

# Research on the Combined Effects of Plant Odor and Traffic Noise on Crowd Behaviors in Urban Environments

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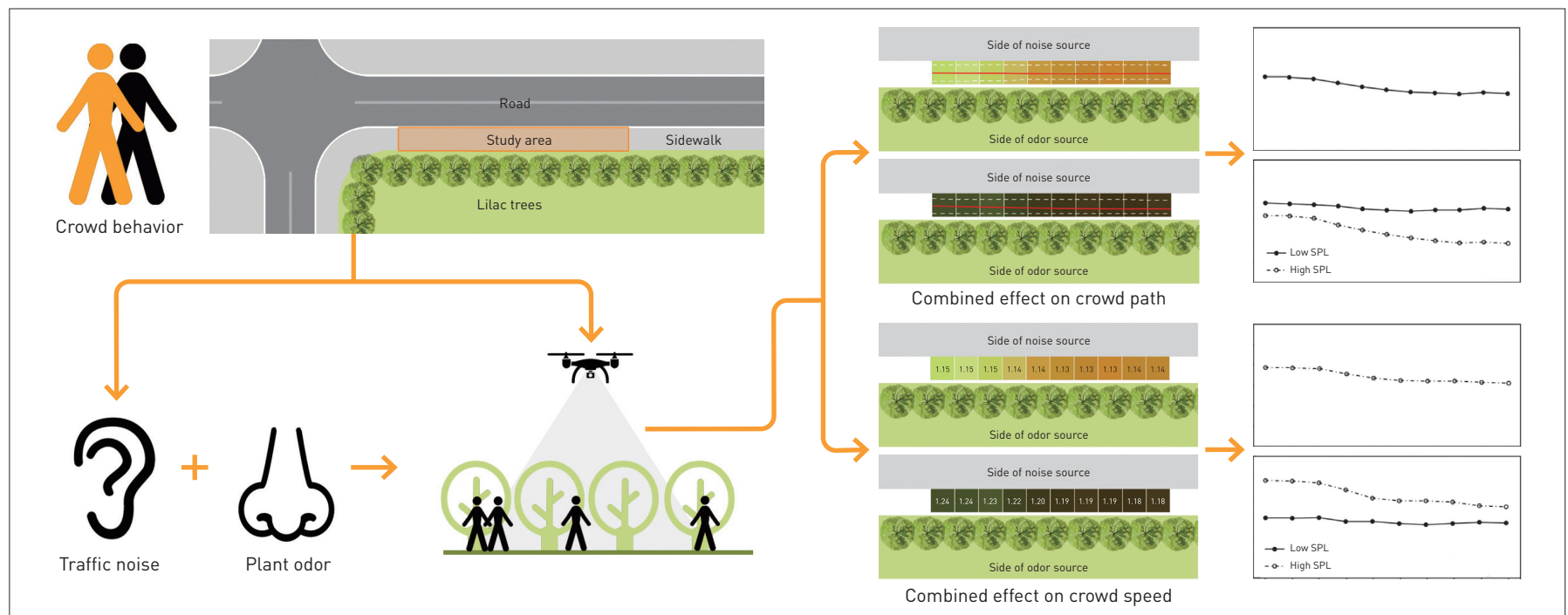
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## GRAPHICAL ABSTRACT



## ABSTRACT

Traffic noise is a typical negative sound source in urban environments with impacts on crowd behaviors. To explore the combined effects of auditory–olfactory interaction environments on crowd behaviors, this study conducted a covert behavioral observation experiment on a typical urban street uniformly planted with lilacs (*Syringa* spp.) to investigate the combined effects of plant odor and traffic noise on crowd path and crowd speed. The results showed that: 1) for crowd path, when the sound pressure level (SPL) was high, the path ranges and their mean values under

different odor concentrations all showed a tendency to be farther away from the sound source than when it was low; the mean values of path ranges gradually moved towards the odor source as the odor went from none to strong, which was more significant at high SPL, with a maximum longitudinal movement of about 0.3 m. 2) For crowd speed, its mean values gradually slowed down from 1.24 m/s at high SPL as the odor went from none to strong and then stabilized at 1.18 m/s; however, those at low SPL were almost unaffected. This research puts forward new ideas to alleviate the

negative impacts of traffic noise, and the study results can provide guiding significance for the improvement of the evaluation system of urban landscape quality and the optimization of urban design mode.

## KEYWORDS

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Plant Odor; Traffic Noise; Combined Effect; Crowd Path; Crowd Speed; Auditory–Olfactory Interaction Environment

## HIGHLIGHTS

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- Crowd path tends to move towards the odor source, especially when the sound pressure level of traffic noise is high
- Crowd speed slows down as the odor concentration increases at high sound pressure level of traffic noise
- Crowd speed is almost unaffected by plant odor at low sound pressure level of traffic noise

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## 1 Introduction

*The Outline of the 14th Five-Year Plan (2021–2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035* clearly puts forward the need to strengthen environmental noise pollution control<sup>[1]</sup>. The problems caused by urban noise are becoming increasingly serious, which has greatly affected residents’ daily life and their physical and mental health<sup>[2][3]</sup>. Among them, traffic noise is the main source that is characterized with high intensity, wide influence range, and long duration<sup>[4]</sup>. The negative impacts of it on residents include sleep disorders<sup>[5]</sup>, reduction of helpful behaviors, decreased attention to the peripheral elements of the environments passing through<sup>[6]</sup>, increase in problematic behaviors of children and adolescents (hyperactivity, inattention, etc.)<sup>[7][8]</sup> and driving violations<sup>[9]</sup>, etc.

At present, in order to better explore urban environmental design strategies to mitigate the negative effects of traffic noise, the research of its impact on psychology and physiology has mainly concerned with the noise annoyance under different conditions<sup>[10]~[14]</sup>. As one of the key components constituting the environment, behavior of spatial users is an outward manifestation of physiological and psychological perceptions<sup>[15]</sup>. In environmental assessment, individual behavior usually refers to the attitude or performance of a person in a given situation, which is greatly influenced by the environment and often tends to be random<sup>[16]</sup>. In contrast, the crowd behavior refers to the performance of the overall crowd in a specific environment, which tends to show a certain regularity<sup>[17][18]</sup>. The latter can be further classified as active and passive behaviors according to motivation<sup>[16]</sup>, or participatory and non-participatory behaviors by their purposes<sup>[19]</sup>. In addition, according to the mobility of research objects, it can also be divided into static behavior (sitting, standing, etc.) and movement behavior (walking around, passing by, etc.)<sup>[20]~[22]</sup>. In comparison, movement behaviors can better reflect the overall tendency of the crowd<sup>[20]</sup>. Currently, traffic noise related studies focus more on the effects on individual behaviors, but less on the effects on crowd behaviors.

Traditional control methods for urban traffic noise often use physical means to reduce the noise level, such as sound barriers and sound-absorbing materials. However, recent studies have shown that only reducing the noise level or the number of noise sources does not necessarily improve human comfort<sup>[4]</sup>. Meanwhile, the research on multisensory interactions provides new possibilities for improving noise control. In recent years, the positive effects of olfactory sensory factors on people’s

perception have gradually received scholarly attention, and it has been demonstrated that positive odor stimuli such as fragrances of plants or food can alleviate the negative effects of traffic noise on residents' self-reported perception<sup>[23]~[25]</sup>. Studies on the combined effects of auditory and olfactory on crowd behaviors using typical sounds and odors in urban environments as sensory variables have shown that food odor can bring crowds closer to the odor source, which could become more significant after introducing either positive or negative sounds<sup>[26]</sup>. It is also worth exploring whether the negative effects of traffic noise on residents' behaviors will be ameliorated by the presence of positive plant odor.

In this study, a typical urban landscape plant, lilac (*Syringa* spp.), was used as an odor affecting factor, and field observations of crowd behaviors were taken place under the combinations with different sound pressure level (SPL) conditions of traffic noise. This study aims to investigate how plant odors (concentration gradients) and traffic noise (low and high SPLs) affect crowd behaviors (movement path and speed). The results of this study will offer new ideas to mitigate the negative impacts of traffic noise on residents from the perspective of multisensory interaction, so as to improve the quality of urban multisensory environments.

## 2 Research Methods

### 2.1 Study Area and the Selection of Plant Odor-Traffic Noise Sources

When selecting the study area, the following factors were taken into account: 1) traffic noise existed in the area, with varied SPLs at different hours throughout the day; 2) both plant odor and no plant odor conditions existed in the area for the control of odor variables; and 3) no restaurants, cafes, markets, factories, or other odoriferous places existed in the area to emit affecting odors.

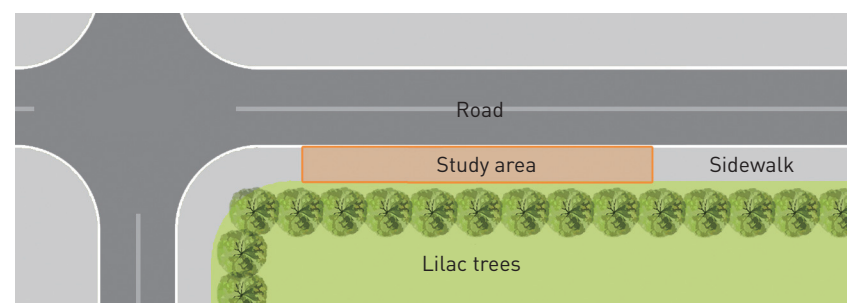
Based on the above considerations, Minsheng Road in Xiangfang District, Harbin City, China was selected as the study area (Fig. 1), where trees of lilac (*Syringa amurensis*) were planted uniformly along the sidewalks of the road at each 1.5 m. These trees were then used as the odor source in this study. Lilac is a deciduous shrub or small tree that is commonly planted in urban greening in China, due to the pleasant shape and odor. Studies have found that factors such as building layout and edge effect at road intersections can affect people's olfactory perception, resulting in a stronger plant odor in the central part and gradually decreasing towards the edge<sup>[23]</sup>. Therefore, the study area fits the plant odor and traffic noise conditions for the research.

### 2.2 Plant Odor-Traffic Noise Measurement Methods

Quantitative measurement and recording of odor concentration is difficult. Although specific chemical components can be detected instrumentally, methods that simply measure certain compounds cannot adequately explain or grade odor concentration. Because such measurements are usually of tracer compounds that are present in limited amounts in the gas, it is not possible to directly measure the odor concentration itself or to correlate the odor concentration with its properties<sup>[27]</sup>. Furthermore, in urban environments, measurements within a single time period or location are not representative of the odor situation in the entire area<sup>[28]</sup>. Therefore, this study mainly adopted the method of measuring odor concentration with pedestrians as "sensors," which is also commonly used in related studies<sup>[29][30]</sup>.

Before the experiment, the study area was first divided into 3 m × 3 m grids, labeled as numbers 1 to 10 from left to right. A questionnaire pre-experiment on plant odor concentration was conducted, which adopted a Likert 7-point scale, with 1 indicating no odor and 7 indicating very strong odor. Both the pre-experiment and the formal experiment were performed on 10 June 2019, when lilacs were in full bloom and the odor was noticeable within in the study area. The experimental day was sunny with a wind speed of about 0.3 m/s and a relatively stable odor condition. In the pre-experiment, at least 30 valid questionnaires were collected from each grid and their mean concentrations were calculated. The study used Cronbach's  $\alpha$  coefficient to test the internal consistency of the questionnaire (with a result of 0.925) and KMO coefficient to test the structural validity (with a result of 0.803), which indicated that the questionnaire had a sound reliability and validity. Meanwhile, during the pre-experiment, participants all reported that they did not smell any other odors other than lilac within the study area, suggesting that the plant odor was the only dominant source and

1. Site plan of the study area.



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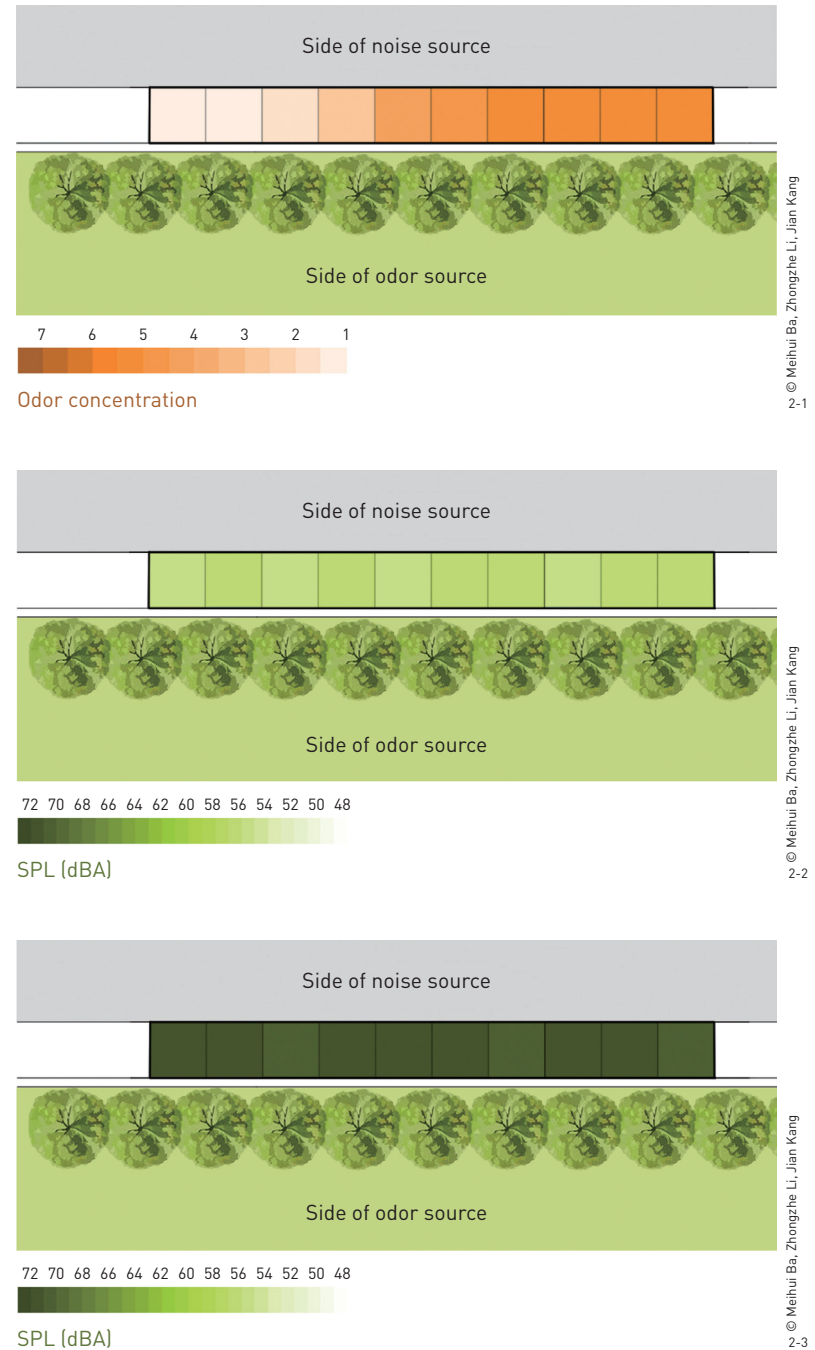
the participants were not affected by other odor sources in the experiment.

In this study, a portable 4-channel acquisition front-end was used to measure traffic noise<sup>[31][32]</sup>. A 1-min recording was made at the center of each grid, and the SPLs of the recordings were subsequently analyzed using HEAD ArtemiS software. During the recording, the crowd density remained less than 0.05 person/m<sup>2</sup>, thus the interference of pedestrians on the sound environment could be ignored<sup>[33]</sup>. Traffic noise was classified into low and high SPLs according to the actual traffic conditions at different hours: the SPL at the noisier hours within the study area was set as the high SPL, determined based on the field observations and SPL measurements in the pre-experiment; the difference between the high and low SPLs was 10 dB or more to ensure that the participants could clearly distinguish between the two. Through A-weighted SPL analysis, the low SPL was finally defined as 55.6 dB ( $L_{10} = 50.3$  dB;  $L_{50} = 54.6$  dB;  $L_{90} = 58.5$  dB) and the high SPL was 70.5 dB ( $L_{10} = 68.9$  dB;  $L_{50} = 70.4$  dB;  $L_{90} = 71.7$  dB). Calculated from the observation videos recorded by drone during the experiment, the average driving speeds in the low and high SPL conditions were 46 km/h and 53 km/h, respectively. The average hourly traffic flow was 1,089 and 696 vehicles, respectively. The evaluation results of odor concentration and SPL distributions within the study area are shown in Fig. 2.

### 2.3 Observation of Crowd Behaviors

This study focused on the movement behavior of crowds. Since the study area was close to an urban road, the crowd behaviors were mostly walking, so pedestrians' movement path and speed can better reflect the pattern of crowd behaviors, which two thus were selected as the analysis indicators for the research—both of them are also common indicators in relevant studies<sup>[34][35]</sup>. Specifically, crowd path refers to the walking trajectory of the participants within the study area, while crowd speed refers to the straight-line displacement of the participant in unit time. It is important to note that pedestrians in both directions were included in the samples in the experiment (Table 1).

The experimental times for low and high SPLs corresponded to the time periods of 13:00 ~ 15:00 and 15:00 ~ 17:00, respectively. Both time periods were set in the afternoon to minimize the difference in environmental conditions caused by temporal factors. The SPL tests were conducted first in both conditions, followed by the observation of crowd behaviors. In the experiment, the drone used to record the crowd behaviors flew at 100 m above to avoid the device sound from interfering with the



2. Participants' self-evaluated results of odor concentration (Fig. 2-1), and distribution results of low SPL (Fig. 2-2) and high SPL (Fig. 2-3) conditions.

**Table 1: The sample size of crowd behaviors (unit: person-time)**

Traffic noise condition	Path	Speed
Low SPL	103	103
High SPL	108	108

experimental results<sup>[34]</sup>. In addition, to ensure the randomness of the crowd behavior, three sets of measurement were taken under both low and high SPL conditions, and each set of video shooting lasted 15 ~ 20 min<sup>[34]</sup>.

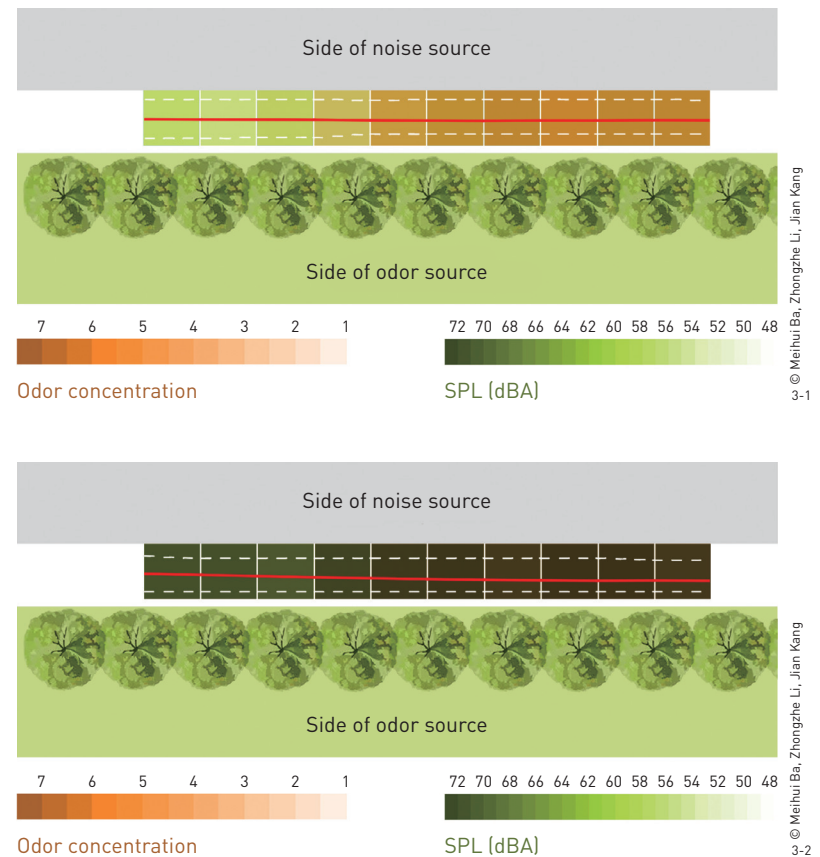
Subsequently, the study took screenshots of the drone-shot videos every 2 s. The bottom-left endpoint of the leftmost grid was set as the origin of the coordinate system. The longitudinal coordinates of the intersection between the path and the longitudinal grid line were recorded as  $y$ . So each path had 11  $y$ -values, from left to right were  $y_1 \sim y_{11}$ . And the path of each sample pedestrian was mapped by connecting the  $y$  points on the coordinate. After that, the mean values of  $y_1 \sim y_{11}$  of all paths in the given time period were calculated. The 5th and 95th percentiles of these  $y$ -values were also calculated, and finally a path range was determined by the means and the percentiles<sup>[26]</sup>. At the same time, the speed of each sample pedestrian ( $N = 211$ ) was calculated as the distance displaced between the video screenshots divided the unit time (2 s)<sup>[26]</sup>.

### 3 Research Results and Discussion

#### 3.1 Analysis of Plant Odor-Traffic Noise Impacts on Crowd Path

The path ranges under low and high SPL conditions are shown in Fig. 3. The upper and lower boundary lines and mean values were more downward when the SPL was high. The noise with high SPL may be the cause of the crowd moving towards the opposite direction to the sound source. At low SPL, the crowd paths showed a gradual movement towards the odor source as the odor concentration grew across the grids; this trend was more significant at high SPL. Thus, the lilac odor may be a potential cause of crowd attraction, which became more obvious as the odor concentration increased and eventually remained stable.

In order to deeply investigate the combined effect of plant odor and traffic noise on crowd path, this study used an all-factor model to conduct a repeated measurement ANOVA on  $y$ -values of paths. As the odor concentration grew from left to right, with  $y_1 \sim y_{11}$  distributed in the grids of different concentrations,  $y$  could represent the overall trend of the odor concentration gradient: an independent variable that indicates the odor concentration (denoted as “odor”) were generated with the repeated measurement ANOVA model that fit the variables of  $y_1 \sim y_{11}$ ; another independent variable was SPLs (denoted as “noise”). The final test results are shown in



3. Crowd path ranges under low SPL (Fig. 3-1) and high SPL (Fig. 3-2) conditions. The solid red line represents the mean longitudinal values of the paths, and the white dashed lines represent the 5th and 95th percentiles of the longitudinal values.

Table 2. In detail, the effects of odor and odor  $\cap$  noise on crowd paths were all significant ( $p < 0.05$ ), proving the interaction of odor concentration and SPL on crowd path, with the effect of odor concentration on crowd path varying with SPLs.

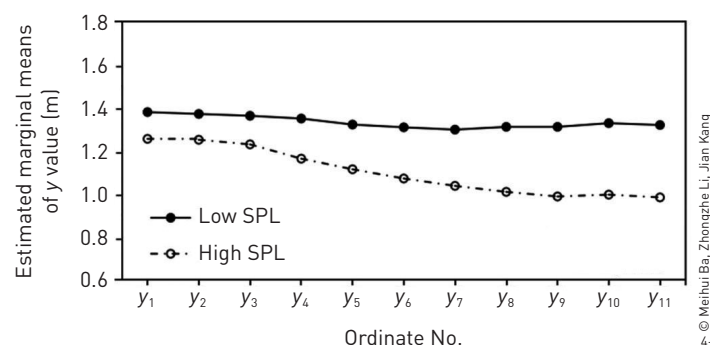
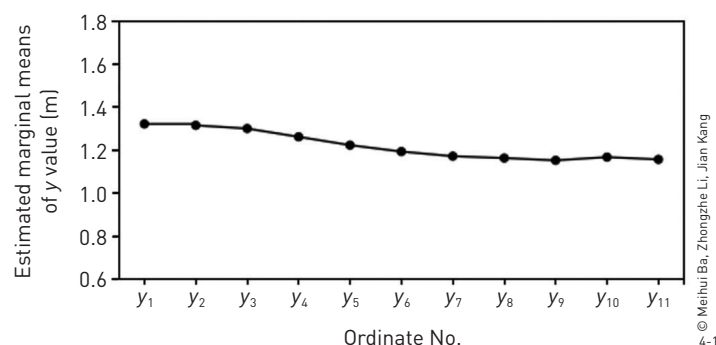
The study calculated the estimated marginal means of the  $y$ -values for the two conditions: the single effect of odor concentration and interaction of odor concentration and SPL (Fig. 4). The estimated marginal mean was used to calculate the average change in a variable for a given condition, with larger values indicating that the crowd was closer to the noise source and farther away from the odor source. The results showed that under the single condition of odor concentration, the crowd path in the grids with strong odor was closer to the odor source (Fig. 4-1). A two-by-two comparison of the 11  $y$ -values under this condition revealed that  $y_1, y_2,$  and  $y_3$  (no odor) were not significantly different from each other ( $p > 0.05$ ), while they and the rest  $y$  values were significantly different from each other ( $p < 0.01$ );  $y_4, y_5,$  and  $y_6$  (weak odor) were different from any

**Table 2: Repeated measures ANOVA of the value  $y$**

Variable	Effect	Value	$F$	Hypothesis $df$	Error $df$	Sig.
The value $y$	Odour	0.247	6.563	10.000	200.000	0.000**
	Odour $\cap$ Noise	0.103	2.290	10.000	200.000	0.015*

**NOTE**

\* means  $p < 0.05$ ; \*\* means  $p < 0.01$ .



4. Estimated marginal means of  $y$  values under the conditions of single odor concentration (Fig. 4-1) and odor concentration-SPL interaction (Fig. 4-2).

of the  $y$  values ( $p < 0.01$ ), but  $y_7 \sim y_{11}$  (strong odor) were not significantly different from each other ( $p > 0.05$ ). These findings indicated that odor could attract crowds to a certain extent, where sensory attraction seems to be motivated by human biological nature and it may further affect emotion<sup>[36]</sup>.

The  $y$  values for the condition of odor concentration-SPL interaction are shown in Fig. 4-2. The difference between the low and high SPL conditions was significant ( $p < 0.01$ ). In detail, compared with low SPL, the crowd moved farther away from the noise source at high SPL. As the odor concentration increased, the crowd path at low SPL also moved slightly closer to the odor source, though not statistically significant ( $p > 0.05$ ). At high SPL, the crowd path tended to move closer to the odor source more significantly, with the maximum longitudinal distance difference between  $y_1$  and  $y_{11}$  being about 0.3 m. A two-by-two comparison of the 11  $y$ -values at high SPL revealed that the differences between  $y_1 \sim y_4$  were not significant ( $p > 0.05$ ), while the differences between them and the rest were significant ( $p < 0.01$ ). Meanwhile, the differences between  $y_5 \sim y_{11}$  were not significant ( $p > 0.05$ ), but the differences between them and the rest were significant ( $p < 0.01$ ). This suggested that pedestrians tend to move away from the noise source and get closer to the odor source in high SPL environments. Previous research on the combined effects of food odor and sounds on crowd behaviors

indicated that the presence of noise may enhance the attraction of odor to crowds<sup>[26]</sup>. Similarly, this study suggests that there may also be some augmented effect of traffic noise on the attraction of plant odor, thus making crowds tend to move away from the noise source towards the odor source of plants.

### 3.2 Analysis of Plant Odor-Traffic Noise Impacts on Crowd Speed

The study also used a full-factor model for crowd speed under both conditions of odor concentration and odor concentration-SPL (Table 3). The effects of odor and odor  $\cap$  noise were both significant ( $p < 0.05$ ), which indicated an interaction of odor concentration and SPL on crowd speed, with the effect of odor concentration on crowd speed also varying with the change of SPL.

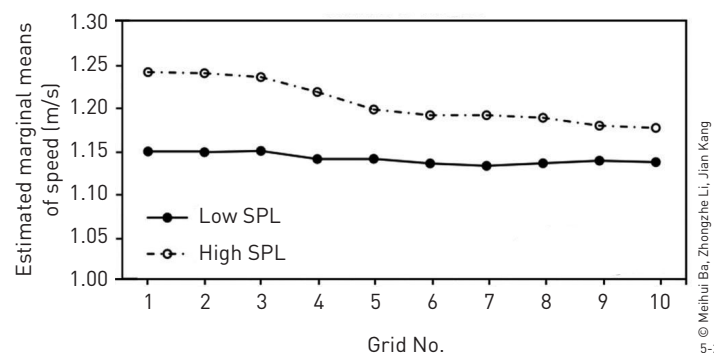
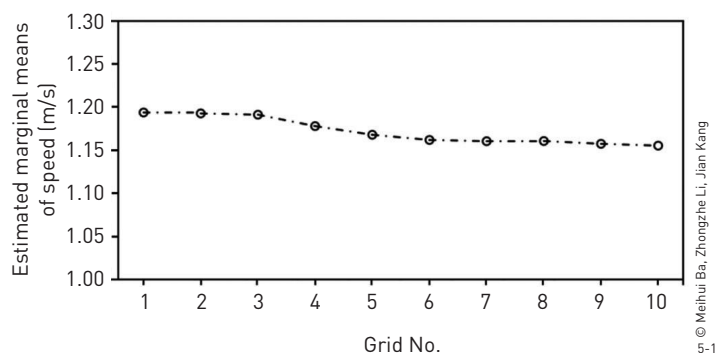
The estimated marginal means of crowd speeds are shown in Fig. 5, which had an overall mean of 1.17 m/s. In terms of the single effect of odor concentration, the crowd speeds showed a gradual decrease and a stabilized trend as the odor concentration increased (Fig. 5-1). A two-by-two comparison of the crowd speeds in the 10 grids under the single effect of odor concentration revealed that there was no significant difference between the crowd speeds in grids 1 to 3 (no odor,  $p > 0.05$ ), while they and the rest differed significantly from each other ( $p < 0.01$ ); grids 4 to 6 (weak odor) differed from any of the grids

**Table 3: Repeated measures ANOVA of the crowd speed**

Variable	Effect	Value	F	Hypothesis df	Error df	Sig.
Crowd speed	Odour	0.133	3.437	9.000	201.000	0.001**
	Odour $\cap$ Noise	0.081	1.970	9.000	201.000	0.044*

**NOTE**

\* means  $p < 0.05$ ; \*\* means  $p < 0.01$ .



5. Estimated marginal means of crowd speeds under the conditions of single odor concentration (Fig. 5-1) and odor concentration-SPL interaction (Fig. 5-2).

( $p < 0.01$ ); grids 7 to 10 (strong odor) did not see significant difference among each other ( $p > 0.05$ ). These results suggest that the higher the odor concentration, the slower the crowd speed.

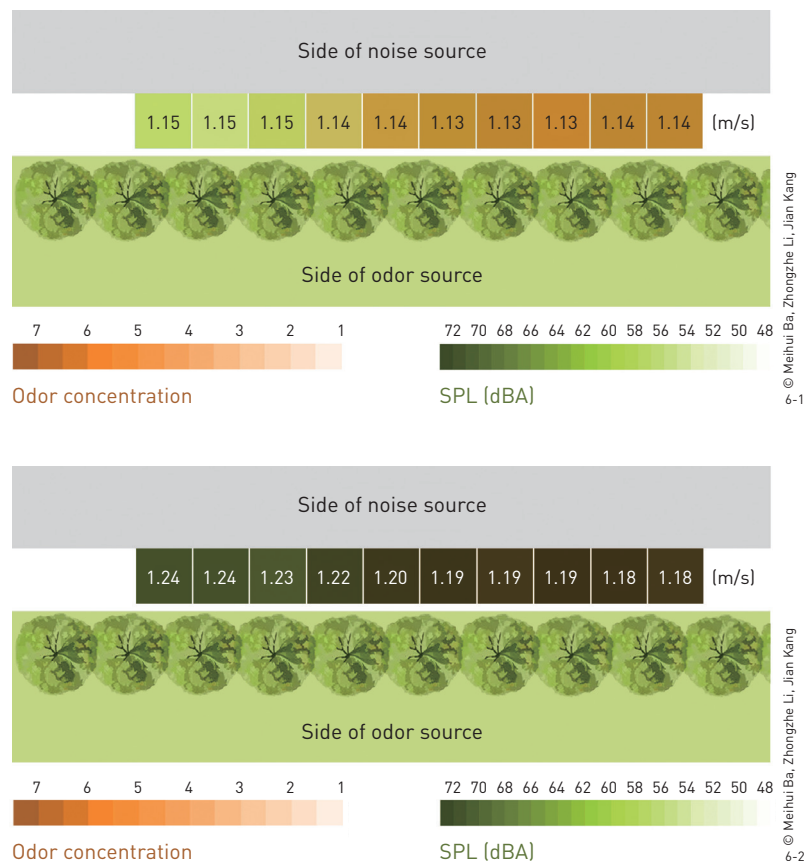
The estimated marginal means of crowd speeds for the odor concentration-SPL interaction are shown in Fig. 5-2. The difference between the low and high SPL conditions was significant ( $p < 0.01$ ). For the overall trend, at high SPL, the crowd speed was significantly accelerated compared with low SPL, which is consistent with previous findings<sup>[37][38]</sup>—this accelerated behavior may be pedestrians’ spontaneous response to noise. At low SPL, there was no significant difference in crowd speeds between all the grids ( $p > 0.05$ ). When the SPL was high, there was no significant difference between grids 1 and 2 ( $p > 0.05$ ), but they were significantly different from the other grids ( $p < 0.01$ ); grids 3 to 5 differed from any of the grids ( $p < 0.01$ ); grids 6 to 10 were not significantly different between each other ( $p > 0.05$ ), but their differences with the other grids were significant ( $p < 0.01$ ). These results represent that the crowd speeds were more significantly affected by odor concentration under high SPL condition, with the most significant effect found around grids 3 to 5.

The analysis results of the mean values show that the crowd speeds across the grids rarely changed when the SPL was low

(Fig. 6). Nevertheless, the changes were more significant at high SPL, with the fastest average speed in grids 1 and 2 (1.24 m/s) and the slowest average speed in grid 10 (1.18 m/s). But the speeds in grids 5 to 10 were relatively stable, indicating that changes in odor concentration did not significantly affect crowd speed. Overall, although the crowd speeds under low and high SPL conditions showed varied patterns, the maximum difference in speeds between grids was not obvious, being only 0.06 m/s.

### 3.3 Correlation Analysis Between Crowd Path and Crowd Speed

This study analyzed the crowd path and crowd speed under two SPL conditions (103 pedestrians at low SPL and 108 pedestrians at high SPL) and tested the correlation between the two under the odor concentration-SPL interaction (Table 4). Since the trend of odor concentration was the same in the grids under both low and high SPL conditions, the study calculated the correlation coefficients between the average y value and the average crowd speed using Pearson correlation analysis. The results showed that under low SPL condition, the crowd path showed a negative correlation with the crowd speed, though not significant ( $p > 0.05$ ). While under the high SPL condition, the crowd path showed a significant negative correlation with the crowd speed ( $p < 0.01$ ), indicating that the closer to the side of



6. Average crowd speeds under low SPL (Fig. 6-1) and high SPL (Fig. 6-2) conditions.

**Table 4: Correlation analysis of average crowd path and average crowd speed**

Traffic noise condition	Correlation coefficient	Sig.
Low SPL	-0.010	0.923
High SPL	-0.259	0.007**

**NOTE**

\*\* means  $p < 0.01$ .

noise source (i.e., the farther away from the side of odor source), the slower the crowd speed. This contradicts the previous findings that higher noise SPL leads to higher crowd speeds<sup>[38]</sup>. It may be due to that such studies usually focus on the overall speed change pattern in the direction parallel to noise source and do not examine the longitudinal distance differences between the noise source and the pedestrians. In addition, people are often more careful when walking closer to the road, thus the shorter the longitudinal distance to the road, the slower the crowd speed.

## 4 Conclusions and Implications

In this study, a covert behavioral observation experiment was conducted on a typical urban road with evenly planted lilac trees to investigate the combined effects of plant odor concentration and traffic noise on crowd behaviors. The results confirm that the positive effect of plant odor can mitigate the negative impact of traffic noise, offering new ideas for traffic noise control. The exploration of auditory-olfactory combined effects on crowd behaviors can provide a more comprehensive evaluation on the quality of urban landscapes, which helps improve the traditional visually-dominated design paradigm of urban spaces. The main findings of this study include as follow.

- 1) For crowd path, the path range under high SPL condition was farther away from the noise source compared with that at low SPL; the crowd path in the area with strong plant odor tended to be closer to the direction of odor source, which was even more obvious under the high SPL condition.
- 2) For crowd speed, as the plant odor concentration increased, the crowd speed at high SPL tended to slow down first and then remained stable; but at low SPL, crowd speed was almost unaffected by plant odor.
- 3) Compared with the low SPL condition, the crowd speed slowed down when the crowd path was closer to the noise source at high SPL.

The above findings are instructive for the improvements of the landscape quality of urban environments. For instance, plants with fragrant scent can be planted in areas with traffic noise or other negative sound sources in urban environments to alleviate the negative impacts.

Furthermore, the present study, as a field experiment on crowd behaviors, is not possible to control the environmental variables completely and precisely. Future studies can be optimised in the following aspects.

- 1) The study area was adjacent to an intersection, and even though it was about 15 m from the nearest end of the crosswalk, this may still cause some interference to the crowd. So future research is recommended to choose central sections of urban roads as the study area, to avoid possible impacts.
- 2) This study explored the common behavioral trends of pedestrians in the study area; however, there may be differences among pedestrians' walking behaviors in different directions. Therefore, subsequent studies could be carried out to investigate the disparity in different walking directions.
- 3) *Syringa amurensis* was selected as the odor source for

this study; however, its strong and distinctive odor may lead to individual preference differences. Other fragrant plants could be selected for subsequent studies.

4) Although the participants reported that they did not smell any odor other than the plant odor, the study area may be potentially affected by other odors such as traffic odors. Subsequent studies may consider more precise control of experimental variables to take odor perception thresholds into account.

5) The preliminary research found that the pedestrian densities of crowd during the two selected time periods were relatively consistent, thus the experimental settings under low and high SPL conditions were considered consistent. However, the crowd density and behavioral characteristics on urban roads may vary at different times, thus future studies can put efforts in the effects of temporal factors and crowd density on crowd behaviors.

6) Plants themselves may also have an effect on crowd behavior (e.g. visual attraction), thus future studies can control the multisensory factors of vision, audition, and olfaction separately, so as to explore the combined effects between the three.

#### ELECTRONIC SUPPLEMENTARY MATERIAL

Supplementary material is available in the online version of this article at <https://doi.org/10.15302/J-LAF-1-020106>.

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# 城市环境中植物气味与交通噪声的交互作用 对人群行为的影响研究

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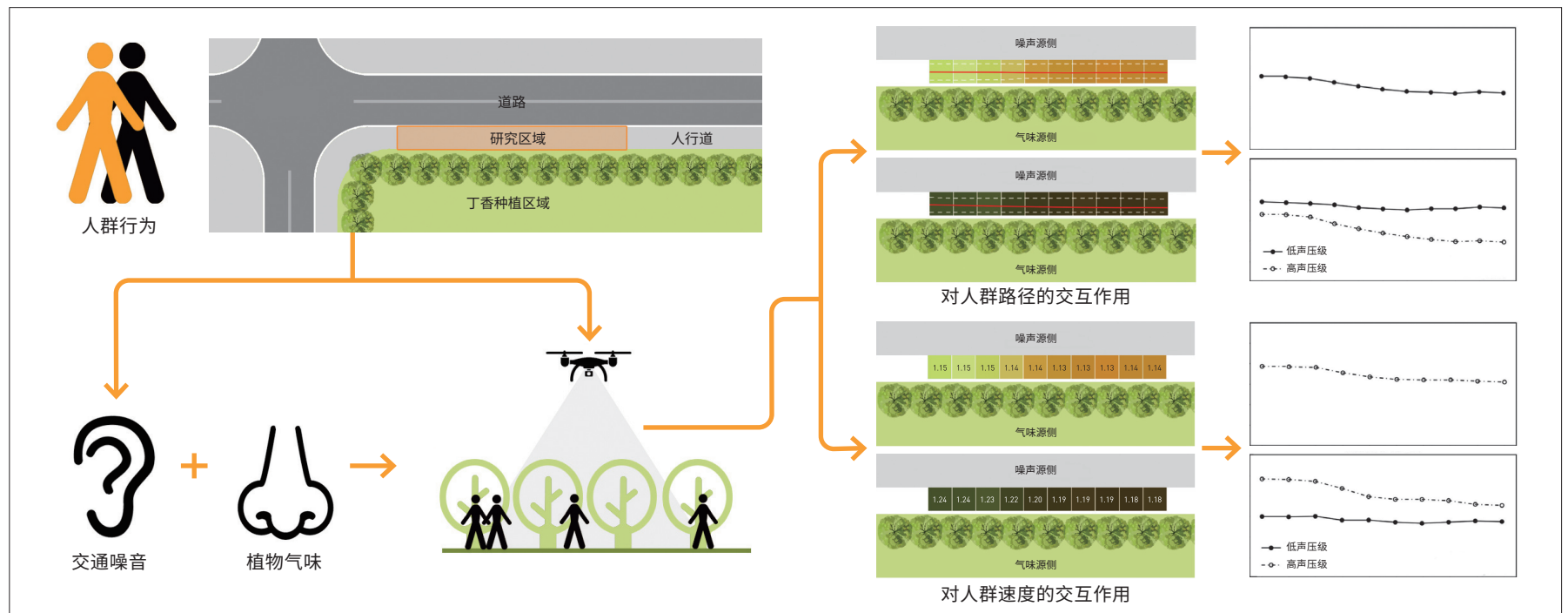
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## 图文摘要



## 摘要

交通噪声是城市环境中的典型消极声源, 于人群行为具有一定影响。本研究针对听嗅感官交互环境于人群行为影响展开了探索, 在均匀种植丁香 (*Syringa* spp.) 的典型城市街道进行了隐蔽的行为观察实验, 旨在探究植物芳香气味与交通噪声的交互作用对人群路径和人群速度的影响。研究表明: 1) 在人群路径方面, 当声压级较高时, 不同气味浓度条件下的人群路径范围及其均值都存在着比声压级较低时更远离声源的趋势; 随着气味从无至浓郁, 人群路径均值逐渐向气味源靠近, 这一趋势尤其在声压级较高时更加显著, 其最大纵向垂直移动距离约为0.3m。2) 在人群速度方面, 当声压级较高时, 随植物气味由无到

浓郁, 人群速度均值由1.24m/s逐步变慢, 然后稳定在1.18m/s处; 然而, 当声压级较低时, 人群速度均值几乎不受气味影响。本研究为缓解城市交通噪声的消极影响提出了新思路, 研究成果对完善城市景观质量评价体系、改善城市设计模式具有指导意义。

## 关键词

植物气味; 交通噪声; 交互作用; 人群路径; 人群速度; 听嗅感官交互环境

## 文章亮点

- 人群路径向气味源移动的趋势在交通噪声的声压级较高时更为明显
- 在交通噪声的声压级较高时，人群速度在气味变浓的影响下会逐渐变慢
- 人群速度在交通噪声的声压级较低时几乎不受气味影响

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## 1 引言

“十四五”规划和2035年远景目标纲要明确提出，需“加强环境噪声污染治理”<sup>[1]</sup>。城市噪声产生的问题日益严峻，已严重影响居民的生活工作及身心健康<sup>[2][3]</sup>。其中，交通噪声是城市噪声的主要来源，具有强度高、影响范围广、持续时间长等特点<sup>[4]</sup>，对于居民的负面影响包括睡眠障碍<sup>[5]</sup>、乐于助人行为减少、对沿途事物注意力降低<sup>[6]</sup>、儿童与青少年问题行为（多动、注意力无法集中等）增多<sup>[7][8]</sup>、驾驶违规率上升<sup>[9]</sup>等。

目前，针对交通噪声对心理与生理影响的研究主要关注不同条件下的噪声烦恼度，以探究缓解交通噪声负面影响的城市环境设计策略<sup>[10]-[14]</sup>。空间使用者的行为作为构成环境的关键部分之一，是生理与心理感知的外显表现<sup>[15]</sup>。在环境评估中，个体行为通常指在特定情况下个人的态度或表现，其受环境影响程度较大，往往呈现随机性<sup>[16]</sup>。相比之下，人群行为则指在特定环境中整体人群的表现，往往呈现一定的规律性<sup>[17][18]</sup>。人群行为可按动机分为主动行为和被动行为<sup>[16]</sup>，或按目的分为参与式行为和非参与式行为<sup>[19]</sup>。此外，按研究对象是否发生位移，可划分为静态行为（如坐、立等）和动态行为（如环绕、穿行等）<sup>[20]-[22]</sup>；且相较而言，动态行为可以更好地反映人群的整体趋势<sup>[20]</sup>。目前，交通噪声相关研究更多聚焦于对个体行为的影响，而针对人群行为的影响关注较少。

传统城市交通噪声控制常采用物理性手段来降低噪声级，如使用声屏障、吸声材料等。但近期研究表明，仅降低噪声级或减少噪声源数量不一定能提高人的舒适感<sup>[4]</sup>。而多感官交互作用研究为提升城市交通噪声控制提供了新的可能。近年来，嗅觉感官因素对人的积极作用逐渐受到学者关注，并已证明植物或食物芳香气味等积极的气味刺激可缓解交通噪声对居民主观感知的消极影响<sup>[23]-[25]</sup>。以城市环境中典型的声音与气味作为感官因素变量、对听嗅交互作用对人群行为的影响进行的研究表明，食物气味可以使人群向气味源头靠近，在施加正面或负面声音后，此效应都会越发显著<sup>[26]</sup>。而交通噪声对居民行为产生的消极影响是否会因积极植物气味因素的存在而得到改善同样值得探究。

综上所述，本研究以典型城市景观植物丁香（*Syringa* spp.）作为气味影响因素，旨在探究植物气味（不同浓度梯度）与交通噪声（低、高声压级）的交互作用对人群行为（移动路径和速度）的影响。研究从多感官交互角度为缓解交通噪声对居民的消极影响提供了新思路，有助于提升城市的多感官环境质量。

## 2 研究方法

### 2.1 研究区域及植物气味—交通噪声源选择

在选择研究区域时，主要考虑以下因素：1）区域内存在交通噪声，且交通噪声在不同时段具有不同的声压级；2）区域内存在有、无植物气味两种情况，以达到气味变量的不同层级；3）区域内没有餐馆、咖啡店、市场、工厂等排放干扰性气味的场所。

基于上述考量，本研究选择哈尔滨市香坊区的民生路作为研究区域（图1）。该路段人行道旁均匀种植丁香（品种：暴马丁香，*Syringa amurensis*），种植间隔约为1.5m，本研究将其作为气味源。丁香是一种落叶灌木或小乔木，因其形态优雅并带有气味，被广泛用于中国城市绿化。相关研究发现，街道中的建筑布局、交叉路口边缘效应等因素会影响气味感知，导致道路中央部分的植物气味较为浓郁，并逐渐向边缘区递减<sup>[23]</sup>。故研究区域内不仅包含植物气味，还存在明显的浓度梯度变化。在噪声源方面，研究区域紧邻城市道路，作为环境中主导噪声源的交通噪声可视为声源，且不同时段的声压级存在显著差异。因此，研究区域存在适合的植物气味和交通噪声条件。

### 2.2 植物气味—交通噪声测量方法

气味浓度的定量测量和记录较为困难。尽管特定化学成分可通过仪器检测，但仪器测量的通常为气体中含量有限的示踪化合物，无法直接测量气味浓度本身，也无法将气味浓度与其属性相关联，所以单纯测量某些化合物的方法不能够充分解释或评定气味的浓度<sup>[27]</sup>。另外，城市环境中单一时段或地点内的测量结果无法代表整个地区的气味情况<sup>[28]</sup>。故

本研究主要采用以人作为“传感器”的气味浓度测量方法，这种方法在相关研究中也较为常用<sup>[29][30]</sup>。

实验前，首先将研究区域划分为 $3\text{m} \times 3\text{m}$ 的网格，自左向右依次标记为1~10号，在网格单元内进行植物气味浓度的主观问卷调查预实验（李克特7级量表，1分表示无气味，7分表示非常浓郁）。预实验与正式实验均在2019年6月10日进行，彼时正值丁香盛花期，研究区域内气味明显；实验当天天气晴朗，风速约为 $0.3\text{m/s}$ ，气味条件相对稳定。预实验中，每个网格单元至少回收30份有效问卷，依此计算各网格的气味浓度平均得分。研究采用Cronbach's  $\alpha$ 系数检验问卷的内部一致性，结果为0.925，并采用KMO系数检验问卷的结构效度，结果为0.803，表明问卷的信度与效度良好。在预实验中，被试者均表示在研究区域内未闻到丁香以外的其他气味，说明植物气味是实验中的唯一主导气味源，被试者未受到环境中其他气味源的干扰。

本研究使用便携式4通道采集前端测量交通噪声<sup>[31][32]</sup>。在每个网格中心分别进行1分钟的录音，随后利用HEAD ArtemiS软件分析录音的声压级。录音期间人群密度始终保持小于 $0.05\text{人}/\text{m}^2$ ，所以可忽略行人对声环境的影响<sup>[33]</sup>。交通噪声按照不同时段的实际交通情况划分为低声压级和高声压级两种：研究区域内较吵时段的声压级设置为高声压级时段（较吵时段根据前期调研的观察与声压级实测确定），低声压级时段与之差值在 $10\text{dB}$ 以上，以保证被试者可明显区分二者。研究采用A计权声压级进行分析，低声压级为 $55.6\text{dB}$ （ $L_{10}=50.3\text{dB}$ ； $L_{50}=54.6\text{dB}$ ； $L_{90}=58.5\text{dB}$ ）；高声压级为 $70.5\text{dB}$ （ $L_{10}=68.9\text{dB}$ ； $L_{50}=70.4\text{dB}$ ； $L_{90}=71.7\text{dB}$ ）。由实验期间经无人机录制的观测视频计算，低、高两种情况下的平均车速分别为 $46\text{km/h}$ 和 $53\text{km/h}$ ，平均每小时车流量分别为1089辆和696辆。研究区域主观气味浓度评价结果及声压级分布如图2所示。

### 2.3 人群行为观测

本研究主要对人群动态行为进行研究。研究区域紧邻城市道路，人群行为多为单纯的行走，故其路径和速度均可较好地反映此类动态行为的变化规律，因而本研究选择路径、速度作为人群行为的分析指标，二者亦为常见观测指标<sup>[34][35]</sup>。路径指研究对象在研究区域的活动轨迹，速度则指研究对象在单位时间内的直线行动距离。实验中双向行进的人群均被纳入样本（表1）。

低、高声压级的实验时间分别对应13:00~15:00和15:00~17:00的时间段。均设置为下午的目的是尽可能缩短两种声压级条件的间隔，以避免时间因素造成的环境条件差异。两种条件下均先进行声压级测试，后进行人群行为观测。实验中，用于录制人群行为的无人机飞行高度超过 $100\text{m}$ ，以避免无人机产生的声音对实验结果造成干扰<sup>[34]</sup>。为确保人群行为的随机性，低、高声压级时段内皆进行了三组测量，每组视频拍摄时长为15~20分钟<sup>[34]</sup>。

表1: 人群行为样本数量 (单位: 人次)

交通噪声条件	路径	速度
低声压级	103	103
高声压级	108	108

随后，研究对无人机拍摄视频样本每2秒进行一次截图。将最左端网格的左下角端点作为坐标系原点，并对每个行人的相应位置进行标记。路径与网格纵线的交点纵坐标值记为 $y$ ，即每条路径有11个标记点，从左至右分别为 $y_1 \sim y_{11}$ 。随后将各标记点相连即可得到每个个体的行进路径。之后计算时段内所有路径的 $y_1 \sim y_{11}$ 的平均值，并计算这些 $y$ 值的第5和第95百分位数，将均值、百分位数对应的点依次连接，中间的围合区域则为路径范围<sup>[26]</sup>。人群中个体的速度计算则以行人（ $N=211$ ）两张连续截图位移距离除以间隔时间（2秒）计算得出<sup>[26]</sup>。

## 3 研究结果与讨论

### 3.1 植物气味—交通噪声对人群路径的影响分析

低、高声压级条件下的人群路径范围如图3所示。当声压级较高时，人群路径范围的上边界、下边界及其均值都比声压级较低时更向下。声压级较高的噪声可能是导致人群向声源反方向移动的原因。当声压级较低时，随着气味从无至浓郁，人群路径在自左至右的网格中均呈现逐渐向气味源移动的趋势，且在声压级较高时，这种移动趋势更加显著。丁香花气味或许是导致人群被吸引的潜在原因，且这种吸引作用也会随着气味浓度的上升而更为明显，并最终呈现稳定的趋势。

为了深入探究植物气味与交通噪声对人群路径的共同影响，本研究采用全因子模型对路径 $y$ 值进行重复测量方差分析。植物气味的浓度变化在网格中从左至右为由淡至浓， $y_1 \sim y_{11}$ 分别分布在不同浓度的网格中，因此 $y$ 可代表浓度梯度的整体变化趋势：将变量 $y_1 \sim y_{11}$ 通过重复测量方差模型进行拟合，可在模型中将其整体生成一个表示气味浓度的自变量（将其记为“气味”），另一个自变量则为声压级（将其记为“噪声”），检验结果如表2所示。气味、气味 $\cap$ 噪声对人群路径的影响均显著（ $p < 0.05$ ），这表示气味浓度和声压级对人群路径的影响之间存在交互作用，气味浓度对人群路径的影响随着声压级的变化而变化。

研究分别计算了气味浓度单一作用、气味浓度—声压级交互作用两种条件下 $y$ 值的估算边际平均值（图4）。估算边际平均值用于计算某个变量在给定条件下的平均变化量，数值越大表示人群距离噪声源更近，距离气味源更远。结果显示，在气味浓度单一作用条件下，气味较浓区域的人群路径更趋近气味源方向（图4-1）。将此条件下的11个 $y$ 值进

表 2: y 值的重复测量方差分析

项目	效应	值	F	假设 df	误差 df	Sig.
y 值	气味	0.247	6.563	10.000	200.000	0.000**
	气味∩噪声	0.103	2.290	10.000	200.000	0.015*

注

\*代表  $p < 0.05$ ; \*\*代表  $p < 0.01$ 。

行两两比较,发现 $y_1$ 、 $y_2$ 、 $y_3$ (无植物气味)彼此之间并没有显著差异( $p > 0.05$ ),但它们和其余 $y$ 的彼此差异均显著( $p < 0.01$ ); $y_4$ 、 $y_5$ 、 $y_6$ (植物气味较淡)与任意 $y$ 值彼此之间均有差异( $p < 0.01$ )。 $y_7 \sim y_{11}$ (植物气味浓郁)彼此间的差异不具有显著性( $p > 0.05$ )。这表示植物气味会在一定程度上吸引人群,已有研究表明这种感官上的吸引力似乎出于人的生物学本性,且其可能会进一步影响情绪<sup>[36]</sup>。

气味浓度—声压级交互作用下的 $y$ 值如图4-2所示。低、高声压级条件之间的差异显著( $p < 0.01$ ):相比于低声压级,人群在低声压级条件下会更加远离噪声源;随着气味浓度的增加,低声压级条件下的人群路径亦轻微向气味源靠近,但这一趋势在统计学分析中尚不显著( $p > 0.05$ );在低声压级条件下,人群路径向气味源靠近的趋势更为明显, $y_1$ 与 $y_{11}$ 之间的最大垂直距离差值约0.3m。将高声压级条件下的11个 $y$ 值进行两两比较,发现 $y_1 \sim y_4$ 彼此间的差异不显著( $p > 0.05$ ),但它们和其他 $y$ 彼此间的差异显著( $p < 0.01$ ); $y_5 \sim y_{11}$ 彼此间的差异也不显著( $p > 0.05$ ),但它们和其余 $y$ 彼此间的差异显著( $p < 0.01$ )。这表示在声压级较高时,人们倾向于远离噪声源、靠近气味源。之前有关食物气味与声音交互作用对人群行为的影响研究指出,噪声的存在可能会增强气味对人群的吸引作用<sup>[26]</sup>。本研究表明,交通噪声对植物气味的吸引作用可能也存在一定的增强效果,从而使人群更倾向于远离噪声源而靠近植物所在方向。

### 3.2 植物气味—交通噪声对人群速度的影响分析

研究就气味浓度、气味浓度—声压级条件下的人群速度同样采用全因子模型进行了重复测量方差分析(表3)。气味、气味∩噪声的影响效

果均为显著( $p < 0.05$ ),这表明气味浓度和声压级对人群速度的影响之间存在交互作用,气味浓度对人群速度的影响随着声压级的变化而变化。

人群速度的估算边际平均值如图5所示,总人群速度的估算边际平均值为1.17m/s。在气味浓度单一作用下,随着气味浓度的增强,人群速度在自左至右的网格中呈现逐步降低并稳定的趋势(图5-1)。将气味浓度单一作用条件下的10个网格中的人群速度进行两两比较,发现1~3号网格(无植物气味)中的人群速度之间不存在显著差异( $p > 0.05$ ),但它们和其余网格间彼此差异显著( $p < 0.01$ );而对于4~6号网格(植物气味较淡),它们与任意网格内的速度彼此间均有差异( $p < 0.01$ );相反,7~10号网格(植物气味浓郁)彼此间则无显著差异( $p > 0.05$ )。这表明植物气味浓度越高,人群速度越慢。

气味浓度—声压级交互作用下的人群速度估算边际平均值如图5-2所示。低、高声压级条件之间的差异显著( $p < 0.01$ )。对于整体趋势而言,相对于低声压级,高声压级会明显加快人群速度的大小——这与前人的研究结果相同<sup>[37][38]</sup>,而这种加速行为可能是人群对噪声的自发反应。在低声压级条件下,各网格间的人群速度均无显著差异( $p > 0.05$ )。当声压级较高时,1号和2号网格无显著差异( $p > 0.05$ ),但它们与其他网格存在明显的差异( $p < 0.01$ );3~5号网格与任意网格内的速度均有差异( $p < 0.01$ );6~10号网格间的差异也不显著( $p > 0.05$ ),但和其他网格的差异显著( $p < 0.01$ )。这表示在高声压级条件下,人群速度受植物气味浓度的影响更显著,且作用最为明显的位置主要出现在3~5号网格附近。

低、高声压级条件下人群速度平均值分析结果(图6)表明,当声压

表 3: 人群速度的重复测量方差分析

项目	效应	值	F	假设 df	误差 df	Sig.
人群速度	气味	0.133	3.437	9.000	201.000	0.001**
	气味∩噪声	0.081	1.970	9.000	201.000	0.044*

注

\*代表  $p < 0.05$ ; \*\*代表  $p < 0.01$ 。

级较低时，不同网格中的速度值基本没有变化；但当声压级较高时，其变化更为显著，其中1和2号网格内的平均速度最快（1.24m/s），10号网格内的平均速度最慢（1.18m/s）；5~10号网格内的速度相对稳定，表示气味浓度的变化不会对人群速度产生显著影响。总体而言，尽管低、高声压级条件下的人群速度具有不同的变化规律，但不同情况下网格间最大速度差值并不明显，只有0.06m/s。

### 3.3 人群路径与人群速度相关性分析

本研究在两种声压级条件下对样本人群的路径和速度进行了分析（低声压级条件103人，高声压级条件108人），并检验了气味浓度—声压级交互作用下二者的相关性（表4）。由于研究中无论是低声压级还是高声压级条件，植物气味浓度在网格中的变化趋势均是相同的，因此研究采用Pearson相关分析计算了每条路径y值的平均值与每条路径平均速度的相关系数。结果表明，在低声压级条件下，人群路径与人群速度呈现负相关趋势，但相关性不显著（ $p>0.05$ ）；而在高声压级条件下，人群路径与人群速度呈显著负相关性（ $p<0.01$ ），越接近噪声源一侧（即越远离气味源一侧），人群速度越慢。这与前人关于更高的噪声声压级会导致人群速度提高的研究结论相悖<sup>[38]</sup>。这可能是因为此类研究通常关注平行于噪声源方向的整体速度趋势，并未对噪声源与人的不同垂直距离进行对比，且人在越靠近道路行走时大多会越小心，因而与道路的垂直距离越近，人群速度越慢。

## 4 结论与展望

本研究在均匀种植丁香花的典型城市街道进行了隐蔽的行为观察实验，以调查植物气味与交通噪声的交互作用对人群行为的影响。研究结果证实，植物气味的积极作用会缓解交通噪声对人群行为产生的负面影响，为交通噪声控制提供了新的思路。对听嗅感官交互环境对人群行为影响的探索，可为城市景观质量提供更为综合、立体的评价维度，并有助于改善城市空间传统的视觉主导的设计模式。本研究的主要发现包括：1）在人群路径方面，相较于低声压级条件，高声压级条件下的路径范围会更远离噪声源；植物气味浓郁区域的人群路径更趋近气味源方向，高声压级条件下此趋势更加明显。2）在人群速度方面，随着植物气味从无至浓郁，高声压级条件下的人群速度有先减缓、后保持稳定的趋势；低声压级条件下，人群速度几乎不受植物气味的影响。3）相较于低声压级条件，在低声压级条件下，人群路径越靠近噪声源方向，其速度会越慢。上述研究发现对提升城市环境的景观质量具有启示意义，如针对交通噪声等城市环境中的消极声源，可在其影响范围内种植芳香气味植物，以达到缓解噪声带来的消极影响的目的。

表 4: 平均人群路径与平均人群速度的相关性

交通噪声条件	相关系数	Sig.
低声压级	-0.010	0.923
高声压级	-0.259	0.007**

注

\*\*代表  $p < 0.01$ 。

此外，本研究为实地人群行为实验，因而无法对环境变量进行完全精确控制，未来研究可在以下方面开展优化。1）本研究实验场地邻近十字路口，即便研究区域距离人行横道最近端约15m，这仍可能会对人群产生一定干扰，建议后续研究选取合适的中部路段以尽量规避此类影响。2）本研究探索了研究区域内行进人群的共同行为趋势，然而不同行进方向的人群行为可能存在差异，因此后续研究可针对不同行进方向的人群展开行为差异研究。3）本研究选取的植物为暴马丁香，其气味较为浓烈且独特，人们对该气味的接受度存在一定的个体差异，后续研究可选取其他芳香植物。4）虽然本研究中的被试者在主观上表示并未闻到除植物气味之外的其他任何气味，但研究区域可能受到交通气味等其他气味的潜在影响。后续研究可考虑更为精准的实验变量控制，将人的气味感知阈值纳入考量。5）前期调研发现，研究区域两个所选时段内的人群密度较为一致，因而认为本研究在同一路段的不同时段的实验场景一致。然而，城市道路在不同时段的人群密度及行为特征可能存在差异，故未来研究可就时间因素对实验结果的影响，以及人群密度对人群行为自身的影响进行精细化探究。6）植物本身也可能会对人群行为产生影响（如视觉吸引），后续研究可对视、听、嗅多感官因素进行分别控制，从而探索三者的交互作用。

### 补充材料

可通过<https://doi.org/10.15302/J-LAF-1-020106>查看本文补充材料。

- 图 1. 研究区域示意图
- 图 2. 研究区域的气味主观浓度评价结果（图 2-1），以及低声压级（图 2-2）和高声压级（图 2-3）分布情况。
- 图 3. 低声压级（图 3-1）和高声压级（图 3-2）条件下人群路径范围情况；红色实线为人群路径的纵坐标平均值连线，白色虚线为纵坐标值的第 5 和第 95 百分位数的连线。
- 图 4. 气味浓度单一作用（图 4-1）和气味浓度—声压级交互作用（图 4-2）条件下的 y 值估算边际平均值。
- 图 5. 气味浓度单一作用（图 5-1）和气味浓度—声压级交互作用（图 5-2）条件下的人群速度估算边际平均值。
- 图 6. 低声压级（图 6-1）和高声压级（图 6-2）条件下的人群速度平均值。