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The effect of technical installations on evacuation performance in urban road tunnel fires

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Abstract: Tunnels are separated from the ground by structural linings, and are enclosed and unfamiliar for occupants. In tunnel fires, occupants are faced with a dangerous environment and they need to evacuate. Conveying and obtaining information about the evacuation is the key issue for evacuees. Since tunnels typically have low lighting and little connection outside the tunnel, technical installations are the only approach to deliver information to occupants in order to guide their fast and safe evacuation. This is particularly an issue for urban road tunnels with large occupants' flow in a large underground space. The present study explores the effect and role of technical installations (alarms, information signs, and lighting) on people's evacuation performance in urban tunnel fires, through field experiments, questionnaires and interviews. Theory of affordance (sensory affordance, cognitive affordance and functional affordance) is taken into consideration and provides an integral evaluation for technical installations. Technical installations are useful in helping occupants notice the emergency, find exits and guide path, and information signs are regarded as the most powerful among those three. Besides, this experiment points out some side effect from alarms and ambiguity of signs which will result in serious consequence potentially. This study leads to guidance on improvement of technical installations on evacuation planning and procedures on urban road tunnels.

Keywords: Technical installation, evacuation in fire, human behaviour, urban road tunnels, lighting, alarms, way-finding signs, theory of affordance

1. Introduction

Tunnels have predominantly been constructed in urban area to solve heavy traffic congestion (Dong et al., 2018; Lee et al., 2019). The length of newly built long tunnels has increased exponentially in some large cities. Tunnel design has also become more complicated, moving to from two lanes to multi-lanes, one layer to multi-layers, and having several exits. Large size and complex structures of tunnels aggravates sense of strangeness for people and provide people huge difficulty to respond fast and efficiently in emergency (Ciepiela, 2019).

Accidents due to tunnel fires have provided tunnel designers with a severe problem to solve (Amundsen, 1994; Amundsen and Ranes, 2000). In tunnel fires, hot smoke and toxic gas will occupy the whole tunnel and result in severe consequences to travellers. Enclosed space and insufficient exits can worsen adverse conditions and cause large tragedies, such as the Jinji road tunnel disaster in China which resulted in 31 deaths (Cui, 2014). In early stages of tunnel fires, trapped occupants often have to act as the first responders in the emergency since tunnels are usually confined spaces with too narrow an area to reach out at once (Haghighat, 2019). Unlike other fires in buildings or open sites, the fires in tunnels burn more fiercely in the enclosed space with the influence of heat feedback (Purser and McAllister, 2016). Trucks are another dangerous factor since a large proportion of vehicles in tunnels are trucks, and those who carry oil or chemicals have the potential to trigger explosions and release toxic gas (Carvel, 2005). The burning gas and smoke, on one hand, is a vital threat with potential asphyxia and intoxication. On the other hand, it affects the visibility in tunnels and leads to a lower moving speed and a longer evacuation time. Prompt self-organised evacuation is essential in tunnel fires since fires spread rapidly and violently in a short time (Burns et al., 2013). Many casualties are induced because occupants remain in their vehicles rather than taking action to evacuate. For instance, most of the victims were found inside their cars in the fire in the Mont Blanc tunnel (Kouabenan et al., 2005; Gandit et al., 2009).

Fire engineers and scientists are devoted to solving this problem including advanced smoke control systems in controlling the fire and smoke, and helpful technical assistant systems in leading occupants to evacuate fast and efficiently (Hu et al., 2008; Li et al., 2016). Smoke control systems could be divided into mechanical smoke control systems (point extraction systems and longitudinal systems), and natural smoke control systems that take advantage of pressure difference inside and outside the tunnel (Ingason and Li, 2011; Guo et al., 2018; Tang et al., 2018). The purpose of smoke control systems is to control the smoke in a certain range and to extract smoke out of the tunnel and, furthermore, to slow down the temperature increase inside the tunnel to prolong available evacuation time (Yan et al., 2018; Zhang et al., 2019; Jiang et al., 2020).

In addition to reducing smoke and temperatures in tunnels to improve evacuations, research has made substantial effort to explore and improve efficient tunnel evacuations by providing proper information and guidance. For example, research from social psychology has demonstrated that people in emergencies tend to feel part of a group due to the shared threat of the emergency. This perception of being in the group leads people help one another, such as helping others to evacuate, providing emotional and social support, and delaying their own evacuation time to help others (Drury et al., 2009a, b). Moreover, research using Virtual Reality (VR) simulations of an underground fire has demonstrated that evacuees who feel part of the same group as others are more helpful and act less competitively with others (Drury et al. 2009c). Besides, Moussaid et al. (2010) analysed group walking patterns in low and high density and pointed out that interaction causes unnecessary speed decrease in high crowd density when people get together and communicate.

Research into technical assistant systems has demonstrated that they provide help during the early stages of evacuations through early warnings of danger, providing instructions for decision-making, and guiding evacuees to exit affected tunnel (Cheng et al., 2009; Kobes, 2010; Jeon et al., 2011; Maluk et al., 2017; Omori et al. 2017; Arslan et al., 2019). Various technical systems have been designed and applied in tunnels to assist evacuation such as information signs, alarming, broadcasting, and extra light. (Kim et al., 2016, Olander et al., 2017, Kinateder et al., 2019). For example, Heskestad (1999) reanalysed a Norwegian experiment and discovered that low location lighting provided correct decision-making between 70% and 80% regardless of whether it was electrically powered or photo luminescent. Moreover, Heskestad also found that a visible system emitting green light had a performance level of better than 90%

accuracy.

Further research by Boer et al. (2007) tested the sound function in a smoke-filled tunnel with 75 experimenters. Here, almost 90 percent of participants found the nearest exit with the sole help of sound instruction. Nilsson et al. (2009) and his colleagues explored the effects of lighting in evacuation and found that flashing lights and strobe lights were more helpful compared to standard emergency exit design, and green lights performed better than blue lights or red lights. More recently, Ronchi et al. (2016a) researched lighting via a VR experiment and suggest that green or white light with a flashing rate of 1 and 4 Hz and emitting diode light source as the combination achieves the best performance in guiding evacuation.

Together, research on lighting and sound technical systems indicate that they can provide substantial improvements evacuation behaviour. However, little research has explored the effects of a whole set of main technical systems (lighting, alarming and information signs) installed in a real tunnel. Technical systems work integrally during the whole evacuation process such as by calling occupants' awareness to fires, helping them interpret the circumstances and offering proper guidance in finding their way out of the risk. The key issue for the technical systems is that each part should provide serviceable information without contradiction or meaningless repetition between the different forms of information. Moreover, each part should collaborate with their unique roles rather than misleading the users or burdening them and make no harm to people's health. To achieve this goal, it is essential and beneficial to ascertain the effect and role of technical systems on people both separately and integrally.

In this paper, we measure the effect of technical installation methods (way-finding signs, pre-recorded alarms over loudspeakers, and light) on evacuation behaviour. We conducted field experiments with four conditions in a large cross-section tunnel with different combinations of mainstream technical installations, as shown in Table 1. Using video recording, questionnaires, and interviews, we measure pedestrians' route choice, pre-movement time, movement time and speed, and their physical condition (pulse and blood pressure). Participants' gender, age and occupation are also measured.

The study presents a set of field experiments to weigh the performance of different technical installation combinations and their influence on people during the evacuation. It contributes to an improved understanding of the effects and roles of technical systems on participants' evacuation in a large-long urban tunnel from the perspective of people. Based on the findings, the paper provides guidance in designing the technical system in a large-long urban tunnel considering people's need in evacuation.

2. Experiment

2.1. Tunnel condition

The experiment was designed and conducted in a tunnel, located in the urban area of Shanghai, China. The tunnel is 1780m in length, and is a bidirectional tunnel with three lanes in each direction, as shown in Fig.1. It connects two of the busiest transportation junctions in Shanghai (the Middle Ring and the Outer Ring), and is loaded with high traffic volume every day. The section applied in this experiment was shown in Fig. 2. The slope of the tunnel is less than 1° and its influence is neglected in this experiment. The experiment section covers a total length of 258m with two evacuation gates 100m apart. The distance of tunnel starting point/end point, evacuation gates, and the size of two evacuation gates are indicated on Fig. 2. The distance from the starting point to Gate A is 60m and Gate B to the end point 98m. Gate A and Gate B each have two doors, sharing the same size of 2 m×1 m in height and width. Evacuation gates allow people to evacuate from one side of the tunnel to the other side of the tunnel in case of fire and smoke. Vertical shafts in the tunnel are set every 50 m with the size of 4 m×10 m, bringing large amounts of sunlight to the tunnel in the daytime.

Technical systems in this experiment consist of three categories: information signs, pre-recorded alarming and broadcast, and light. The schematic diagram is shown as Fig. 3 (a).

Three types of information signs are installed in this tunnel. All signs were all back-lit with the size of 23 cm×14 cm, followed by the requirements of Ministry of Housing and Urban-Rural Development, China. There are two signs of the first type, showing exits with "EXIT" hung over both exit door. The other two types were way-finding signs pointing towards the exits in the tunnel, as shown in Fig. 3. They were installed on both sides of the tunnel wall every 20m in the tunnel and each type owns four signs in the tunnel. The difference was the second type showing directions solely, and the third type showing directions and distances to the two nearest exits in two directions. Signs on Gate A and Gate B were "EXIT" signs hung over the gates. Signs with light blue background were showing the evacuating direction, as shown in Fig. 3. Signs with dark blue background were written with distance to the two evacuation gates.

The pre-recorded alarm and broadcast were played by the tunnel public announcement system after the system tested smoke and fire. In this experiment, we simplified the starting time as 10s after the smoke was ignited. The aim of the alarm and broadcast were separate. The alarm was to call attention of the occupants in the tunnel including the drivers and the passengers, and the broadcast was to give instructions during their process of evacuation and escape. The content announced in the tunnel included alert rang for 10s as an alarm for attention accompanied by a sentence informing people there was a fire in the tunnel and instructing people leaving their vehicles and escaping through the nearest exits. All the sentences were recorded in Chinese by a Chinese woman. The alarms were installed in the middle of two exits both sides of the tunnel. The whole broadcast lasted for 30s and repeated per minute. The setting of alarms got help from the research conducted by Omori et al. (2017). Alarms were placed in both sides on the tunnel in the middle part.

The light was composed of two parts in this tunnel. Sunlight went through vertical shafts of the tunnel. Apart from sunlight, complementary lights were installed in the tunnel to maintain good visibility for participants. Light 1 and 2 were sunlight through opening on the ceilings. Light 3 and 4 were supplemental light installed in the upper zone of the tunnel to ensure good visibility. The visibility keeps 100m as a minimum value in the daytime. The visibility was at least 100 m, generally better on the experiment day

2.2. Experiment setup

2.2.1. The participants

There were 40 voluntary participants in total. The participants were divided into four groups with the experiment conditions as listed in Table 1. 10 participants were assigned into Group A with all three types of technical installations. The rest were separated by three groups as Group B, C and D with 10 participants respectively. Four conditions namely A, B, C and D are in accordance with participants in Group A, B, C and D. Paper cards (size: 21cm×30cm) with written numbers were stuck on the back and front of participants' bodies. Cards were tested to be clear enough to record with a certain amount of smoke via cameras. We obtained and recorded participants' basic information including gender, age, occupation and related physical condition prior to the experiment. The detailed information is listed below in Table 2 for each of the four groups.

The ages for all participants ranged from 22 to 55, with 27 males and 13 females. Males and females were distributed evenly in four groups with similar average ages. The age fluctuation of male was relative larger than female with an SD (standard deviation) of 10.6 and 6.7 respectively. We randomly assigned participants into four groups and shortened their difference in sociodemographic data. It is regarded as a useful tool to diminish the possibility of the nuisance variables concerning sociodemographic feature. Participants' pulse and blood pressure were recorded prior to and after the evacuation experiments. 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.

2.2.2. Technical installations and their theory of affordance

Technical systems aim to assist occupants throughout the process of fire emergency evacuations in tunnels. In order to achieve maximum assistance, technical systems ought to be designed to offer or afford according to the need of users. The idea was first put forward by Gibson (1977), as the original theory of affordance (abbreviated as ToA). It contains four types, namely physical affordance, sensory affordance, cognitive affordance and functional affordance. Ronchi et al.(2016b) pointed out physical affordances could be neglected in evacuation systems except using a tool physically like doorknobs. Hence, sensory, cognitive and functional affordance are explained briefly.

(1) Sensory affordance: It is the first step before the evacuation of an accident. Technical installations should provide sensory affordance like seeing/hearing/smelling etc. to catch

people’s attention and make them aware what happens. It is the pre-condition to a fast and effective evacuation. Technical installations with sensory affordance should operate quickly and be easy to recognize.

(2) Cognitive affordance: It helps occupants understand the situation and sometimes gives explanation. Mostly, technical installations with cognitive affordance explain what happens, how it happens and how is everything now. It conveys information through ringing, simple sentences, signs, light or other ways. Expression should be simple to save space/time in spreading the information. To ensure the information be interpreted as intended and do not bring about ambiguity in limited units, the design should be clear and accurate and in accordance with common sense and construction code.

(3) Functional affordance: It helps occupants achieve their goals in evacuation such as where to go, how to go and how long it takes and guides them to reach the safe place eventually. Sometimes, one piece of technical installation plays a dual/triple role with functional and sensory/cognitive affordance together, and sometimes it plays with the help of other technical installations on sensory and cognitive affordance.

Based on ToA, we select three common technical installations in tunnel to investigate in this experiment, namely alarms, way-finding signs, and lights.

1) Alarms consisted of two parts: ringing and warning message. Ringing, as sensory affordance, on one hand, is a common way to express an accident occurs. On the other hand, it catches people’s attention so that they could notice the following message. The warning message usually contains a description of the accident like the type of accident, the exact place it happens, what should people do and when they should take action. Alarms are applied as a combination of sensory affordance and cognitive affordance. It sometimes provides functional affordance depending on if it conveys instructions in the warning message.

2) Way-finding signs play an important role on offering functional affordance. It usually provides information about location and distance to exits and instructs people to find correct way to safe places. In order to be seen easily, signs are designed to be back lit, which add their sensory affordance.

3) Lighting provides good visibility of the evacuation environment for occupants to obtain information. It is the precondition for occupants to get sensory affordance from other technical installations. Lighting are divided into two types in tunnels. Artificial lights are installed to maintain visibility since tunnels are enclosed with little sunlight. The other light, sunlight is based on special construction design with ceiling openings, which permit sunlight through the tunnel in the daytime. Brightness help drivers find the way during their driving in the tunnel. It also helps in cases of emergency for occupants to find guidance and information for evacuation.

2.2.3. Recording routes

We applied various methods to record participants' movement, physical condition, and emotional state via video, health equipment, questionnaires and interviews. We made our best efforts to obtain the data as comprehensively and reliably as possible.

Eight fixed video cameras were applied to record the experiment, covering the tunnel section, two evacuation gates and participants. The video recorders filmed the whole process from when participants entered the tunnel until they got out of the gate and reached the other tunnel (the safety zone). All video recordings were only obtained for to measure their speed, route choice and trajectories in this research.

Three questionnaires were used in this experiment to explore participants' physical and emotional states after the evacuation experiment. The first questionnaire was to evaluate people's physical condition by providing ratings about headaches, sweating, dizziness etc. The questionnaire was adapted from the Simulator Sickness Questionnaire (SSQ: Kennedy et al., 1993) like do you suffer headaches during the evacuation and the level. The second questionnaire aimed to measure the anxiety level in the tunnel: Tunnel Anxiety Questionnaire (Mühlberger and Pauli, 2000) like how much anxiety do you feel when you see the exits of the tunnel. The third questionnaire measured participants' approval towards the function of the technical installations: lighting, way-finding signs, and loudspeakers like have you noticed way-finding signs and did the signs help your evacuation. All questionnaire results were used to complement the behavioural data of evacuation behaviour. Besides, interviews were carried out after the questionnaires about technical installations like the lighting, alarming and way finding signs. Participants' emotional state, their perception towards the technical installations during evacuation were also focused and presented in the next section.

2.2.4. Preparation

A project group in Department of Geotechnics in Tongji University prepared the experiment with the assistance of staff in the tunnel construction program. Specific tunnel section clearance, specification of the accident scenario, installation of related signs, lighting, broadcast pre-recording, design of questionnaires and the checklists for the interviews were done prior to the experiment.

Smoke cakes were chosen as the smoke source without open fire, as shown in Fig. 4. The locations of smoke cakes are shown in Fig. 2. Two sites are set on both sides of the starting area to ensure participants are immersed in smoke with no obvious directional difference. The starting area is in the middle of two adjacent signs. Considering the distance to signs will affect participants' choices, it is the optimal way to minimize this influence on participants.To imitate the traffic congestion in the tunnel once in fire, 200 traffic cones were placed in groups of four on three traffic lanes to form cordoned areas assumed to be vehicles, as shown in Fig. 3(b). Participants were instructed that the cordoned-off area represented cars in the tunnel, and they were only allowed to walk in space that was not cordoned off. To point out, though the cordoned-off area is effective to offer a restricted area the same as a tunnel with traffic jam, it could not block the participants' view as real traffic jam as vehicles own a certain height. This could build a comparable positive condition for evacuation when participants are more likely to see the surroundings and information signs.

2.2.5. Ethical considerations

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 and 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.

2.3. The experiment

The experiment lasted eight hours from 09:30 to 17:30 on 14th Sep. 2018 in the tunnel in Shanghai, China. The experiment repeated 40 times in the following order of Group A, B, C and D, with each participant evacuated individually. We arranged a timetable for 40 participants in four groups. Participants stayed at the nearby rest room on the ground near the tunnel half an hour before the scheduled time. Prior to the experiment, participants were asked to read instructions about the study and were informed that the purpose of the experiment was to study 'human behaviour in road tunnels'. Participants provided their informed consent prior to participation.

Participants' height, weight, ages, pulse and blood pressure were recorded prior to the evacuation. On their way to an assigned starting point in the tunnel, the participants were given blindfolds, earplugs and a bracelet recording their pulse and blood pressure fluctuation. Participants were then led downstairs by assistants to the adjacent tunnel. They were randomly assigned to an entrance of the experiment tunnel and starting point within the tunnel. They were requested to circle around for three times and then took off the blindfolds and earplug. The pre-recorded alarm began the broadcast with an interval time of 10s. The participants then evacuated the tunnel. We regarded a successful escape when the participant got out of their evacuation gate and reached the adjacent tunnel. The smoke produced by smoke cakes filled with the tunnel throughout the experiment. One member of the research staff controlled the smoke levels to maintain the visibility with a range of 5m-10m. Another member of the research staff operated the technical installation changes according to the experimental condition.

After the experiment, participants' pulse and blood pressure were recorded, and they were invited to answer questionnaires. All the questions were printed in advance in Chinese including all the questions and options. Participants were informed that they were free to ask questions and the research staff were available to provide assistance.

3. Results and analysis

The whole evacuation repeated 40 times of 40 individuals consecutively. No injuries or accidents occurred throughout the experiments. All participants evacuated from the gates and reached the adjacent tunnel within four minutes, regarded as a high-security criterion (PIARC, 1999). Results below are based on 40 participants in four groups with different technical installations. Data was statistically analysed by a one-way ANOVA (Analysis of variance). A significance level of five per cent was used in all statistical tests

3.1. Response time

Participants in four groups reacted in a short period less than 10s. The fast reaction could be explained that they were told to be involved in an experiment. There was no significant difference in response time in four groups. However, information from the interviews suggested that the behaviour was not due to awareness of being in an experiment and therefore guessing how to act. Some people in Group C (offered technical installation without alarms) reported they were confused when they were left in the tunnel. Some even said they were imagining if it was a game about seeking treasure. In contrast, people in other three groups did not talk about misunderstanding the task. Though nobody was told about the aim of the experiment, some participants explained that they realized it was an emergency when they heard the alarm ringing.

Considering the theory of affordance, alarms provide sensory affordance and cognitive affordance. In order for occupants to evacuate as intended, the accident must be sensed firstly. As to sensory affordance, alarms catch people's attention and are noticed (heard). It is a warning in case of emergency with general acceptance, therefore, it provides cognitive affordance in the meantime. It supports that people understand the situation they are trapped in. The appropriate interpretation is essential to lead to proper and optimal behaviour. The key issue is that the information should be based on common sense and experience.

A large proportion of people stated they knew it was an emergency experiment due to the alarms, but they could not clearly hear the information from the broadcasts over the loudspeakers. Self-reports suggest that half of them could understand almost 70% content and the other half could only understand less than 50%. It reflects a common problem in broadcasting in sensory affordance, cognitive affordance and functional affordance. The sentences are hard to perceive clearly which causes difficulties in conveying details of the technical systems and the accidents. It fails to provide detailed information and diminishes occupants' understanding of the accidents and ability to make decisions accordingly. Moreover, people could not obtain helpful information from the broadcast and thus they could not follow the suggested evacuation route. Under this circumstance, the functional affordance is diminished partly or wholly according to the quality of the broadcasting.

3.2. Route choice

Participants' route choices are indicated in Fig. 5. Trajectories of Group A, B， C and D were traced and we made a comparison of them below.

Participants started randomly in the grey part of the tunnel shown in the upper part of the figure as starting points. The lines indicated people's route from starting points till they evacuated to the adjacent tunnel. For trajectories affected by technical installations apparently and discussed below emphatically, we draw with full line and the rest with dash line. For all participants in four groups, they preferred to walk along the right side during the evacuation. This has also been found in other experiments such as Zhang et al. (2019b).

The trajectories of Group A (Fig. 5(a)) and C (Fig. 5(c)) are similar in range and distribution while some participants in Group C ran a "circle" or "detour" at the beginning. It could be explained some of participants were confused at the beginning and made some attempts to figure out the scenes, which is in accordance with statements from interview. It suggests ringing from the alarms sent clear message of emergency and evacuation to occupants. From comparison of Fig. 5 (a) and (b), there are big differences in participants' route range. Participants in group A ran between two evacuation gates and evacuated from either gate smoothly. Data from the questionnaires/interviews suggest that the signs with direction and distance helped them locate themselves and the gates. Participants made estimations according to the information signs instead of finding routes at a venture. In contrast, some participants in group B ran beyond the evacuation gate. It shows more obviously in the left part of the tunnel when people tended to run along their right side and the gate was located at the other side.

People stated that they could not locate themselves in the smoke and did not know the rough direction of the gates.

Information signs provide both cognitive affordance and functional affordance. The signs showed the direction and the distance, two key factors in escaping. People made their escaping plans according to obtained information. It is essential for information signs to provide clear and non-misunderstanding information for people understand properly and easily. The design should apply common description and be considered thoroughly in avoidance of misinterpret or chaos.

Four people made a turn at points with more light (both sunlight and complementary light) in group A and three people did that in group B. We concluded that some people preferred to turn to places with more light (see Fig. 5 (a) and (b)). To testify this conclusion, we turned off two extra lights (light 3 and light 4) in group D. Fig. 5 (d) recorded people's trajectories with no extra light. Two people made a turn with light 1 or 2 (openings on the ceiling) but no one turned at light 3 or 4 (turned off). This suggests that light would guide people's evacuation somehow and makes them change their original path to some extent. It appears to be effective to increase the brightness at important points and exits to arouse occupants' attention.

3.3. Time consuming and speed

Average total time of evacuations for that four groups are listed in Table 2. People spent similar time evacuating in group A, C and D from 38s to 48s. Considering their response time was similar, movement time of Group A, C and D was almost the same. According to the route trajectories and route length, the average speed showed no substantial difference around 1.5m/s. In contrast, average total time in Group B was longer than other three groups with a difference of 10s. Three experiments (No. 12, No. 17, and No. 20) in Group B ran a longer distance, as shown in Fig. 5 (b). Fig 6 depicts the curve of participants' speed change and time. The figure shows that participants ran a relatively fast speed in the beginning. The initial speed kept the same level as the other three groups. However, their speed fluctuated in the following section. They increased their speed and then they slowed down, stopped or even returned. They experienced a "trapped" period and then they sped up again until they saw the exit and ran towards the exit with a speed similar as their initial speed.

Three participants explained their speed change in the later interview. They expressed that they became anxious after a short period in the tunnel and tried to run faster to cover more distance in order to find the exit. They turned to slow down or stop because they thought if they missed any guide or hidden exits. It consumed a large amount of time in their evacuation. This phenomenon shows that the decisive factor in the evacuation is not the movement ability, but people's choice and their trapped stage in the whole process. A certain period without finding the exit would arouse anxiety and doubt and this will slow down the running speed, and leads to a long time in evacuation. "Trapped period" will bring about more serious consequence if there were congestion in the tunnel or the route was complex. The evidence suggests that signs, with the affordance of functional, can be helpful to guide people's evacuation.

3.4. Physical condition and emotional state

Physical condition was evaluated by heartrate and blood pressure (Systolic blood pressure, abbreviated as SBP; and Diastolic blood pressure, abbreviated as DBP) in this evacuation experiment. All participants' pulse and blood pressure were recorded before and after the experiment by OMRON HEM-8732T.

We adopted the difference value of pulse twice as Δ_p

$$\Delta_p = pulse_{after} - pulse_{before} \tag{1}$$

Mean arterial pressure (abbreviated as MAP) was applied to value blood pressure difference (Moran, 1995).

$$MAP = DBP + (SBP - DBP)/3 \tag{2}$$

$$\Delta_{MAP} = MAP_{after} - MAP_{before} \tag{3}$$

All the results were shown in Fig. 7. The pulse of participants in Group A, B and D were almost the same with a value of 16, and people in Group C had a smaller pulse increase in the experiment. People in group C also had a smaller MAP increase compared to the other three groups.

Questionnaires were adopted to measure the degree of feeling sick; rewrite from Simulator Sickness Questionnaire (Kennedy et al., 1993) and the degree of anxiety; rewrite from Tunnel Anxiety Questionnaire (Mühlberger and Pauli, 2000), see appendix A and B. The first questionnaire is applied to measure if and how people feel sick during the evacuation aiming to specific symptoms like vomiting, dizzy and short breath. The second questionnaire is applied to measure the anxiety degree from the start of the experiment till their successful evacuation through exit gates.

The emotional condition of group C was similar (Fig. 8). Group C (without alarms) reported a lower level of anxiety than Group B and D, and participants in Group C were not likely to feel sick compared to Group B and D. The index of Group A and C show a similar level in emotional state. It reflects that the effect and side effect of alarms play a comparable role in people's emotional change in evacuation. Considering the side effect of alarms, the design should be careful and scientific based on related performance and test. On one hand, it should be easy to identify alarms from its surrounding with a noticeable contrast in a disordered environment as the sensory affordance. On the other hand, it could minimize the disturbance for occupants while it offers help. Participants without signs reported a higher level especially No. 12, No. 17 and No.20. Their high level of anxiety was not only reflected from the questionnaires but also in the interviews after the experiment. Proper signs decreased people's anxiety, leading to effective action in evacuation. Light also affects people's emotional state to a certain extent. Lack of light aroused people's anxiety and they are more likely to feel sick with related physical symptoms. Sufficient light ensured people could notice signs and exits, and moreover helped people keep calm and feel good.

4. Discussion

The experiment compared participants' evacuation behaviour when subjected to one of three common technical installations: lighting, alarms and way-finding signs. Data concerning response time, route choice, time consuming and speed, and physical condition and emotional state were applied to analyse the effect and role of technical installations based on sensory, cognitive and functional affordance. Fig. 9 shows the integral condition concerning evacuation movement choice of four groups. The figure shows the flow of all participants from group assignment to movement choices. Equal number of participants were assigned to four groups with corresponding technical installations. The second parameter indicates the exit choices of four groups. Though a slight preference could be observed from Exit A over Exit B from Group A and Group D, there is no significant difference of four groups in choosing Exit A or Exit B from statistic results. The third parameter is trajectories range, which refers to participants move between two exits and evacuate from either when approach; or miss the exits and run beyond it. From the curve, almost all participants run towards chosen exit when approach it while two participants in Group C missed it. It suggests that participants are likely to overlook exits without the help of information signs and way finding signs play an important role in guiding exit positions. Regarding to participants' trajectories, most participants run along their right side instead of left side, and there is no distinction among four groups.

Apart from the movement choice, technical installations' awareness and assistance are acquired from questionnaires and interview (see results in Table 3 and Table 4) with the guidance of theory of affordance. The questionnaire involves if people notice the specific types of technical installations and how much they obtained help from the installations during the evacuation. The awareness is evaluated by yes or no regarding to each piece of technical installation, and help is evaluated by four grade rating from 1 (very useless) to 4 (very useful). Average score and SD are presented in Table 4. Below is integral analysis of technical installations considering theory of affordance.

(1) Alarms:

Alarms get wide awareness to most participants during the evacuation. Nearly two thirds participants notice the alarms in Group A, and a slight increase of participants are aware in Group B and D, which they are only offered two types of installations. Participants expressed they got help from alarms with a score between 2 to 3. To point out, the scores were not varied in each group, and the SD keeps small, which suggests alarms play a stable role when combined with other types of technical installations. Though alarms helped participants, which could be verified from the answers in Table 3 and 4, it led to a higher increase in pulse and blood pressure change, see as Fig. 7. One explanation is that sound regarded as noise could stimulate large amount of epinephrine in a short period and bring about increase in pulse and blood pressure

(Peterson et al., 1981). Apart from sensory affordance from ringing, the cognitive affordance of warning message was verified from this experiment since it provides clear explanation of the accidents as a kind of passive information. It passes on information directly without occupants' seeking. To point out, the side effect of alarms on people's health should be taken seriously and treated reasonably and scientifically. High level of sound, regarded as noise, would stimulate the secretion of epinephrine. Epinephrine will bring about excitement, which can either stimulate physical ability, or increase the anxiety level, and trigger high pulse and blood pressure. A noticeable problem in the experiment is the low quality of sound due to the broadcast system and the large size of the tunnel. It would be helpful to diminish echo instead of turning up the volume. The content and presentation need more investigation in future research including the order of the content, how many details should be added, the length of one sentence, how many times repetition and the length of interval.

(2) Way-finding signs:

Three types of signs were applied in this experiment. Among three installations, information signs gained the most attention during the evacuation from Table 3 integrally. Besides, the signs got a higher score in rating assistance. Information signs consist of three types namely exit, direction and distance, and were scored separately, as listed in Table 4. To point out, though three types gained a similar score in each group, their SD ranges differently. The SD of exit and distance are higher than direction, which indicates the rating fluctuations are strong. This could be resulted from participants' varied attitude towards exit and distance, which some of them obtained large aid from those two signs and the others did not. Aiming this issue, more interview was followed and some participants rating low scores claimed that they discover the exit gate without the help of exit signs and some ignored the numbers on the signs showing the distance. Other participants with high scores gave the opposite explanation, stating the exit signs showed gates and the distance helped them to locate the exits. The above indicates that though signs are useful during evacuation, some participants do not fully take advantage of them and make judgements without those hints. Guidance for signs layout suggest that the height of signs is important. Since smoke accumulates in the upper area of the tunnel, people tend to bend their bodies running and finding ways in avoidance of exhausting dust and smoke, as shown in Fig.

10. Thus, signs should be installed with the height of an adult bending his body. People are likely to overlook them if too high or too low. We put forward the optimal height of 1.0m. Design should be in accordance with common sense and construction code to fulfil cognitive affordance. Conflicting information would contribute to a long evacuation and cause unpredictable consequence like congestion or getting lost. Some related research has been conducted by Kinateder et al. (2019) and Ronchi (2016a) to investigate the ambiguity of signs with unclear expression or sign color. The results showed any ambiguity tend to bring about unpredicted worse evacuation. Engineers should make every effort to avoid contradictory or repeated information in pointing the way. It should also be noticed if there were any different meanings interpreted by occupants.

(3) Lighting:

Lighting brings good visibility in the tunnel and therefore ensures participants observe the surrounding layout, read way-find signs and find exits. An interesting comparison were showed in Table 3 and 4 as to the awareness and help of lighting. Lighting gained the least awareness among three installations and had a highest score rating assistance. Some participants explained they were not aware of lighting as sunlight is surrounding daytime and then they realized that their movement towards exit and other behaviour like reading information on signs relied on sunlight. Apart from this, we found lights own cognitive affordance in this experiment that people tend to walk towards light on purpose or even unconsciously sometimes. Engineers are expected to take advantage of this point like increasing the brightness near the exit to catch occupants' attention. Brightness also contributes to a safer feeling on mental health in emergency from participants' later interview. This may be a reasonable explanation to participants' approach to lights/ceiling openings in the experiment. Another different light to point out is flashing lights, usually installed at emergency exit portals. Ronchi (2016a) and his group did a set of VR experiments about the colour, flashing rate, light source etc. It proved that flashing lights own both sensory affordance and cognitive affordance in helping occupants' evacuation.

5. Conclusion

This paper conducted a set of field experiments with four groups to investigate the role of technical installations for evacuation in fire in large-long urban road tunnels. Four groups were provided with different technical installations and evacuated individually from the tunnel with fire (smoke) to an adjacent tunnel. The effect and role of technical installations are measured and analysed according to occupants' evacuation behaviour from various ways including: video recording, questionnaires and interviews. Some of the main conclusions are as follows:

(1) The performance of three typical technical installations: alarms, way-finding signs and lighting are analysed and discussed based on ToA (Theory of affordance: sensory affordance, cognitive affordance and functional affordance).

(2) Alarms offer important sensory (ringing) and cognitive (warning message) affordance. Meanwhile, the side effects from noise on health care e.g. fast pulse rates, high blood pressure, and high anxiety level are observed. Therefore, engineers should take it seriously in evacuation planning and improve the effect of alarms via proper volume and frequency.

(3) Way-finding signs were significant in guiding evacuees route finding. Information about distance and direction were helpful for people locating themselves in comparison to the location of exits.

(4) People were likely to be trapped (slowing down, stopping, or running back) after they search exits for a short period, and the trapped stage expanded the evacuation time and greatly decreased the evacuation efficiency.

(5) Both supplemental light and light through openings on the ceiling attracted some participants on the way to exits and a certain number of people made a turn at brighter points. Brightness suggests a safer feeling for people during their evacuation mentally.

In summary, key evacuee behaviour was recoded and analysed response time, route choice, time and speed, and physical condition and emotional state in this experiment. It is regarded as valuable data to investigate human behaviour in a full-size field experiment in a large urban road tunnels. It gives a comprehensive understanding of relationship between current technical installations in tunnels and occupants' need in evacuation. This research gives suggestions in providing proper information from technical installations to guide occupants' evacuation based on ToA. Considering people's need and health care, we should be responsible and take care of both the effects and side effects of every piece of information we offer.

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Appendix A Sickness Questionnaire

In this survey, you need to evaluate your sickness during the experiment Please tell us directly about the feeling you had during the experiment. Mark your answers by the ratio of numbers.

The number indicates

0 = none;

1 = slight;

2 = moderate;

3 = strong;

4 = Extreme.

1. General discomfort	0 1 2 3 4
2. Fatigue	0 1 2 3 4
3. Headache	0 1 2 3 4
4. Eye strain	0 1 2 3 4
5. Difficulty focusing	0 1 2 3 4
6. Increased salivation	0 1 2 3 4
7. Sweating	0 1 2 3 4
8. Nausea	0 1 2 3 4
9. Difficulty concentrating	0 1 2 3 4
10. Blurred vision	0 1 2 3 4
11. Dizzy	0 1 2 3 4
12. Vertigo	0 1 2 3 4
13. Stomach awareness	0 1 2 3 4
14. Burping	0 1 2 3 4

Appendix B 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

Table 1. Four groups of participants and provided technical installation settings

Condition	Group	Number	Technical installations
A	A	10	Lighting, alarms and information signs
B	B	10	Lighting and alarms
C	C	10	Lighting and information signs
D	D	10	Alarms and information signs

Table 2. Basic information for participants in four groups

Group	Male/Female	Min/Max age	Average age	Time
A	7/3	24/53	32.1	38.1
B	7/3	22/50	35.2	53.7
C	7/3	22/45	32.2	42.4
D	6/4	22/55	33.1	48.1

Table 3. Participants' awareness towards technical installations

Group	Lighting	Alarms	Information signs
A	53.3%	63.3%	67.7%
B	60%	80%	—
C	70%	—	70%
D	—	70%	80%

Table 4 Participants' four-grade rating towards 3 kinds of technical installations

Participants	Value	Information signs			Alarm	Lighting
		Exit	Direction	Distance		
Group A	Average	2.96	3.34	3.01	2.57	3.27
	Sd	2.32	1.01	2.01	0.91	0.89
Group B	Average	—	—	—	2.53	3.15
	Sd	—	—	—	0.90	2.04
Group C	Average	2.98	3.31	2.93	—	3.25
	Sd	2.37	0.96	1.95	—	0.92
Group D	Average	2.98	3.31	2.93	2.48	—
	Sd	2.37	0.96	1.95	0.99	—

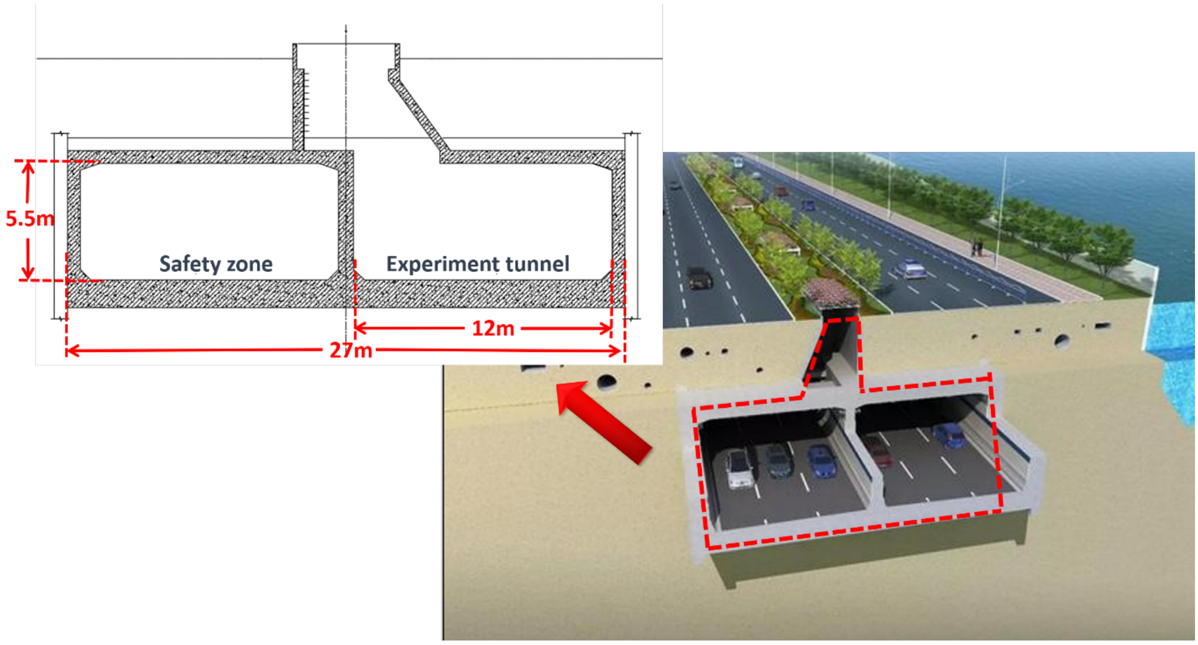
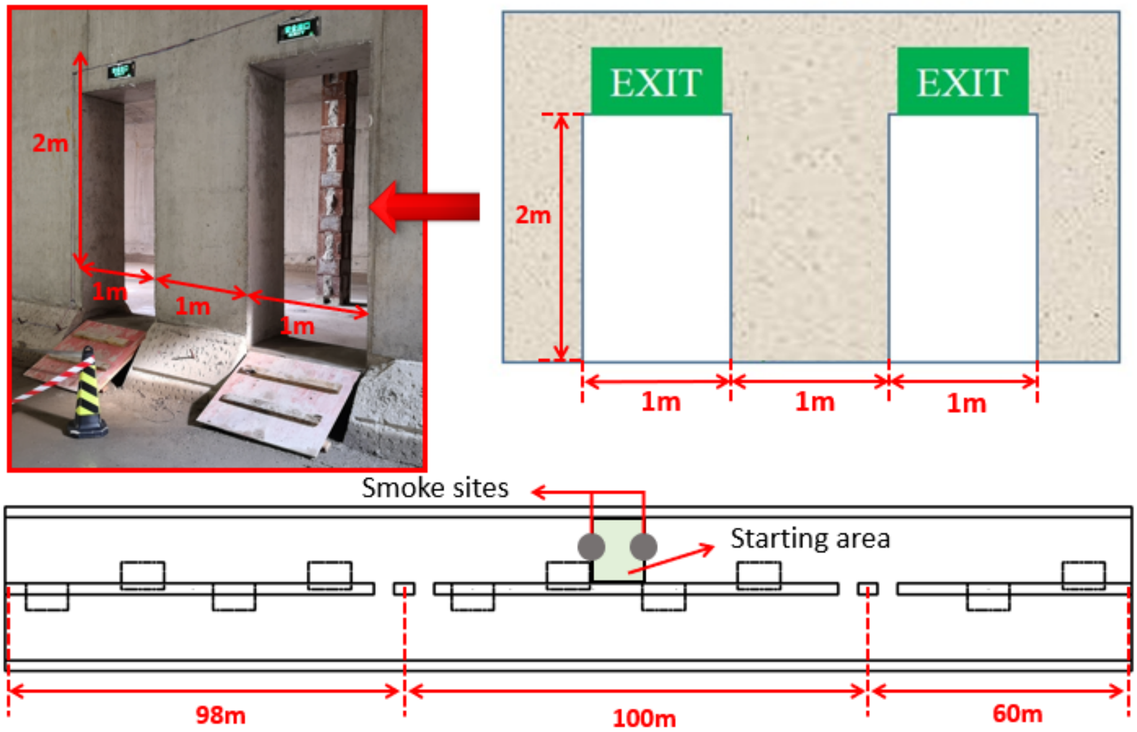
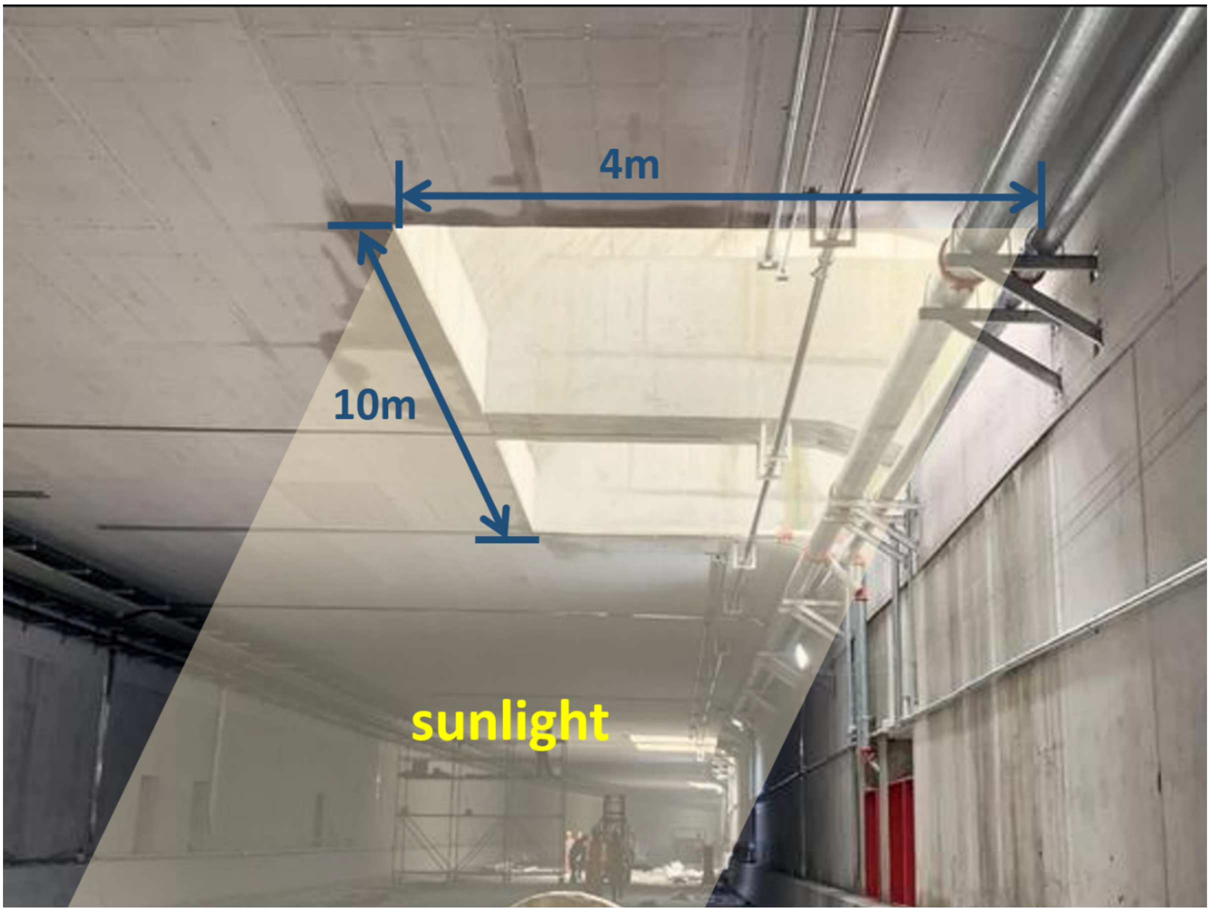


Fig. 1 The outlook and cross section of the experiment tunnel



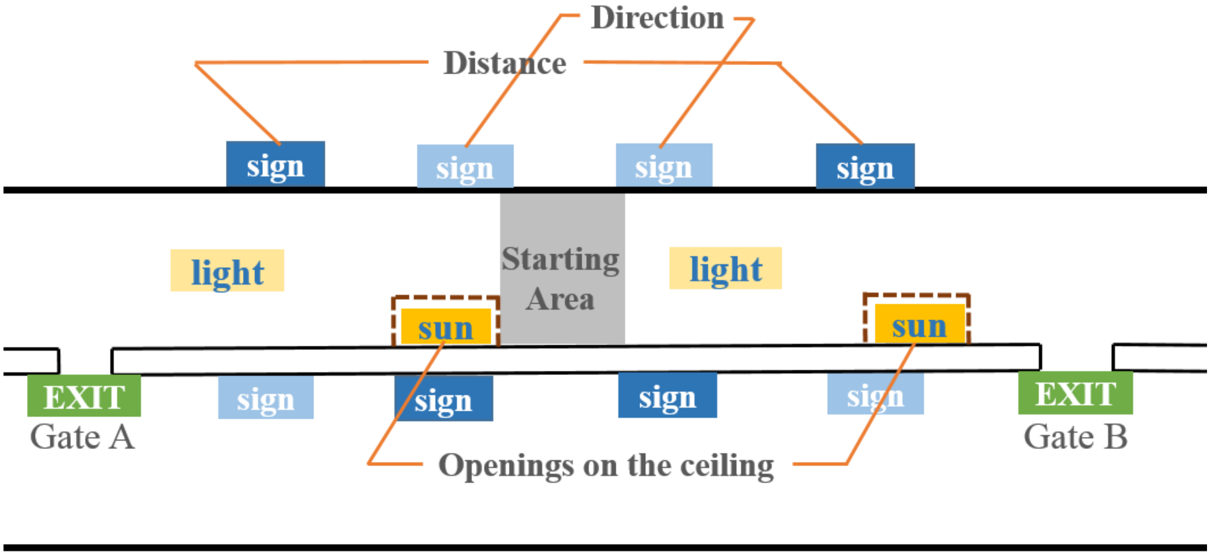
2m
1m
1m
1m
EXIT
EXIT
2m
1m
1m
1m
Smoke sites
Starting area
98m
100m
60m

(a)

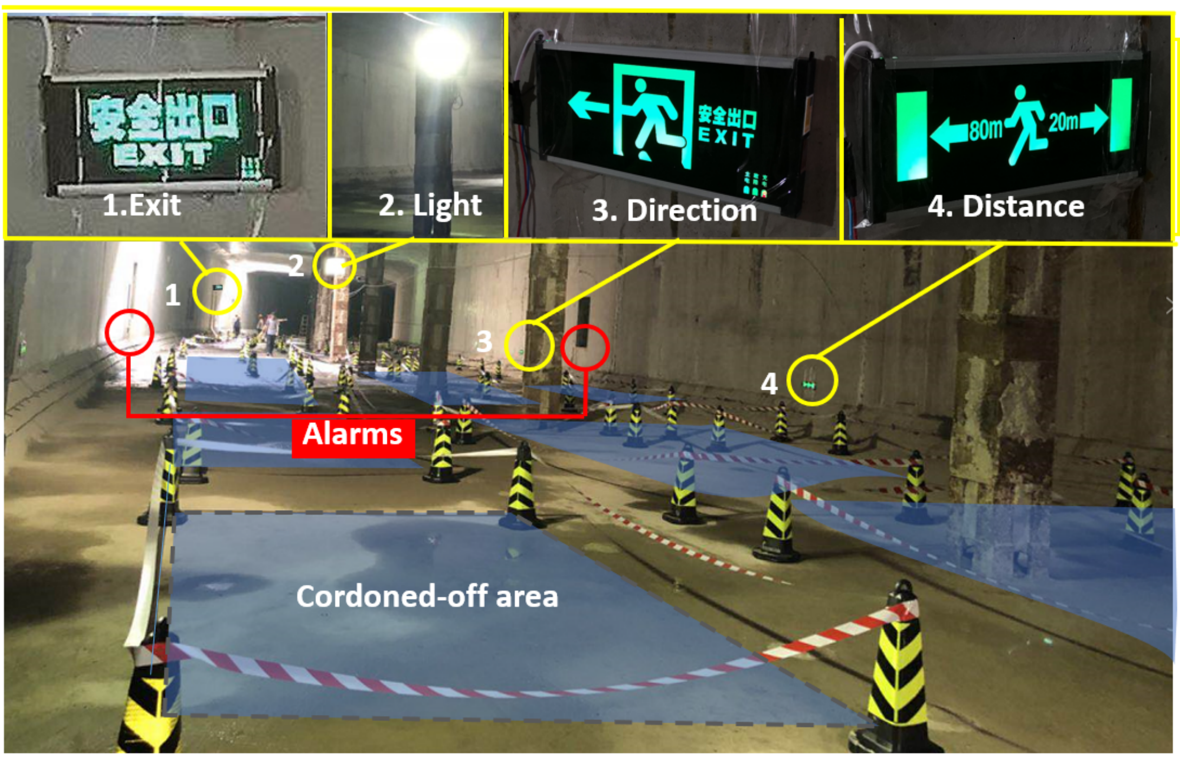


(b)

Fig. 2 Experiment section tunnel size and layout:
(a) Top view of experiment section and evacuation exits dimensions
(b) Cross section of the experiment tunnel



(a)



(b)

Fig.3 Technical installations in the tunnel

(a) Schematic diagram of technical installations

(b) Cordoned-off area and three kinds of way-finding signs, alarms and light in the tunnel

(a)

(b)

Fig. 4 Smoke in the tunnel:
(a) Ignition of smoke cakes
(b) Tunnel filled with smoke

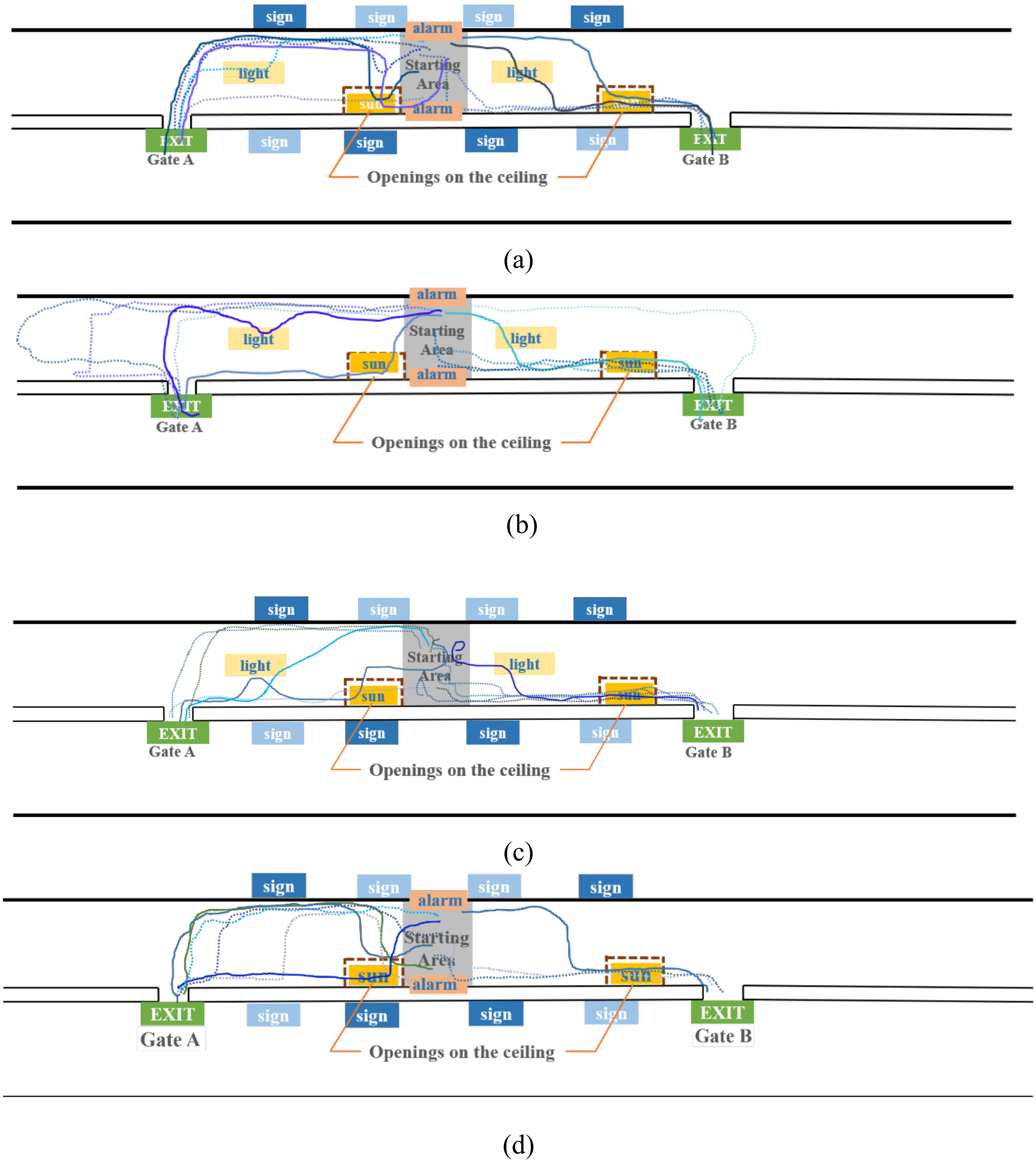


Fig. 5 Route choice of experiments

(a) Group A/ Condition A
(b) Group B/ Condition B
(c) Group C/ Condition C
(d) Group D/ Condition D

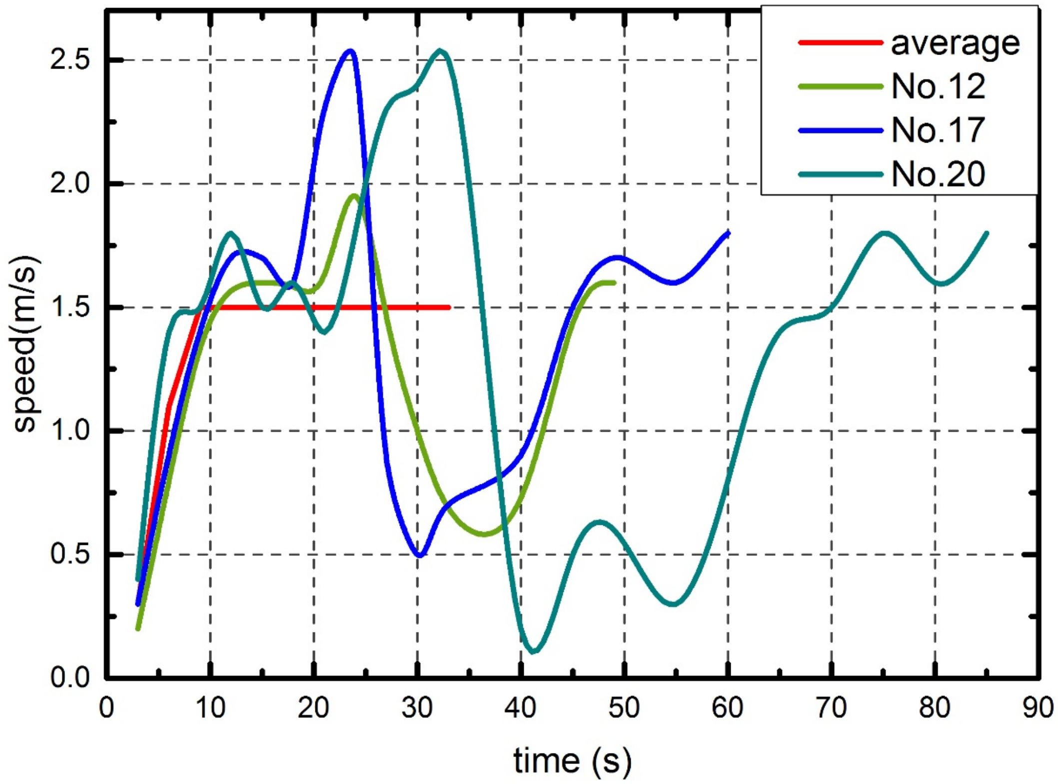


Fig. 6 Average speed and speed change of three particular participants

(a) (b)

Fig. 6 Occupants ran towards their right side along the tunnel during the evacuation
(a) move to the right side
(b) move forward

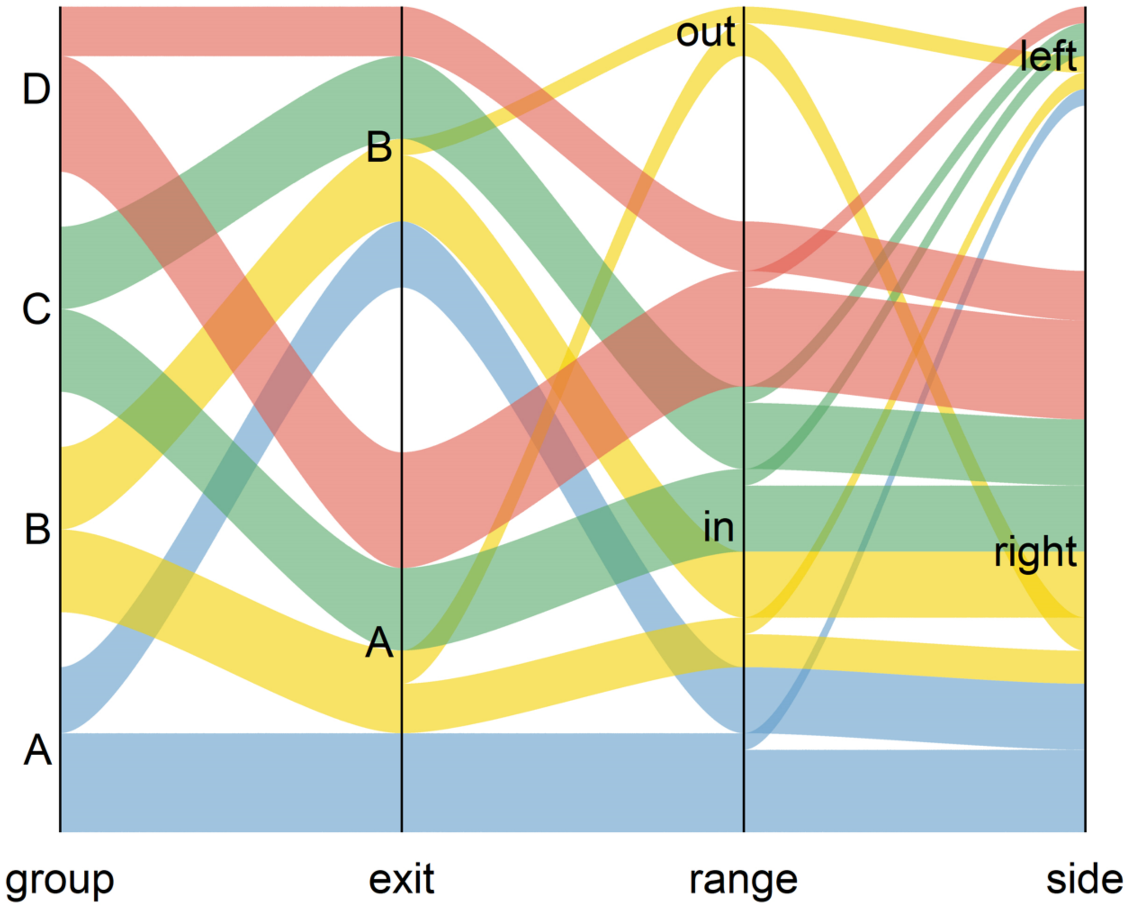
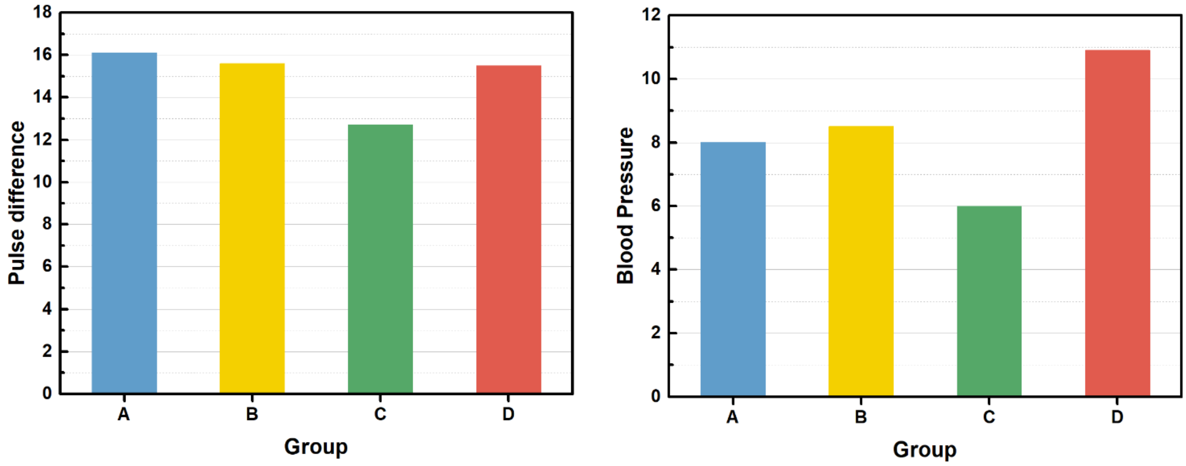


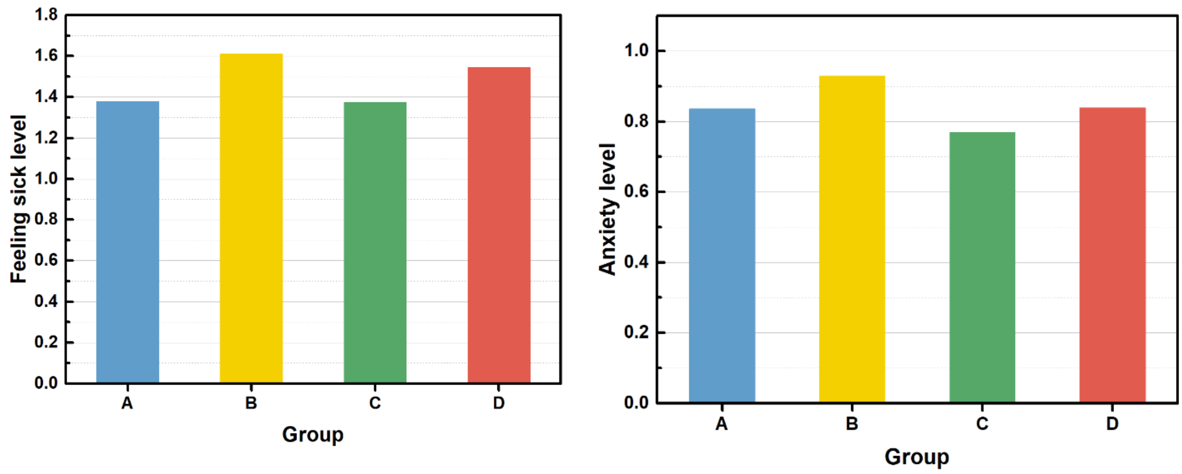
Fig. 7 Occupants' groups and their movement during evacuation

Fig. 9 Occupants bend their bodies during their evacuation



(a) Pulse difference for four groups (b) Blood pressure difference for four groups

Fig. 10 Average pulse and MAP difference of four groups



(c) Feeling sick for four groups (d) Anxiety for four groups

Fig.11 Emotional state for four groups