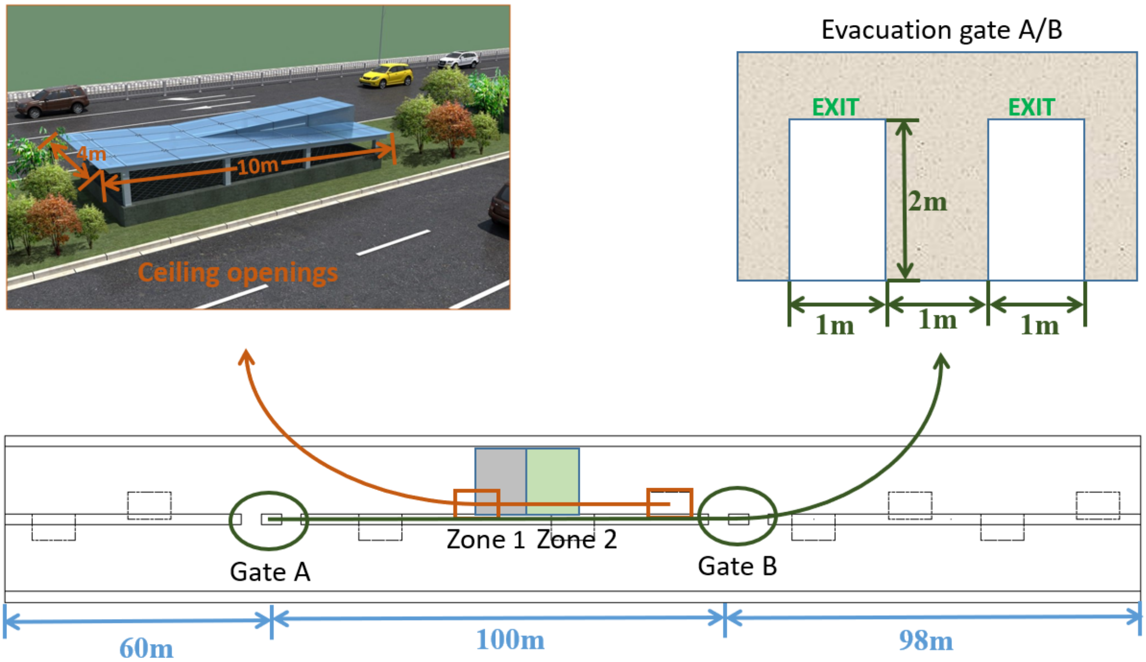

Fig. 3 Detailed size and layout of the experiment section tunnel:

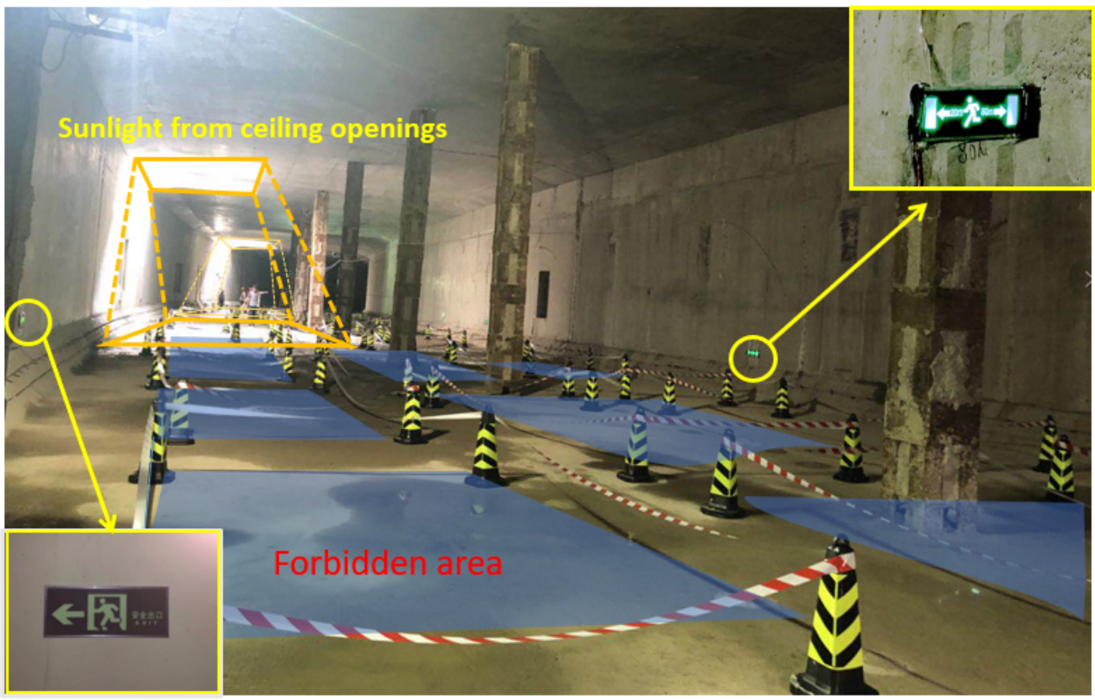

Fig.4 Tunnel with traffic cones and information signs

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(a)

(b)

Fig. 5 Smoke source in the tunnel:

(a) Tunnel with smoke

(b) Smoke cake as smoke source in the tunnel

(a) (b)

(c) (d)

Fig. 6 Four evacuation stages:
(a)Participant took off the blinders and were ready to evacuate
(b) Participants searched for exits in the tunnel
(c) Participants found the exits and ran towards them
(d) Participants evacuated from the smoked tunnel carefully.

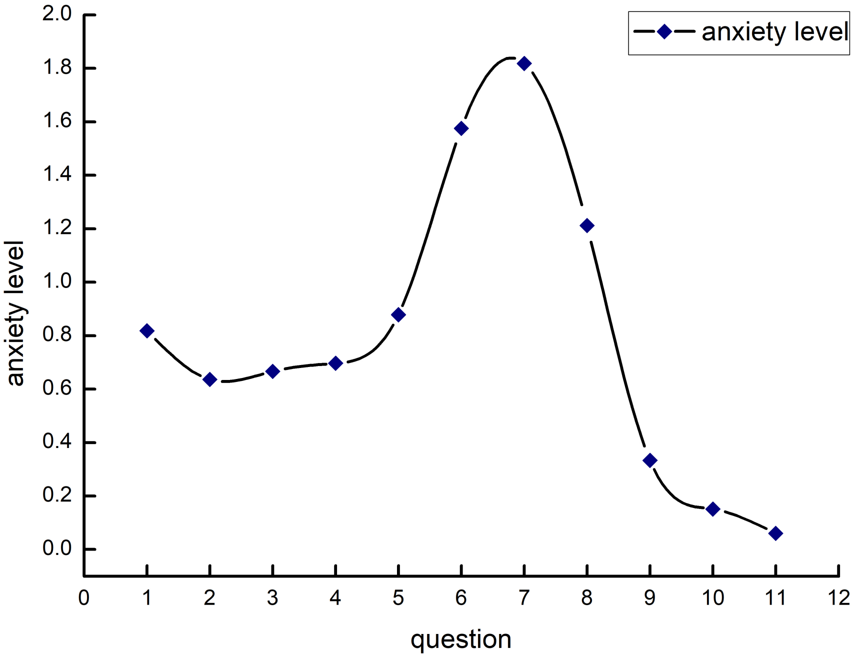

Fig. 7 Average anxiety level change

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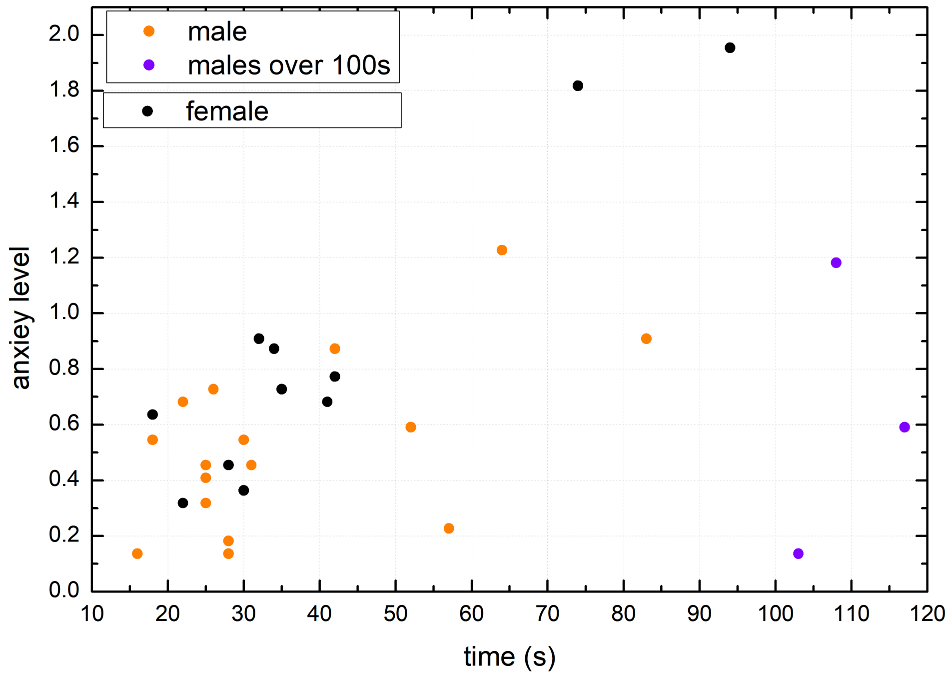

Fig. 8 Individual anxiety level and movement time

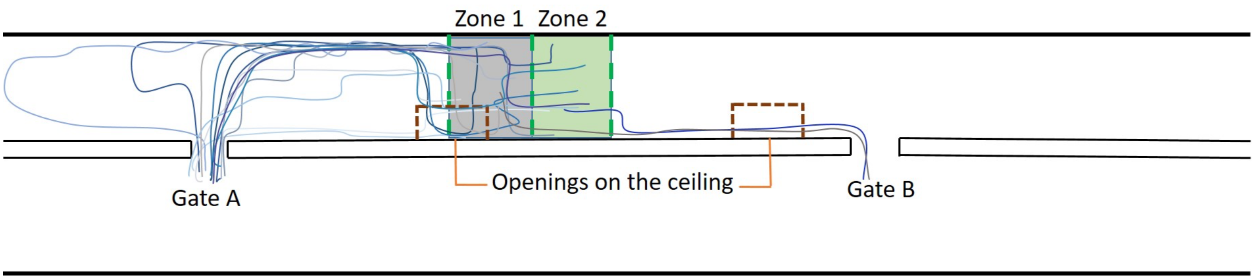

Fig. 9 Track of participants from Gate A

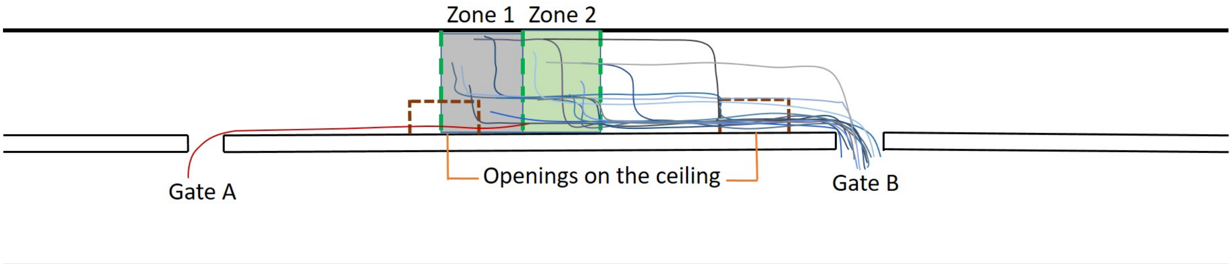

Fig. 10 Track of participants from Gate B

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Tables

Table 1 Participants basic information

Gender	Number	Age	Height（cm）	Weight（kg）	Heart rate
Male	19	33.46	172.54	68.21	74.9
Female	11	31.63	162.02	53.85	78.2

Table 2 Participants' exit choice and their original entrances

Entrance	Starting Zone	Exit	Number	Percentage
A	1	A	7	23
A	1	B	1	3
A	2	A	6	20
A	2	B	1	3
B	1	A	0	0
B	1	B	7	23
B	2	A	1	3
B	2	B	7	23

Note: Entrance A and Exit A is the same pairs of doors, as shown in Fig. 4 as Gate A.

Table 3 Participants' awareness and four-grade rating towards 3 kinds of technical installations

<table>
<tr><td colspan="2" rowspan="2">Technical installations</td><td rowspan="2">Lighting</td><td colspan="3">Information signs</td><td rowspan="2">Alarms</td></tr>
<tr><td>Exit</td><td>Way pointing</td><td>Distance showing</td></tr>
<tr><td colspan="2">Awareness</td><td>53.30%</td><td colspan="3">63.30%</td><td>67.70%</td></tr>
<tr><td rowspan="2">Rating</td><td>Average</td><td>3.27</td><td>2.96</td><td>3.34</td><td>3.01</td><td>2.57</td></tr>
<tr><td>Sd</td><td>0.89</td><td>2.32</td><td>1.01</td><td>2.01</td><td>0.91</td></tr>
</table>

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Appendix Tunnel Anxiety Questionnaire

In this survey, you need to evaluate your anxiety during the experiment Please tell us directly about the feeling of fear in the following situations. Mark your answers by the ratio of numbers. You are free to jump some questions if you did not have similar experience.

The number indicates

0 = no fear at all;

1 = slight anxiety;

2 = moderate anxiety;

3 = strong anxiety;

4=Extreme anxiety.

1. You wore earplugs and blindfolds and the experiment began. 0 1 2 3 4
2. You took off earplugs and blindfolds. 0 1 2 3 4
3. You looked around the surroundings. 0 1 2 3 4
4. You heard the alarms and began to move. 0 1 2 3 4
5. You started to run. 0 1 2 3 4
6. You could not see the surroundings clearly with the smoke. 0 1 2 3 4
7. After searching, you did not find exits. 0 1 2 3 4
8. You saw some signs or some light in the tunnel. 0 1 2 3 4
9. You saw exits in the tunnel. 0 1 2 3 4
10. You ran towards the exit. 0 1 2 3 4
11. You left the tunnel. 0 1 2 3 4

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