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Research article

A study of the cognitive process of pedestrian avoidance behavior based on synchronous EEG and eye movement detection

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ABSTRACT

Pedestrian avoidance behavior often occurs in underground public spaces that connect urban rail transit and commercial complexes. This study proposes a co-monitoring method based on eye movement and electroencephalogram (EEG) to study pedestrian avoidance behavior in a real environment, taking the underground public space of the commercial complex of the Luoxiong Road railway station in Wuhan City as an experimental site. It is found that pedestrian avoidance behavior is influenced by both personal and environmental factors. The pedestrian avoidance behavior is a comprehensive response to the evaded person and the current environment. The personal factors mainly affect the pedestrian avoidance mode, while the environmental factors mainly affect the frequency of avoidance behavior. Avoidance patterns are related to the tendency of Chinese pedestrians to walk right, and the frequency of avoidance behavior is related to the complexity of the intersection of pedestrian walking routes within the environment, so avoidance behavior can be reduced by using spaces with good spatial connectivity in the design of underground public spaces. These findings provide theoretical support and data supplement for future environmental design optimization of underground public spaces.

1. Introduction

Whether it is an urban complex or underground public space development, the purpose is to create space for pedestrian walking activities [1,2]. Pedestrian activity-oriented study is receiving more and more extensive attention in the field of urban planning and architecture [3,4]. If the impact of pedestrian behavior is adequately considered in the design of underground public spaces, a more comfortable public space is bound to arise. The high speed, convenience and powerful capacity of rail transit provide huge and stable pedestrian flow to the whole commercial complexes in the subway station area [5]. Pedestrians from all directions are often intertwined in the underground public space of the commercial complex in the subway station area, so pedestrian avoidance behavior often occurs in these public spaces. Based on these points, avoidance behavior is the key to the study of pedestrian walking in public spaces. The core of this key point is to analyze the movement patterns of pedestrians, that is, how they avoid colliding with each other [6]. Unlike study conducted under artificial conditions, this study was conducted under natural conditions. The spatial environmental factors during walking are also different from those in other situations. In addition, the frequency of avoidance behavior is essential evidence to study the availability of a comfortable walking environment in public spaces.

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For the study of avoidance behavior, most of the previous experimental methods are simulations of pedestrian flow, and it is difficult to describe the process of individual avoidance behavior rationally. Wearable instruments such as eye-movement can not only accurately record the gaze information of the human eye during avoidance behavior [7], but also capture the subconscious avoidance behavior of individuals. These instruments can therefore provide a more objective picture of individual avoidance behavior. In view of the complexity and subjectivity of avoidance behavior, this paper takes the underground public space of the commercial complex of the Luoxiong Road underground station in Wuhan as an experimental case and conducts eye-tracking experiments in a real-life environment to explore the avoidance behavior of pedestrians in the underground public space of large commercial complexes, to explore the similarities and differences in the avoidance behavior of pedestrians in complex underground public spaces. This experiment provides theoretical support and data validation for the optimization of underground public space design.

The main objective of this study is to elucidate the characteristics and influencing factors of pedestrian avoidance behavior in underground public spaces.

a. Clarify the differences in avoidance behavior when pedestrians are confronted with different avoidance targets.
b. By analysing the factors influencing avoidance behavior, an optimal design strategy that is more in line with the characteristics of the underground pedestrian public space is proposed.

2. Experiment

2.1. Underground public spaces

The 'underground public space' in this study refers to the space between the commercial complex and the metro, which shares the function of the metro exit and the access or entrance to the commercial complex. It also serves as a link between the two different functions of evacuation space and commercial activity space. The "underground public space" is a complex space that is closely linked to the metro station concourse and the commercial complex and influences each other. The design and use of this space has a direct impact on the efficiency and safety of the pedestrian flow through the commercial complex [8].

The underground public space is mainly used by the underground rail system, the surface transport system and the underground pedestrian system. Compared to the surface, underground transport systems are walking system and have a simple flow, making them safer and more convenient, and their enclosed spatial properties are less susceptible to natural weather [9].

The underground public space connected to the Wuhan World City Plaza and Yuexinhui at the Luoxiong Road underground station in Wuhan was selected for the study, this metro station is located on the southern extension of Wuhan's rail line 2 [10]. The experiment was conducted on weekday at an ambient temperature of 23–27 °C and humidity of 40%–65%.

2.2. Tool

The NE8 wireless EEG device from Neuroelectrics (Spain) captures the electrical signals from the cerebral cortex by fixing electrodes to the scalp, amplifies the raw physiological electrical signals through an amplifier, converts them into digital signals and transmits the data via wireless Bluetooth to a PC for further analysis by software. The Dikablis Pro eye-tracking device (wireless) from ERGONEERS, Germany, records the visual field scene of the test subject through the scene camera of the head-mounted device and superimposes the gaze points on the scene video, which is further analyzed statistically. The tools used in this study were a digital camera and Dikablis Pro eye-tracking device (wireless) and NE8 wireless EEG; the mapping and analysis software used were NIC-offline, D-lab, Depthmap, AutoCAD, PS and Excell.

2.3. Experimental subjects

The NE8 wireless EEG and Dikablis Pro oculomotor were used to record real EEG data and eye movements in the visual field during the experiment, allowing for a consistent calibration process and minimising data loss in the event of extreme action behavior. Twenty-five subjects (double-blind) were recruited, 14 males and 11 females, all aged 18–26 years, 6 office workers and 19 students, all of whom followed the specific criteria for this experiment, i.e. normal naked eye vision, non-color blind and color blind [11]. The experimental procedure was conducted under conditions that protected the privacy of the subjects and the people appearing in the video, and the experiment had no self-evident adverse physical or psychological effects on the subjects.

The relevant procedures of this experiment were carried out after obtaining the informed consent of the subjects.

2.4. Experimental design

The task of the experiment was to have the subjects find a specific location at the experimental site. In order to reproduce as realistic a scenario as possible, the experimental design only limited the target nodes on the way, without imposing or pre-determining a specific route. At the same time, taking into account the differences in the behavioral habits and range of activities of users of different genders in underground public spaces, targets with less obvious gender characteristics (e.g. signs, food and beverage shops, etc.) were selected as target nodes as far as possible to avoid experimental errors caused by the differences in familiarity of subjects with the environment due to gender differences [12,13]. The spatial layout of Stage 1 was linear, with a regular arrangement of businesses; the spatial layout of Stage 2 was an asymmetrical ring, with a scattered and irregular arrangement of businesses; the spatial layout of Stage

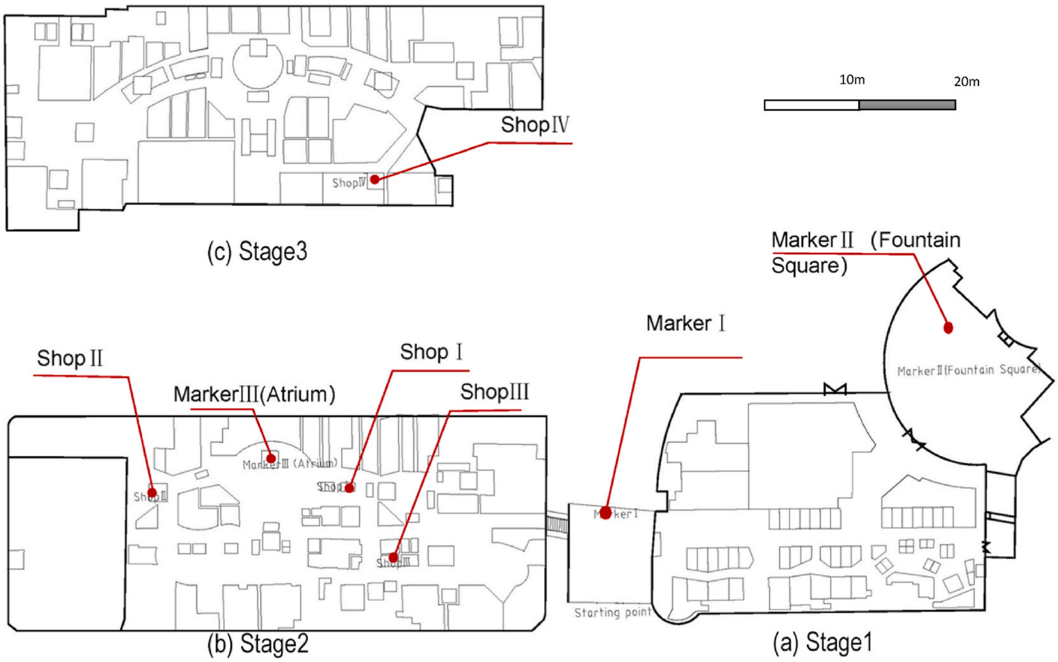


Fig. 1. Schematic diagram of the experimental site plane and the target task point.

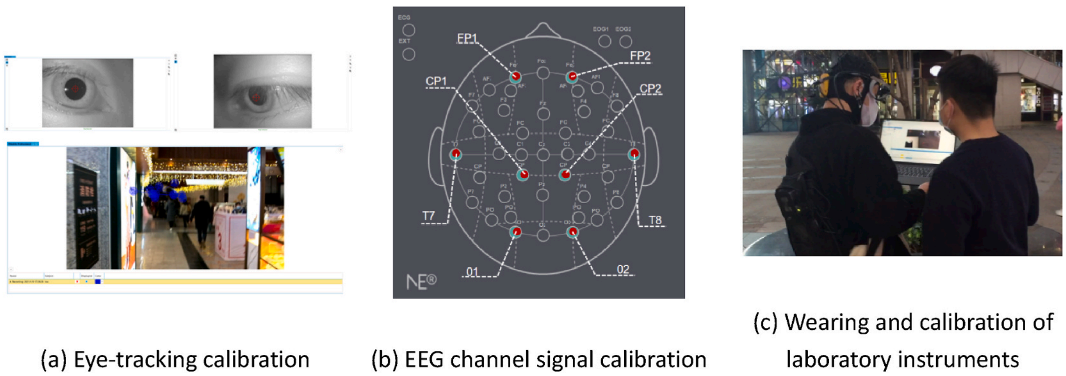


Fig. 2. Experimental calibration.

3 was a symmetrical ring, with a scattered and regular arrangement of businesses (Fig. 1).

Stage 1 route: underground entrance to the mall (starting point) - Marker I - Marker II (fountain plaza) - escalator.

Stage 2 route: escalator - Shop I - Marker III (Atrium) - Shop II - Shop III - escalator to the upper level.

Stage 3 route: Escalator - Shop IV (Each stage task point is shown in Fig. 1).

The specific location of each stage task point was not given in the experiment and subjects were required to find their own way according to the signage instructions.

2.5. Experimental procedure

The specific steps of the experimental process are.

a. The subject is guided by the experimenter to the designated task starting point, where the experimenter introduces the experimental procedure and precautions to the subject.
b. The subject is helped to put on the EEG and oculomotor and calibrate them, and only after the calibration is completed (Fig. 2) can the next step of the experiment be carried out.
c. The subject completes the pathfinding experiment while the experimenter follows the experiment with the camera equipment.

Fig. 3. Trajectory diagram of the subject's travel.

d. At the end of the experiment, the experimenter confirms with the subject whether avoidance behavior has occurred based on the screenshots and EEG movements.

2.6. Research object

Usually, the research on avoidance behavior is to simulate the pedestrian flow through software, and the variables involved are mostly changes in the walking speed of pedestrians. However, pedestrian avoidance behavior is also of great significance to the study of architecture. We used eye movement EEG monitoring to obtain the subject's walking movement line. On the movement line timeline node, we use the follow-up video and D-lap software to intercept the subject's movement in this area. The eye movement trends of time nodes were used to determine the time and space points of the subjects' avoidance behavior. The time point of the subject's avoidance behavior is first determined by the time axis of the subject's walking line, and then the inflection point of the walking path at this time node is the space point of the avoidance behavior.

Therefore, the definition of avoidance behavior in this paper is that the main direction of pedestrian walking in the underground public space remains unchanged, but the walking behavior of the inflection point of the path occurs.

3. Analysis of pedestrian movement attributes

3.1. Differences in pedestrian walking behavior

3.1.1. Static traffic characteristics of pedestrians

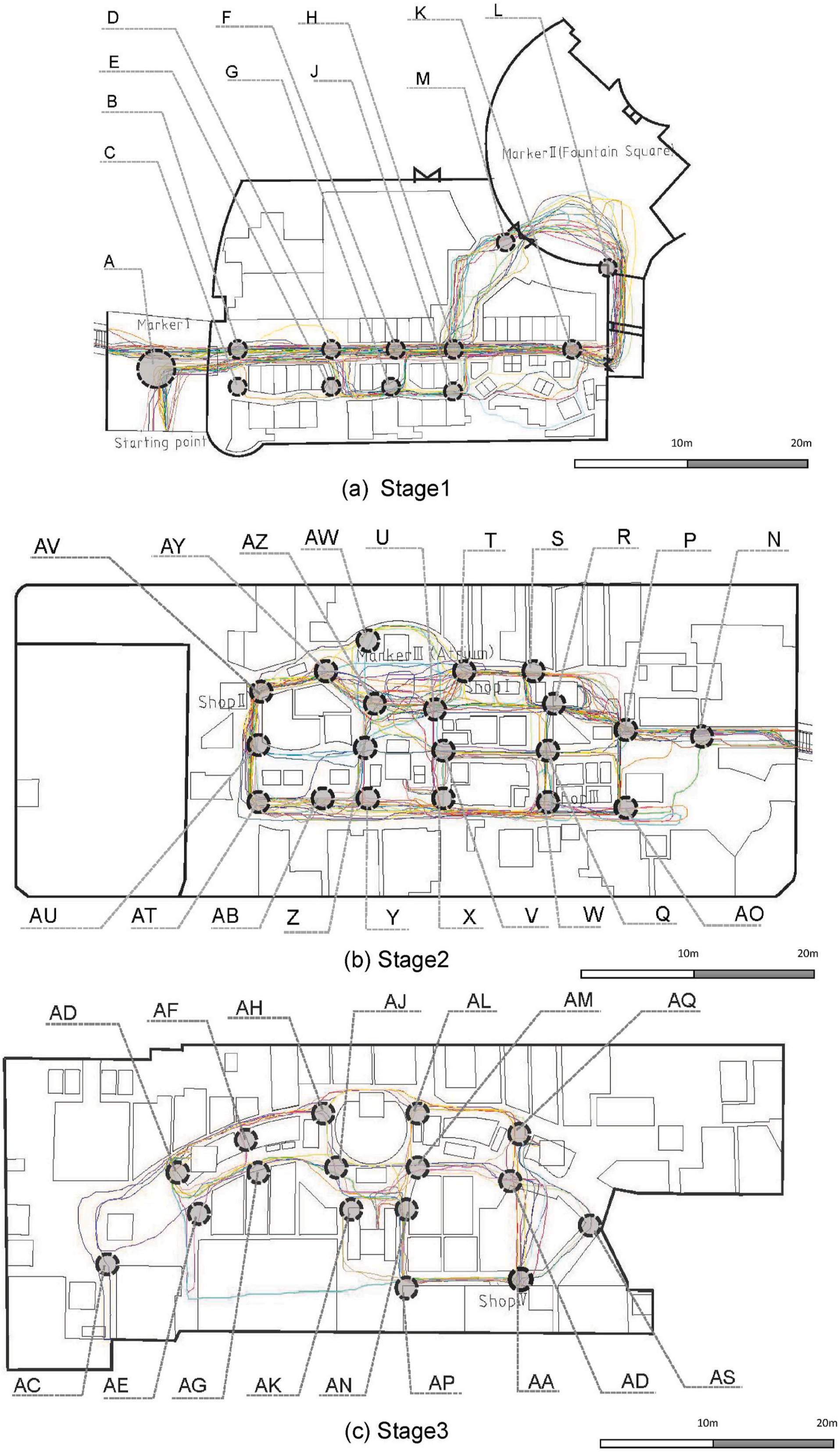
Static traffic characteristics are the state attributes of an untraveled pedestrian at rest [14]. This state attribute refers primarily to the spatial extent and the relevant factors are firstly the individual pedestrian's physical condition and secondly the safe distance between the pedestrian and other pedestrians or obstacles [15,16]. The size of the pedestrian is mainly determined by the size of the pedestrian himself, with two reference indicators, shoulder width and chest thickness [17].

In the previous related studies, Fruin views stationary pedestrians as an elliptical area with a short axis length of 0.5 m and a long axis length of 0.6 m, which breaks away from previous studies of circular particle-like pedestrian flows [3]; Still's study of the static spatial demand for pedestrians in different regions of the world also shows that it is reasonable to view stationary pedestrians as elliptical when studying pedestrian flows [18].

Based on the static traffic characteristics of pedestrians, this study considers the avoidance object as an ellipse when drawing the subject's movement line so that it has the side-to-side property.

3.1.2. Pedestrian dynamic traffic characteristics

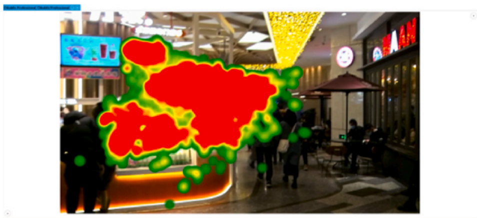
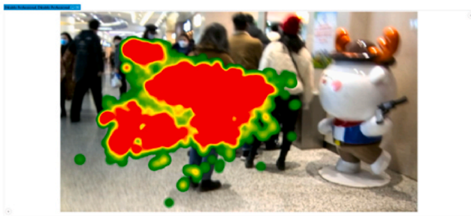
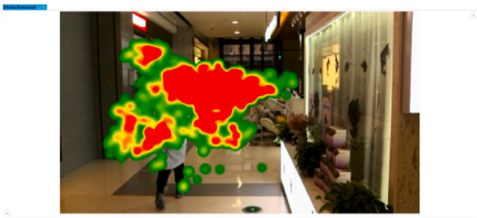
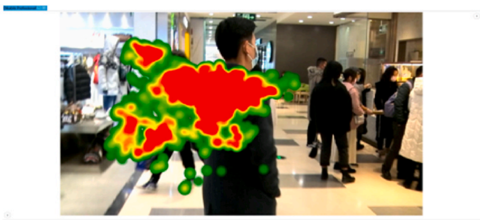
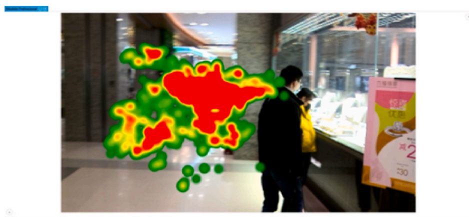
The main reference indicators for the dynamic traffic characteristics of pedestrians are step frequency, step speed, step length and



(caption on next page)

Fig. 4. Schematic diagram of the partitioning of the experimental Stages.

Table 1
Eye movement data analysis of subjects' avoidance behavior.

Avoidance of objects	Left	Right
Obstacles		
Opposite direction Pedestrian		
Same direction pedestrian		
Stationary Passerby		

the dynamic demand space of pedestrians while walking, which are described as follows [19].

3.1.2.1. Step frequency. Step frequency is the frequency of steps taken by a pedestrian during a walk, and refers to the number of times a pedestrian has landed on both feet per unit time [20]. The experimental environment studied in this article is an underground public space where pedestrian step frequency is relatively consistent.

3.1.2.2. Step speed. Step speed is the general sense of walking speed, and the speed of pedestrians is related to their own physical

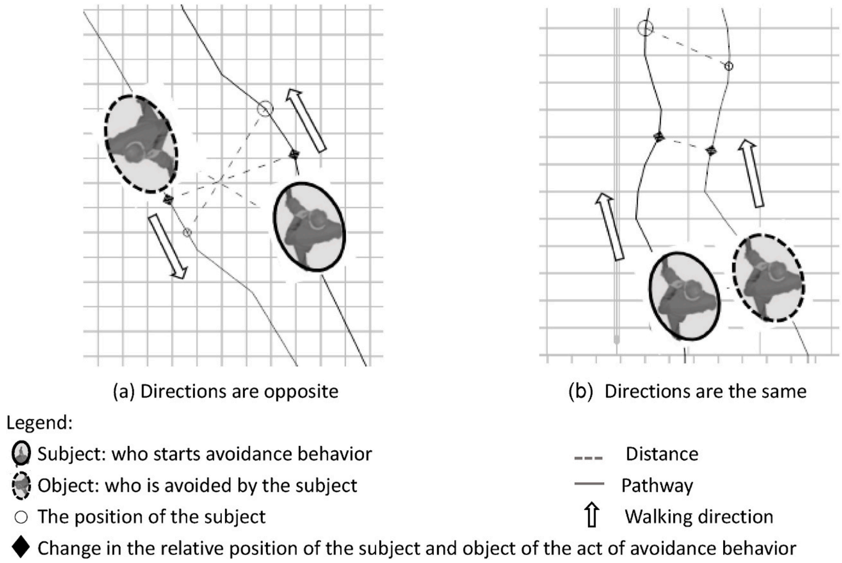


Fig. 5. Diagram of pedestrian avoidance behavior.

fitness and age and gender differences, etc [21]. According to the road capacity handbook, pedestrian gait speed ranges from (0.5–1.7 m/s) [22]. As the study site is in an underground public space, the average speed is relatively low.

3.1.2.3. Step length. Step length is the distance between the feet of a pedestrian in a walking state and tends to be stable under normal conditions [23]. It is also related to the age, gender and height of the pedestrian, as well as to the environment in which the pedestrian is walking [24].

3.1.2.4. Dynamic demand space. The dynamic demand space is the pedestrian's own psychological perception of safety when walking, similar to his or her own domain, which changes in response to interactions with other pedestrians or repulsive forces with obstacles, and also in response to changes in the environment. Pedestrians will therefore take measures, such as avoiding or overtaking, to avoid colliding with other pedestrians or with obstacles to ensure their own safety [25,26].

The pre-test found no significant differences in step frequency, step speed and step length between the subjects wearing the device and those not wearing it.

3.2. Partitioning of the subject's walking trajectory

Based on the CAD diagram of the path trajectory formed by all subjects completing the overall experimental task (e.g. Fig. 3), it was possible to observe the turns in the line of motion and to determine the corresponding avoidance behavior in conjunction with the experimental screenshots. As the experiment was based on pathfinding experiments to observe subjects' avoidance behavior, differences in the perception of pathfinding at the turns led to variability in the subjects' movement lines. When analysing the specific movement lines, areas where individual subjects passed through and where avoidance behavior occurred very infrequently were eliminated based on the actual avoidance points.

The three Stages of the experiment were labelled with different areas, and the eye-movement data from these areas and the EEG data from some of the subjects were analyzed to provide a clearer picture of what subjects were observing when they performed the avoidance behavior, and thus the factors influencing the avoidance behavior of the subjects.

3.3. Subject motivational line variability

As there was no compulsory planning of the subjects' walking routes in this experiment, the subjects' walking behavior was highly random and the turning of the walking routes reflected not only the subjects' avoidance behavior, but also their choice of path-finding direction in an unfamiliar environment. Therefore, in order to better study the subjects' avoidance behavior and reduce the variability of individual subjects, most of the subjects' avoidance behavior areas occurred in the same space during the experiment were marked and counted. It is possible to divide Stage 1 into roughly 12 regions (e.g. A, B … M) and Stage 2 into 20 regions (e.g. N,P … AU). The partitioning of the trajectories in Stage 2 shows that the trajectories of subjects in the narrow corridor are consistent, with most subjects starting to diverge in the open areas and creating more circuitous routes. After completing the Stage 2 task, the subjects each searched for the nearest escalator to the next floor. The starting point for Stage 3 was different as the subjects took different escalators to the next floor. The avoidance behaviors on the subjects' paths were labelled and counted according to the subjects' behavioral movements in

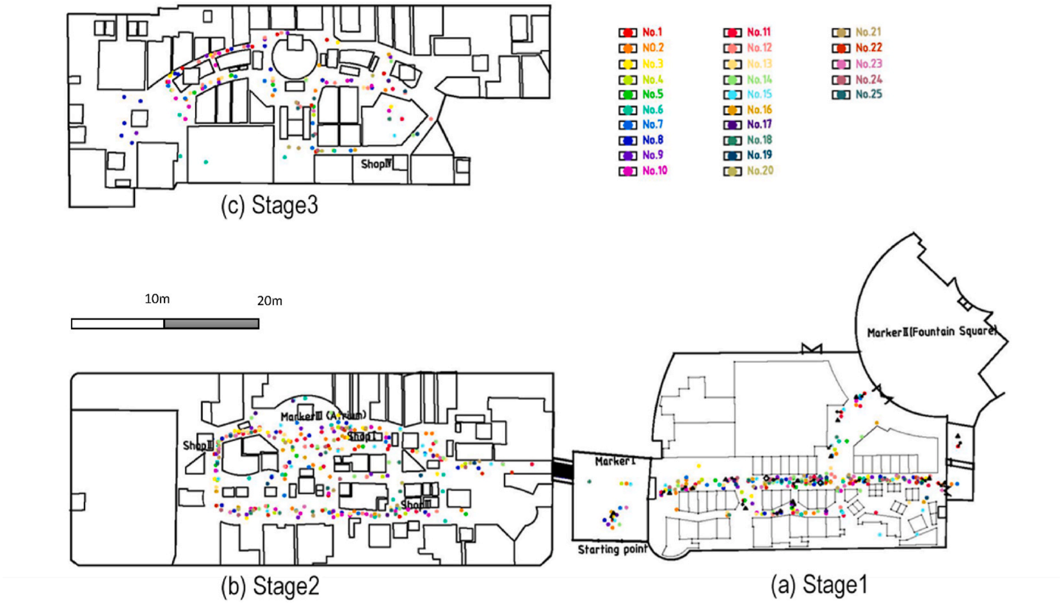


Fig. 6. Statistical chart of subjects' avoidance points.

Table 2
Position statistics of avoidance behavior of pedestrians in the opposite direction.

Avoidance of objects	Avoidance tendencies	Site		
		Stage1	Stage2	Stage3
Opposite direction Pedestrian	Turn left	A1,F1,F–H1,A2,B2,H–F2,F-D2,A3,G3 H3,D-E4,H–K4,B-A4,D-E5,F5,H5, D-F6,H–K6,M-H6,H–F6,F6,E-G7,H–K7,F-D7,A8,A9,E-G9,F–H9,F-D9,G-J10,J-H10, H–F10,H11,H–F11,M-H11,K12,H12,H–F12, H12,B-D13,K-J13,A14, K-J14,H-J14,A15,D-F15,A16,K–H16, A17,K–H17,D17,A-N18,D20,H21,D22,K23, F23,B24,K24,	U1,X–W1,R1,N–P2,V2,V-AZ2,U-AW2,AV-AY3T3,S-T3,AW-AZ4,AZ-V4,A-W5,P5,U5,U-AZ5,Y5,Q-W6, AY-AV6,AV-AU6,T-AW7,AZ7,Y-X7,X–W7,AU7,A-N8,N8,R–S8,Z8,U9,T-AY9,Y-X9X9,R–S10,S-T10, X–W10,W-X10,Y10,R11, AZ-Z11,V-Q12,P13,AV13,N–S14,Q-V14,AY14,U14, U-R15,U18,N19,Q20,Y22,N24,	AD1,AF3,AJ5,AN5, AD7,AE7, AJ7,AD8,AC8,AJ8, AL-AH9, AC9,AG-AE12, AS12,AM14, AR20,AN22,AK-AN24, AN-AP24,AK-AN25,
	Turn right	D1,E1,E-G1,G1,H–K1,K-L1,M1,M-H1,C2,C-E2,G-J2,H2,H–K2,K2,K-L2,M2, B- A2,H–K3,K3,K–H3,H–F3,D-B3, E-G4,M-H4,F-D4,D-B4,G5,H-M5, K–H5,H–F5,F5,H6,J-G6,G-J6,M6,A7, K7,M-H7,D7,D-B7,F–H8,K8,D9,G9, B11,D11,E-G10,G10,G11,H–K10,M10, M11,F–H12,D-F13,D-F14,F14,H-M14, K–H14,D14,M15,H–F15,D16,F16,G16, F-D16,J17,G17,K17,D17,E18,F18, M18,D-F19,K19,K–H19,F20,B20, H–K21,K–H21,B22,F–H22,H22,K–H22, D24,H24,F25,H–K25,H25,	P1,T-U1,X1,R–U1,AY1,AY-AV1,AV1,AU-AV1,Q-V2, V–U2,U-T2,S2,W2,X–W2,N–S2,AZ2,Z2,Y2,R–U2, AY-AV2,X3,Y-AT3AY3,AW3,AW-T3,AZ-AY3,AY-AW3,V-Q4,X4,Z5,AU-AV5,N-Q6,N–W6,W-X6,AV6, Z6,P7,Z-Y7,X7,W7,Z7, AZ-Z8,AT8,AV8,AY-U8,X8,Y-AT8,Q9,AV9, V-X10,W10,X10,Y-AT10,A-N11,N–P11,AZ11,Y-AT11,AV-AY11,AZ-Z12,N–P13,AY13,X13,W13, S13,AY13,R-Q14,AV14,AW-T14,S14,P15Z15,S-T16,AZ16,AT16,W16,N–P17,AW17,Y17 AZ18,AY18,AV18,W18,Q-R18,Z19,AV19, AS19,AY20AV20,Y20,W20,AZ21,AV21, AT-Y21,W21,N22,AY22,AT22,X22,N–P23, AY-AV23,Y23,U24,AZ24,AV24,AV25,W25,	AF1,AF-AH1,AL1, AD2,AG2, AM2,AD3,AE-AG4, AD5,AE5,AD6,AE-AG7,AG7,AJ-AK7, AN-AP7,AP7,AD-AC8,AR8, AF-AH8,AQ9,AH9, AD10, AD-AE10,AE-AG10,AN12, AH12,AH-AF12, AD-AF12, AF12,AM-AR12, AD13,AE13, AG13,AM-AR13, AQ14,AQ16, AA18,AK21,AP21, AP22,AP24, AN25,AN-AP25,

*D-E4: Between D area and E area, subject No. 4 had avoidance behavior.

Table 3
Position statistics of avoidance behavior of pedestrians in the same direction.

Avoidance of objects	Avoidance tendencies	Site		
		Stage1	Stage2	Stage3
Same direction pedestrian	Overtaking from the left	B1,E-G2,D-B2,B-D3,D-E3,B-D4,H4, H–K4,F–H5,K5,B6,B-D6,B-D7,F–H7, F8,B9,D-E9,B-D10,B-D11,E-G11, H–K10,D12,K12,Y-AT12,AY-V12,H13, B14,F–H15,B-A15,B16,H16,B-D17, H17,D18,H18,D19,B-D20,G20,B21, D21,H21,A23,F23,H23,D-B23,F–H24, D25,	V-X1,S–N2,W-X2,N–S2,N3,N-Q3,AU3, AZ4,W4,AU4,AU-Z6,T-AZ8,T-AY9, N–P10,W10,AY-U11,U11,U–V11,AV12, R–U13,X14,A-N15,Y15,U15,AR15, W17,U17,AR17,AT18,X18,Q18,Q19,AR19, AT20,N21,Y-X21,AZ-AY23,AV23,AT23,	AJ-AK2,AR2,AR-AA3,AN-AP4 AP-AA4,P5,AC8, AH8,AM8, AG9,AM-AR9,AG-AF10 AM-AR10,AR-AA11,AJ12 AR-AS12,AM13, AS-AA14, AM16,AK-AP20, AN23,
	Overtaking from the right	F-D1,K1,M-H1,M-H2,D-B2,K3,D-B5, J6,M7,H–F8,D-B8,K–H9,J11,J12, K–H12,E-C13,H14,M-H15,D15,M16, D-B16	W1,R–U1,AZ3,Y4,R–U5,N–W6,W8,Q-V9, AY-AV9,AT-Y9,X–Y10,W–N11,N–S11,W-X12, AU13,AT-Y13,Y-AT14,AW15,U16,AU16, S-T21,AT24,	AH1,AR1,AL-AQ3,AG4,AG5, AC-AD8,AR-AA10,AL-AH12, AF12,

*D-E3: Between D area and E area, subject No. 3 had avoidance behavior.

Table 4
Position statistics of avoidance behavior of stationary passersby.

Avoidance of objects	Avoidance tendencies	Site		
		Stage1	Stage2	Stage3
Stationary Passerby	Turn left	H–K1,K–H3,F4,B5,K–H5, H–F7,B-D8, K–H8,F8,K9,J-K11,H–F11,E-G12, J-G14,G-E14,H–K15,B18, H19,F-D19, F21,K22,D23,K–H23,F-D23, K–H24,	N4,T-AW6,R–S7,V-Z7,AY9, AN10,AU10, T-AZ11,AV12,N–W12,A-N14, S–N14,W14, AU15,Y18,N20,V21,V25 ,	AD-AF1, AH1,AE2,AP6, AP-AA7,AC8,AD8,AH-AF9, AF9,AF10,AM10,AR11,AM12,AE-AG13, AJ13,AA16,AP20,
	Turn right	H–K2,H–K3,H-J6,K-L7,E13, D-F24, H–K24,	X–W2,T-AY13,AW-AZ15,AV15, S15,AA15, AV17,U20,A-N22,W23,V24,	AD4,AR10,

*H–K1: Between H area and K area, subject No. 1 had avoidance behavior.

Table 5
Position statistics of avoidance behavior of obstacle avoidance.

Avoidance of objects	Avoidance tendencies	Site		
		Stage1	Stage2	Stage3
Obstacles	Turn left	/	T1,T2,T3,T8,T9,T10,T11,T12,T13,T16,T17 T18,T20,T21,T22,T23,T24,	/
	Turn right	/	T4,T6,T7,T15,	/

*T1: T area, subject No. 1 had avoidance behavior.

Stage 3, which were roughly divided into 16 areas (e.g. AA, AD … AS) (Fig. 4).

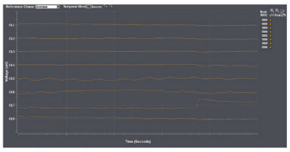
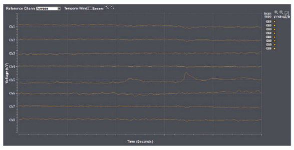
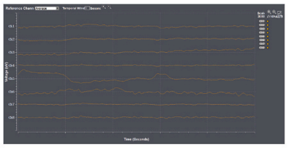
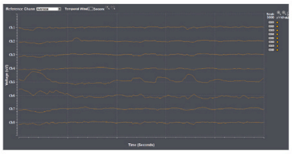
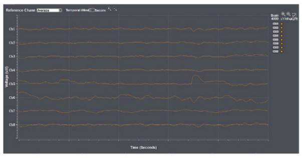
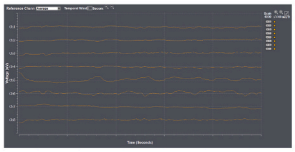
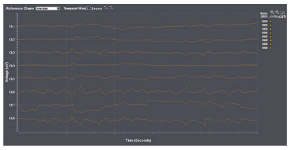
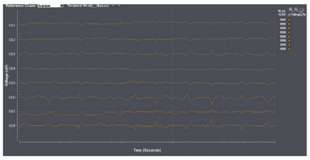
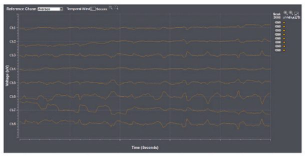
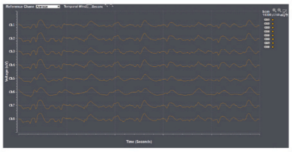
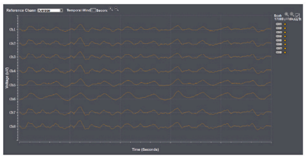
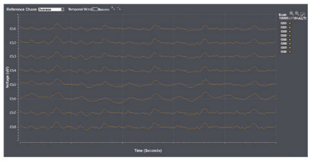
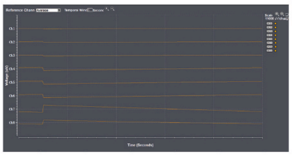
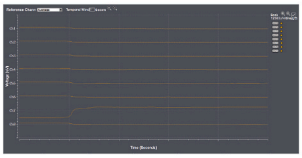
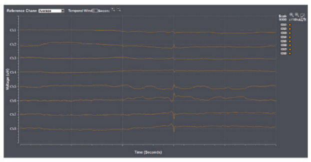
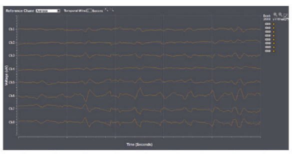
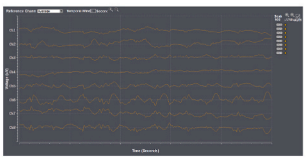
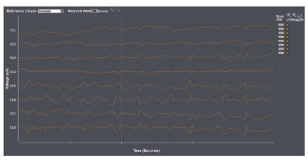
4. Avoidance behavior statistics and analysis

4.1. Analysis of experimental data

4.1.1. Location of the subject's avoidance behavior

In this experiment, the avoidance objects were classified into four categories: opposite pedestrians, same-direction pedestrians, stationary passers-by and obstacles. The subjects who performed avoidance behaviors were recorded with the locations labelled and categorised (Table 1). The subjects' avoidance behavior in different areas was counted by combining the eye movement recordings with the subjects' behavioral trajectory maps (Fig. 5). The factors associated with the occurrence of each avoidance behavior were analyzed by combining EEG eye movement data.

Table 6
Brain waves data analysis of some subjects' avoidance behavior.

Avoidance of objects		Stage1	Stage2	Stage3
Opposite direction Pedestrian	Left	F1 	R1 	AD1 
	Right	K7 	Z7 	AP7 
Same direction pedestrian	Left	H23 	AV23 	AN23 
	Right	J12 	W-X12 	AF12 
Stationary Passerby	Left	K9 	AY9 	AF9 
	Right	H-K24 	U20 	AR10 

*L means left; R means right.

At the same time, due to the large variability of the subjects' movement lines, the nodes through which individual subjects passed could be excluded to ensure the scientific validity of the data according to the statistical map of the subjects' avoidance points. It can be seen that the avoidance behavior in the first stage mainly occurred in the long aisle space; the second stage is more complex than the first stage, and the difference in pedestrian movement lines is also more obvious, but it can still be seen that the avoidance behavior points in the long aisle space are more dense; Stage 3 is simpler than Stage 2, and due to the difference in the properties of the shops (there are almost no food and beverage shops in Stage 3). Therefore, the pedestrian flow in Stage 3 is less than in Stage 2, and the overall frequency of avoidance behavior is the lowest (Fig. 6).

4.1.2. Avoidance behavior of the subjects

In this experiment, the avoidance objects were classified into four categories: opposite pedestrians, same-direction pedestrians, stationary passers-by and obstacles, and the subjects' avoidance habits were also classified into leftward and rightward tendencies according to the avoidance objects (Tables 2–5).

In the case of obstacle avoidance, as the obstacle was only present in the T-area in the second stage and did not appear during the experiment in two subjects, two other subjects' routes avoided the T-area. 17 of the remaining 21 subjects chose to avoid the obstacle to the right and only four chose to avoid it to the left.

In Stage 1, when the avoidance object was a pedestrian in the opposite direction, 60% of the subjects had a rightward avoidance habit and 40% had a leftward avoidance habit. When the avoidance targets were pedestrians in the same direction, 69% of the subjects' avoidance habit was to pass on the left and 31% to pass on the right. When the object of avoidance was a stationary passerby, 78% of the subjects avoided to the left and 22% avoided to the right.

In stage 2, subjects may pass the same spot within a shorter time difference due to the change in spatial layout. To exclude the influence of personal factors on the experiment, repeated avoidance behavior made by subjects towards the same avoidance object was counted once by comparing the screenshots of the experiment. When the avoidance object was a pedestrian in the opposite direction, 67% of the subjects' avoidance habits were to the right and 33% were to the left. When the object of avoidance was a pedestrian in the same direction, 64% of the subjects had the habit of passing to the left and 36% to the right. When the object of avoidance was a stationary passerby, 62% of the subjects avoided to the left and 38% to the right. When the object of avoidance was an obstacle, there was a clear tendency to avoid to the right.

Although the spatial layout of Stage 3 was simpler than that of Stage 2, the number of avoidance behaviors did not decrease substantially. When the avoidance object was a pedestrian in the opposite direction, 68% of the subjects' avoidance habits were to the right and 32% to the left. When the avoidance target was a pedestrian in the same direction, 70% of the subjects had the habit of passing to the left and 30% to the right. When the object of avoidance was a stationary passerby, 89% of the subjects avoided to the left and 11% avoided to the right.

By comparing the evasive habits of the subjects in the three stages, it was found that when the evasive object was a pedestrian in the opposite direction, more subjects chose to evade on the right side, which was related to the Chinese habit of walking on the right side; meanwhile, when the evasive object was a pedestrian in the same direction, more subjects chose to overtake on the left side, which was also due to the right side walking habit of the evasive pedestrian; and when the evasive object was a stationary pedestrian, more subjects chose to evade on the left side, which was also due to the stationary pedestrian standing on the right side.

When comparing the avoidance habits of the subjects in the three Stages, it was found that 60% of all avoidance behaviors occurred when the object of avoidance was a pedestrian in the opposite direction, 26% when the object of avoidance was a pedestrian in the same direction, and 14% when the object of avoidance was a stationary passerby.

The characteristics of avoidance behavior were selected from individual subjects and their video screenshots and EEG data were analyzed (Table 6). Subject 1 showed only weak fluctuations in individual channels during left avoidance of the opposite pedestrian in stage 1, area G (F1); during left avoidance of the opposite pedestrian in stage 2, area R (R1), the EEG showed significant fluctuations in only one channel and weak fluctuations in other individual channels; during left avoidance of the opposite pedestrian in stage 3, area AD (AD1), the EEG showed significant fluctuations in only two channels. Subject 7 showed significant fluctuations in only two channels of the EEG in Stage 1 K, Stage 2 Z and Stage 3 AP when facing the right avoidance of the pedestrian. Subject 23 showed significant fluctuations in all channels of the EEG in Stage 1 H, Stage 2 AV and Stage 3 AN when facing the left avoidance of the pedestrian in the same direction. Subject 12 showed significant fluctuations in all signal areas of the EEG when facing a pedestrian in the same direction in Stage 1 J, Stage 2 W-X, and Stage 3 AF. Subject 9 showed no significant fluctuations in the EEG when facing a stationary passerby in Stage 1 K, Stage 2 AY, and Stage 3 AF during a left avoidance. No significant fluctuations were observed in the EEG waves of subject 24 when he was facing a stationary passerby in Stage 1 H–K, subject 20 in Stage 2 U, and subject 10 in Stage 3 AR when he was facing a stationary passerby in right avoidance.

Modern scientific study has already known that when the human brain works, it produces its own brain waves, which can be detected by electronic scanners, and there are at least four important bands [27]. Studies have shown that the brain has at least four distinct brain waves [28].

1. "α" (Alpha) brain waves, the frequency of which is 8–12 Hz.

α waves are brain waves that occur when the human brain is in a completely relaxed state of mind, or when the mind is focused [29]. We absorb information faster and more effectively when we are 'relaxed and active' [30].

2. "β" (Beta) brain waves, the frequency of which is 14–100 Hz.

β Waves are brain waves that occur when the human brain is in a usual, everyday waking state [31]. It reflects the pulsations of the brain in the general waking state [32]. In this state, logical thought and conscious activity occur in humans [33]. For example, when people have their eyes open and their gaze fixed on everything in the world, or when they are performing specialized tasks such as problem solving and talking [34,35].

3. "θ" (Theta) brain waves, the frequency of which is 4–8 Hz.

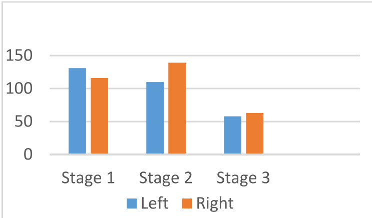
This stage of brain waves is the early stages of human sleep [36]. When you start to feel drowsy (the transition area between full wakefulness and full sleep), your brain waves are present at a frequency of 4–8Hz [37].

Table 7
EEG value impressions ratio.

Avoidance of objects		Stage1	Stage2	Stage3
Opposite Direction Pedestrian	Left	F1 **4.2**	R1 **6.0**	AD1 **4.3**
	Right	K7 **3.8**	Z7 **4.0**	AP7 **3.5**
Same Direction Pedestrian	Left	H23 **8.2**	AV23 **7.8**	AN23 **8.8**
	Right	J12 **7.6**	W-X12 **9.0**	AF12 **6.5**
Stationary Passerby	Left	K9 **1.2**	AY9 **0.6**	AF9 **0.8**
	Right	H–K24 **4.2**	U20 **4.5**	AR10 **3.9**

Table 8
Statistics on the number of avoidance behaviors by stage.

Stage	Number	
	Left	Right
Stage1	131	116
Stage2	110	139
Stage3	58	63



4. “δ" (Delta) brain waves, the frequency of which is 0.5–4 Hz.

The brain waves in this stage are those in the deep sleep stage of people [38]. When a person falls into a deep sleep, the brain wave frequency is presented at 0.5–4 Hz [39].

Each frequency band represents a different brain region, and the mental state of each individual can be determined from the collected EEG waveforms [40]. The experiment was conducted using a wireless EEG device, which recorded the brain wave values of the subjects while walking in an underground public space [41]. To corroborate the avoidance impression, an impression ratio was introduced [42].

Impression ratio = β wave/α wave.

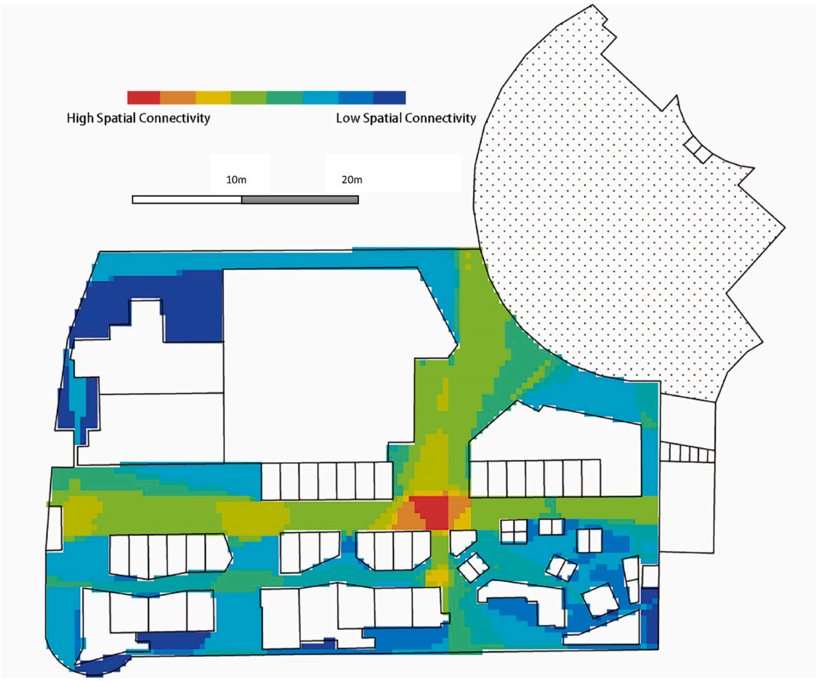
The ratio of the alpha wave to the beta wave can therefore represent the degree of arousal of the human brain, and can also be thought of as the magnitude of the brain's impression of a perceptual event. So, the ratio of β to α waves is used to illustrate the effect of environmental factors on avoidance behavior. In the actual calculation, the intensity of the 2 frequency bands divided by frequency in the alpha wave were averaged to obtain the alpha wave. In the beta wave, the intensities of the bands are also averaged to obtain the beta wave (Table 7).

The change in EEG waveform shows that the brain response to avoidance behavior varies considerably when the avoidance object is different. The comparison shows that the EEG response to the overtaking behavior is significantly stronger than the avoidance of opposite pedestrians versus stationary passers-by. Comparing the EEG signal calibration maps, it is clear that the frontal regions of the brain, which are responsible for motor center and behavioral programming, were extremely active during the subjects' avoidance behavior. This shows that the subject's avoidance behavior is influenced not only by the object of avoidance but also by environmental factors, so that relevant areas of the brain are involved.

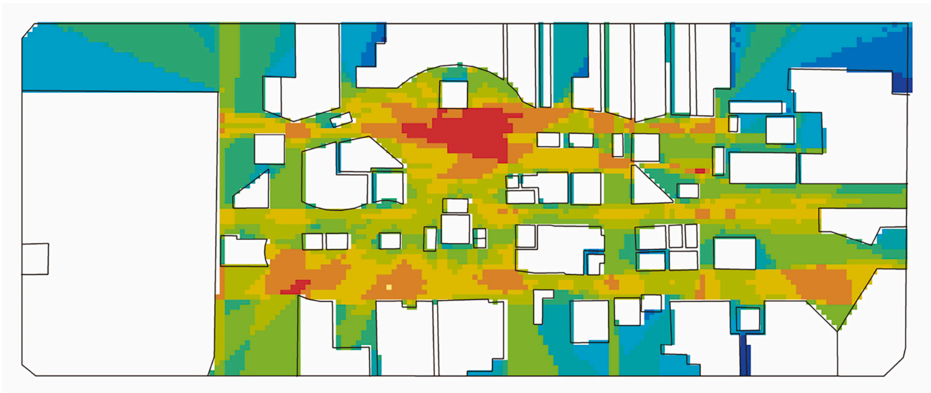
4.1.3. Frequency of subject avoidance behavior

As can be seen from the graph, avoidance behavior occurs most frequently in Stage 2, slightly less frequently in Stage 1 than in Stage 2, and significantly less frequently in Stage 3 than in the first two stages. The second stage plane is more complex than the first stage plane, but the frequency of avoidance behavior is only slightly higher than that of the first stage. And because subjects repeated their paths more in the second stage, the data on subjects' avoidance behavior towards the same object in a shorter period of time were excluded from the statistics (Table 8).

The Depthmap software is used to analyze the three-stage planes visually to obtain the spatial integration and spatial connectivity visualization graphics of the plane space (Fig. 7), and four areas with high spatial integration are selected for analysis.



(a) Stage 1



(b) Stage 2

(c) Stage 3

(caption on next page)

Fig. 7. Spatial integration and spatial connectivity visualization graphics.

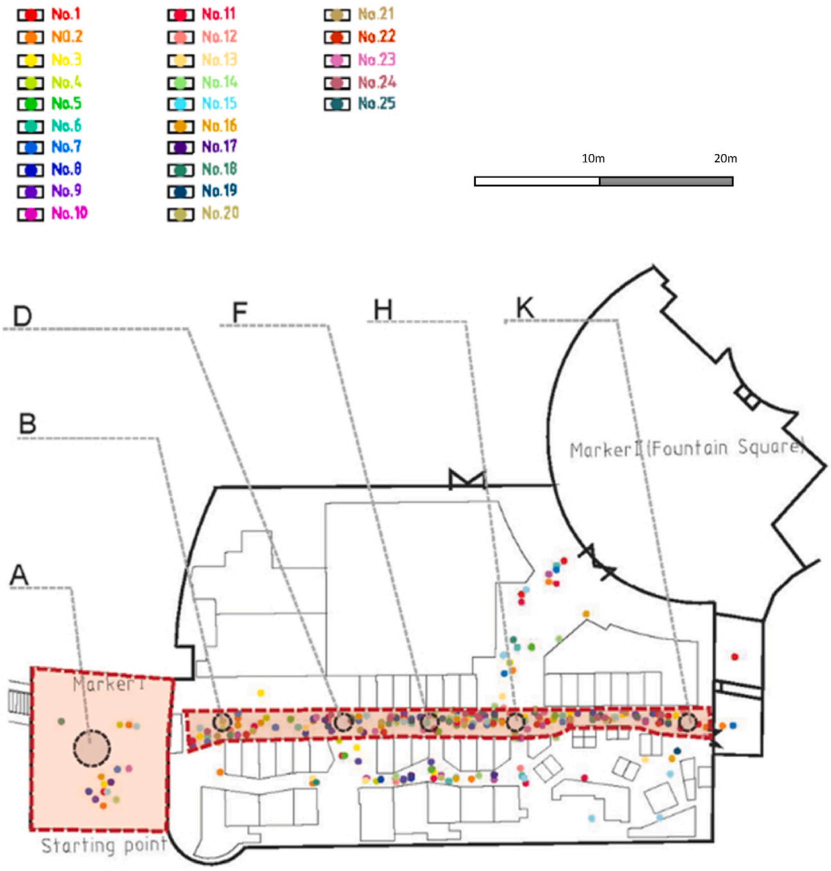


Fig. 8. Spatial map of the frequency of avoidance behavior in the first stage.

4.2. *Characteristics of avoidance behavior*

4.2.1. *Personal factors in avoidance behavior*

Pedestrians' avoidance patterns vary considerably when the avoidance target is different. Influenced by the Chinese tendency to travel right, pedestrians have a distinct tendency to avoid on the right when the evasive object is a pedestrian in the opposite direction; when the evasive object is a pedestrian in the same direction, pedestrians have a distinct tendency to overtake on the left; when the evasive object is a stationary passerby, pedestrians have a distinct tendency to avoid on the left.

4.2.2. *Environmental impact of avoidance behavior*

The frequency of avoidance behavior in the same direction is significantly lower than the frequency of avoidance behavior in the opposite direction. Only in complex pedestrian flows do pedestrians desperately want to leave the area with high pedestrian density and choose to overtake.

A space with good spatial connectivity such as the square or circular buffer space (Figs. 8 and 9) can be designed to reduce the frequency of avoidance behavior in areas where dense pedestrian flows cross, providing a more comfortable walking environment for pedestrians.

5. Conclusion

1. Avoidance behavior is a reaction to the environment and the behavioral tendencies of the people around you, not simply an avoidance of the current conflict situation. Pedestrian avoidance behavior is usually divided into two stages:

   a. Subconscious avoidance behavior based on the current conflict environment;
   b. Integrated avoidance behavior following awareness of the environment.

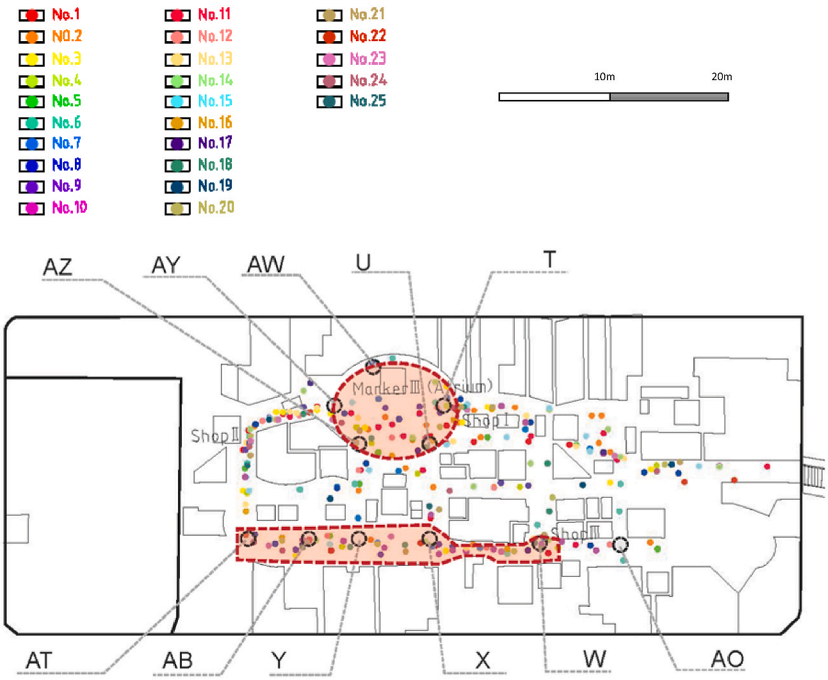


Fig. 9. Spatial map of the frequency of avoidance behavior in the second stage.

2. Overtaking does not usually occur when there are few intersecting pedestrian routes in the current environment and mostly in the same direction, but usually occurs when there are many intersecting pedestrian routes in the current environment [2,6]; when avoiding objects, pedestrians usually do not consider objects and conflicting pedestrian flows together and will make separate avoidance behavior.
3. Avoidance behavior often occurs when there are many crossings of pedestrian routes. As the space narrows, the range of avoidance behavior becomes progressively narrower and the frequency of avoidance behavior increases. Therefore when designing underground public spaces：

a. It is possible to design a square or circular space by designing a square or circular space. We provide enough space for the path of pedestrians in a limited space.

b. Using designing skills to reduce the repetitive crossing of paths.

6. Discussion and outlook

The study of pedestrian movement and avoidance behavior in China has long been based on the simulation of pedestrian flow, and the common study method is pedestrian flow simulation. As a basic method of scientific study, the pedestrian flow simulation method has accumulated a large amount of rational study data for the study of pedestrian flow in public space in China, and occupies a large position. However, individual avoidance behavior perceptual data often requires further processing by the researcher or the subject before it can be collected, and data on the subject's unconscious cognitive behavioral responses cannot be obtained. The experimental study method of synchronous EEG and eye movement monitoring allow for quantitative perception studies of pedestrian behavior in underground public spaces. The data obtained from the study on pedestrian movement and avoidance behavior are more referable than previous related studies in terms of human factors design applications in urban underground public spaces, and provide data support for future urban underground public space design. However, the sample sizes for the different age groups were not adequate because of the low acceptance of the relevant device by older people and younger children. As technology advances and research progresses, it is hoped that future experiments will increase the sample size of older and younger people to increase the generalisability of the study.

Author contribution statement

Shouni Tang: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.Jun Wang: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.Yawen Tian: Performed the experiments; Analyzed and interpreted the data.Wei Liu: Contributed reagents, materials, analysis tools or data.Zhihao Ma; Guoqing He; Huizhen Yang: Analyzed and interpreted the data.

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Data availability statement

Data will be made available on request.

Declaration of competing interest

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

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