



The multi-dimensional perceptions of office staff and non-office staff about metro noise in commercial spaces

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Abstract – Indoor acoustic environment has become a critical factor in architectural design, and some researchers argued that the reactions from people of varied age, gender, etc. to indoor noise should be considered. While the office staff along metro lines get used to frequent metro noise, their metro noise perceptions, which are supposed to be different from non-office staff, need to be clearly examined. Based on on-site physical measurements and questionnaire surveys, this study aims to analyze the multi-dimensional perceptions (annoyance, dissatisfaction and unpleasantness) of office staff and non-office staff about metro noise in the underground commercial spaces of a high-rise building. The results indicate that due to lower adaptability and tolerance to metro noise, the non-office staff were more sensitive to the change of metro noise than the office staff, and compared with the office staff, the non-office staff expressed obviously more intense multi-dimensional negative moods under the same metro noise environments. Furthermore, for the non-office staff, their annoyance and dissatisfaction ratings due to metro noise correlated well with A-weighted equivalent sound pressure level (LA_{eq}) and maximum A sound pressure level (LAF_{max}). Among the psychoacoustic measures, loudness and sharpness mainly influenced their annoyance and dissatisfaction perceptions.

Keywords: Metro noise, Multi-dimensional perceptions, Office staff, Non-office staff, Commercial space

1 Introduction

Recently, the rapid development of urbanization has not only brought convenience to our life, but also caused a series of urban environmental problems such as environmental pollution, green area reduction, and traffic congestion [1]. To protect urban ecology and alleviate urban traffic pressure, governments from all over the world began to vigorously develop metro public transport systems. Since the reform and opening-up, the metro transport system of China has been developing at full speed. For example, the metro network in Guangzhou has been progressively constructed since 1993 [2], and by the year of 2019, it had 14 lines with a total length of 513 km and 164 stations, serving approximately 9.06 million passengers on a daily basis. With the rapid expansion of urban rail transit, people's complaints about metro noise along railway lines are also increasing [3]. A low-frequency noise with a main range of 20–200 Hz [3], this kind of environmental noise is detrimental to human health by causing immediate effects such as sleep disorder [4, 5], concentration and activity disturbance [6] as well as serious problems such as cardiovascular diseases, high blood pressure [7, 8], children's learning

disabilities [9] and other negative psychological and mental influences [10, 11]. Therefore, metro noise has become a major environmental problem for rail transit management departments.

To provide foundation for better controlling the negative emotions resulting from metro noise, the previous studies have discussed the objective influencing factors of metro noise perceptions and put forward some evaluation methods. Walker and Chan investigated human response to the metro noise in dwellings near underground railway tunnels, and believed A-weighted sound pressure level, or A-weighted sound pressure level difference between noise and background could be used to well predict metro noise annoyance [3]. Li et al. analyzed the impact of noise caused by metro train on passengers based on the questionnaire survey on the perceptions of 601 respondents, pointing out that 50.6% of the interviewees were disturbed by the varying noise along metro lines, and they felt most annoyed and disturbed by wheel-rail squeal [12]. Liu et al. aimed to analyze the perceptual evaluation for annoyance of metro interior noise based on 42 noise samples, and they proposed that the annoyance of metro interior noise was mainly influenced by the loudness, sharpness and A-weighted equivalent sound pressure level (LA_{eq}) [13]. Liu et al. adopted a fuzzy comprehensive method to explore the perceptions of

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metro interior noise. They believed that the passengers felt less annoyed in the middle carriage than at the front or rear of metro, and the interior noise of underground metro caused more annoyance than that of overground metro [14]. Hou et al. evaluated the noise distributions at different locations of underground metro station platforms, recommending the maximum A-weighted sound pressure level (LAF_{max}) to serve as an auxiliary evaluation index for annoyance ratings [15]. Ji et al. assessed the perceptions of railway-generated noise on straight and curved sections of track in residential areas, and the results show that the noise occurring on the curved section was perceived to be far noisier than on the straight section [16]. However, past metro noise researches mainly focused on the subjective and objective evaluations of acoustic environments inside metro, at metro station or in dwellings along metro lines, and neglected the commercial areas in office buildings. With the aim of utilizing spaces more effectively, commercial areas are commonly designed on the lower floors of office buildings, and as the spaces on lower floors are closer to metro lines, the impact of metro noise to these spaces ought to be greater. Thus, it is necessary to evaluate the perceptions of people in commercial spaces, which might be different from those inside metro, at metro station or in the housing areas due to different acoustic demands, and the analysis results furnish a basis for taking effective measures to control metro noise and could affect the development of commercial areas to a certain extent. Unfortunately, there is a lack of study to assess metro noise environments in commercial areas.

On top of that, the acoustic characteristics of noise sources are not the only causes of negative mood. There are also non-acoustic factors that are believed to influence noise perceptions, including personal variables related to visibility [17, 18], sensitivity [19, 20], mood [21], attitude [22, 23], tolerance and adaptability [24–27] towards noise sources, experience and knowledge about noise [28], dependence on the modes of transport [29], availability and accessibility of information about the noise abatement procedures [30, 31] and activity pattern [32], sociodemographic variables related to age [33], gender [34], health status [35] and socio-economic situation [36], specific features of noise exposure related to place [37, 38], time of day [39] and type of exposure [40, 41] as well as a number of building characteristics related to floor level, window orientation and sound-absorbing materials [42]. It can be seen from the above studies that noise perceptions are believed to be affected by population characteristic factors, while few studies have discussed the differences in metro noise perception between different types of people. Furthermore, previous studies have shown that noise tolerance and adaptability are important factors influencing people's noise responses. As the staff working in office buildings near metro lines are exposed to metro noise throughout the working time while the non-office staff enter metro noise environments only briefly and infrequently, their tolerance and adaptability to metro noise ought to be different, which might in turn influence their noise perceptions and needs deeper research combined with metro noise environments.

In order to describe the impact of noise on people's multi-dimensional negative emotions, researchers from all over the world have proposed some evaluation indexes of perceptions, such as annoyance, dissatisfaction, unpleasantness, discomfort, affectedness, etc. Although annoyance, as a multifaceted psychological concept used to describe the negative feeling associated with noises [43], was widely adopted to evaluate the unpleasant perception caused by noise [44, 45] and could reflect the main impact of noise on people in some cases [46], it could not cover and represent all the negative moods brought by noise [47]. With the aim of selecting subjective indexes which could more accurately reflect the impacts of various noises on people within different acoustic environments, some studies explored the applicability of various kinds of subjective indexes. Data indicated that the reliability and validity of dissatisfaction and affectedness scale were found to be more acceptable than those of annoyance for the perceptual evaluation of aircraft and traffic noise [48–50]. Fields [51] suggested that because individual judgments lacked repeatability and people reacted differently to the same noise, the use of annoyance as subjective index to evaluate the acoustic environments of residential areas had uncertainty. Only few studies focused on which perceptual evaluation indexes could be used to effectively show the impacts of metro noise on different kinds of people.

Given all of these, when the specific indoor acoustic environments are designed or evaluated, different people's multi-dimensional acoustic perceptions should be considered with reference to their specific population characteristics, such as age, gender and other influencing factors, and the acoustic parameters responsible for noise perceptions need to be clearly revealed. This study selected three subjective evaluation indexes of noise-induced negative mood (annoyance, dissatisfaction and unpleasantness) as quantitative standards, and aims to analyze people's multi-dimensional perceptions to metro noise as well as to investigate the acoustic parameters influencing the negative perception ratings of metro noise in the underground commercial spaces of a high-rise office building. It is based on the on-site physical measurements and questionnaire surveys targeting the office staff and non-office staff, and is expected to provide potential information for the commercial space designs of buildings along metro lines.

2 Materials and methods

2.1 Research site

The investigations were conducted in the underground commercial spaces of a super high-rise office building near the metro line 5 in Guangzhou, China. The target building is one of the landmarks of Guangzhou, with 67-storey high and a construction area of 180 000 square meters. The reason for choosing this high-rise building as research site is that similar to most of the office buildings near metro lines, the metro noise is an important noise source inside buildings, and the commercial areas are distributed on lower floors, where metro noise could be heard clearly especially

under quiet environments. Therefore, with the rapid development of urban metro systems, the results of this study could provide references for a great number of space designs related to commercial areas of buildings along metro lines. The surveys were taken place on the underground floor of this high-rise building, which is divided into several commercial areas. To reflect the biggest influence of metro noise to the underground spaces, the investigations were conducted in the areas closer to the edge of metro line 5, which are divided into two commercial areas, typically rectangular and trapezium space, at around 72 m^2 and 45 m^2 in area, respectively, and the nearest distance between the edge of metro line 5 and the commercial areas is around 19 m. The layouts of investigated sites are shown in Figure 1. These two commercial areas are Chinese restaurants (Fig. 2), which are crowded and busy between 12 and 1 pm on weekdays. In order to avoid the influence of crowd noise or other types of noise on the perceptions of metro noise, data collections were conducted on weekends or before 12 pm or after 1 pm on weekdays, during the survey period (December 2020–January 2021), the survey areas were relatively quiet without too many people. In addition to the secondary radiation noise generated by the rolling stock, the vibration due to metro operation would also produce some secondary vibration noise. Besides, the maximum running speed of metro line 5 is about 90 km/h, and due to the differences of factors like the direction, carrying capacity of metro as well as space environment, the level and frequency spectrum characteristics of metro noise samples collected within the two underground spaces showed certain degree of differences. Every 5 min or so, people could clearly experience the metro vibration and hear the noise. As the upstairs of underground spaces are business and office areas, the customers of commercial areas include the staff working in the building, as well as the outsiders who go to the office building for work or entertainment. Finally, 76 participants in survey area 1 and 35 participants in survey area 2 took part in this field study.

2.2 Questionnaire design and survey

For the survey (Fig. 3a), with the aim of obtaining enough questionnaires for analysis, some non-office staff were invited to eat and experience the metro noises before finally completing subjective surveys on the target metro noises in the two underground commercial spaces. Besides, this study also selected on-site interviewees randomly near the measurement equipment. After each obvious session of noise occurred within the underground spaces, the on-site interviewees were firstly asked if they had heard such a noise, and the survey would begin if the answer was affirmative.

Questionnaire was carefully designed following the guidelines and recommendations of Fields et al. [52] with slight modifications to fit the purpose of this research. Considering that people may react to noise with various negative emotions like anxiety, distraction, exhaustion, anger, frustration, disappointment, and fear [46, 47, 53], some studies have put forward a series of evaluation indexes of

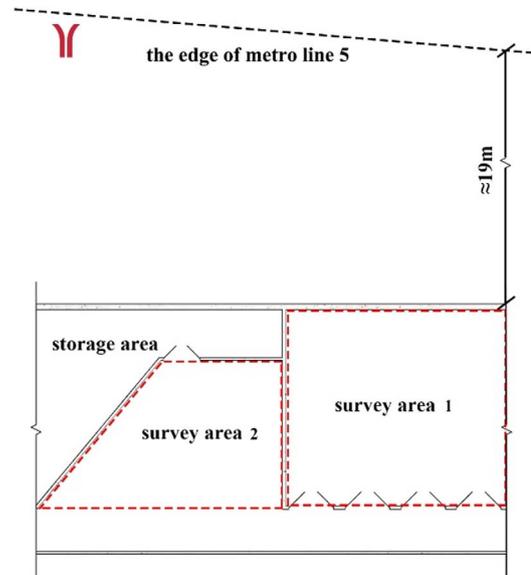


Figure 1. The investigated sites in Guangzhou near metro line 5.



Figure 2. Survey areas. (a) Survey area 1; (b) Survey area 2.

noise negative emotion and observed their differences in evaluating the influence of noise. For instance, Job's study pointed out that annoyance, dissatisfaction and affectedness differed in characterizing aircraft noise responses [48]. Following the previous study, this study chose three subjective indexes (annoyance, dissatisfaction and unpleasantness), which are commonly used to evaluate the negative feelings of noise [54–56], to examine whether there are differences for the three subjective indexes in evaluating people's reactions to metro noise in such two underground commercial spaces. Among these, annoyance described the disturbing response caused by noise. Similar to annoyance, unpleasantness is used to estimate people's unhappiness reaction with noise, while the negative emotion level of which is generally lower than annoyance. Dissatisfaction is a psychological state, referring to people's subjective definition of noise environmental quality. Before the survey,



Figure 3. Conducting measurement and filling in questionnaire in the field study.

the meaning of each subjective index was explained to interviewees. A 11-point numeric scale (from 0 as “not at all” to 10 as “extremely”) was used in the ratings of annoyance, dissatisfaction and unpleasantness. We advised that if the sound is among the least annoying, dissatisfied and unpleasant ones, options 0 or 1 are chosen, and if the sound is among the most annoying, dissatisfied and unpleasant ones, options 9 or 10 are chosen. Besides, according to the previous field survey, four types of typical activities including conversation, entertaining, eating and concentrating which frequently take place in the underground commercial spaces were selected, and the participants were asked to assume themselves doing these four activities and rate the impact of metro noise to the above activities using a 5-point numeric scale (from 1 as “not at all” to 5 as “extremely affected”). According to some previous studies [57–59], the noise sensitivity and attitude ought to be evaluated based on a series of questions, which were proved to be highly reliable and valid [60], however, in order to simplify the evaluation process, some studies also use single questions to evaluate noise sensitivity and attitude [54, 61, 62], which was adopted by this study, in particular, the questionnaire obtained information on people’s sensitivity to metro noise using a 5-point numeric scale (from 1 as “not at all” to 5 as “extremely sensitive”) and people’s attitude to metro noise regarding its noise level using a 5-point numeric scale (from 1 as “not at all” to 5 as “extremely noisy”). These evaluation methods are likely to not fully characterize the sensitivity and attitude of respondents to noise, thus for further studies, it is necessary to make accurate assessment of noise sensitivity and attitude based on multiple items. In addition, the questionnaire also collected the population characteristics of interviewees including gender, age range and whether they worked in this high-rise office building or not.

Finally, this study obtained a total of 111 valid questionnaires, the socio-demographic characteristics of investigated individuals are shown in Table 1. The participants

Table 1. Socio-demographic characteristics of the studied population.

Characteristics	<i>N</i>	% <i>N</i>
Gender		
Male	61	54.95%
Female	50	45.05%
Age		
20–30	84	75.68%
30–40	27	24.32%
Whether they worked in the target office building		
Office staff	54	48.65%
Non-office staff	57	51.35%

consisted of 54.95% male and 45.05% female. The number of investigated non-office staff (57) was a little higher than that of office staff (54). In terms of age, the respondents were all young people, and the highest percentage (75.68%) of participants aged from 20 to 30 years old, followed by 24.32% of participants aged from 30 to 40 years old. In this study, four of non-office staff were excluded from the analysis as the outliers (much higher or lower than other data in the same group) in regression analysis. To verify the validity of the remaining data, reliability and validity tests of data were conducted, and the results show that the reliability coefficients (Alpha) reached more than 0.95, and effectiveness coefficients (KMO) was nearly 0.80, with the significance coefficient of Bartley spherical test evidently less than 0.05, demonstrating the results of the questionnaire survey have sufficient reliability and good structural validity.

2.3 Metro noise environment measurement and extraction

The noise recordings were carried out at the same time (Fig. 3a) using a Brüel&Kjær2270 handheld analyzer (Fig. 3b) which complies with the provisions of ISO 1996 [63], could display acoustic environment data at any time and save noise samples as 16-bit wave files. The equipment was placed at a minimal height of 1.5 m from the ground and a minimum distance of 1 m from the nearest façade [64–66]. To prevent sound reflection, the distance between the sound level meter and the recorder’s torso was set to be at least 1 m.

In order to capture metro noise samples, continuous recordings were conducted within the indoor spaces, and since the metro noise could be clearly heard indoors, the approximate start time of each metro noise sample was also recorded. Based on the wave files and the recorded start time, the metro noise signals could be selected. Considering metro noise is intermittent, which lasts for around 10 s including the coming and leaving of vehicle [3], Maigrot et al. made use of 10 s metro noise samples to examine the influence of metro noise on people’s perceptions [67]. According to this study, the metro signals were divided into 10 s sessions without deleting the arrival and departure phases, so as to represent the exposure time to metro noise

of the participants in the field study. Each metro noise sample could be input into program to calculate LA_{eq} and LAF_{max} .

2.4 Psychoacoustic metrics calculation

In addition to LA_{eq} and LAF_{max} , this study also selected four commonly used psychoacoustic metrics – loudness, sharpness, roughness, and fluctuation strength [68] – to investigate the effects of sound quality characteristics on people’s multi-dimensional metro noise perceptions, and the loudness, sharpness, roughness, and fluctuation strength of metro noise samples were calculated using the Sound Quality software. As the measured metro noises are non-steady-state sounds, this study used the software to calculate the time-varying loudness values of metro noise samples on the basis of DIN 45631/A1 [69] from a time-varying 1/3 octave band spectrum using exponential averaging with a 2 ms time constant, and the software calculated sharpness and roughness based on the Aures method [70]. As for fluctuation strength, the software calculated it from a pressure-time history, which measures the energy in 47 overlapping barks and weights the level in each band by a frequency-dependent weighting function [71].

2.5 Statistical analysis

Considering the data of acoustic parameters and perception (annoyance, dissatisfaction, unpleasantness, disturbance) ratings were not typical normal distributions, and the data of perception ratings and personal characteristic (sensitivity, attitude, gender, being office staff or not) were ranked data, the nonparametric statistics were conducted, say Spearman’s correlation analyses were conducted to test the correlations for the data in this study. In addition, taking into account that the mean annoyance and dissatisfaction ratings of non-office staff conformed to normal distributions, and the variance of mean annoyance and dissatisfaction ratings under the influence of acoustic parameters corresponded to homogeneity, linear regression analyses were conducted to establish the prediction equations of mean perception ratings based on acoustic parameters, and step-wise regression was also used to find out the optimal regression equations to define mean perception ratings.

3 Results

3.1 Acoustical characteristics of metro noise samples

In terms of the sound pressure level of the collected metro noise samples, the commercial areas’ average LA_{eq} was 61.2 dBA and average LAF_{max} was 65.0 dBA, the highest LA_{eq} and LAF_{max} values appeared at survey area 2, at 68.6 dBA and 74.4 dBA, respectively, and the lowest LA_{eq} and LAF_{max} values were at survey area 1, at 59.0 dBA and 61.5 dBA, respectively. The sound pressure levels measured at survey area 2 were generally higher than those measured at survey area 1, and more secondary vibration noise was produced at survey area 2. The relative standard deviation

(RSD) of LA_{eq} and LAF_{max} were 4.90% and 6.84%, separately, indicating that compared with that of LA_{eq} , the data of LAF_{max} tended to be more discrete.

In terms of the psychoacoustic metrics of the collected metro noise samples, the fluctuation range of time-varying loudness was the widest, from 10.24 sone to 24.24 sone, followed by fluctuation strength, from 0.51 vacil to 2.03 vacil, and sharpness, from 1.26 acum to 2.56 acum, roughness had a narrowest fluctuation range, from 0.17 asper to 0.32 asper. The highest LA_{eq} and LAF_{max} measured at survey area 2 accompanied the highest time-varying loudness, sharpness and fluctuation strength values. The RSD of fluctuation strength was highest, at 45.79%, followed by time-varying loudness and sharpness, at 31.60% and 23.74%, respectively, while the lowest RSD value was for roughness, at 18.98%, demonstrating that compared with those of LA_{eq} and LAF_{max} , the data of psychoacoustic acoustic parameters tended to be more discrete, and the fluctuation strength data was the most discrete among all acoustic parameters data.

Following the previous study [72], the frequency spectrum characteristics of metro noise were analyzed based on the 1/3 octave spectrum ranging from 63 to 8000 Hz. In this study, the metro noise not only contained the secondary radiation noise due to passing vehicles but also included the secondary vibration noise caused by metro operation. According to Figure 4, which shows the averaged linear sound pressure level (SPL) for metro noise samples under each 1/3 octave spectrum, it can be seen that the energy of metro noise mainly concentrated on the frequency range of lower than 200 Hz, showing that the metro noise had obvious low-frequency noise characteristics. With regard to the change trend of metro noise spectrum curve, the mean linear sound pressure level of metro noise increased obviously from 63 Hz and reached its maximum value (74.9 dB) at 80 Hz. Following that, it decreased significantly towards 400 Hz, then went down slowly until 8000 Hz. Table 2 shows the Spearman’s correlation coefficients between various acoustic parameters of the measured metro noise samples. The strongest correlations were found between the LA_{eq} and LAF_{max} , LA_{eq} and sharpness, as well as LAF_{max} and sharpness. Besides, the LA_{eq} , LAF_{max} , loudness (N), sharpness (S) and fluctuation strength (F) showed relatively significant and positive correlations with each other at 0.01 or 0.05 levels, whereas statistically significant relationships were not found between the roughness (R) with other acoustic parameters.

3.2 Multi-dimensional perception ratings and population characteristics

Table 3 shows the Spearman’s correlation analysis between the personal characteristics of interviewees with their multi-dimensional perception ratings of metro noise. Given that the interviewees in this study were all young people aged from 20 to 40 years old, the correlation analysis between age and multi-dimensional perception ratings was not conducted. The results indicated that the most important non-acoustic factor which influenced the multi-dimensional perceptions of metro noise was being the staff

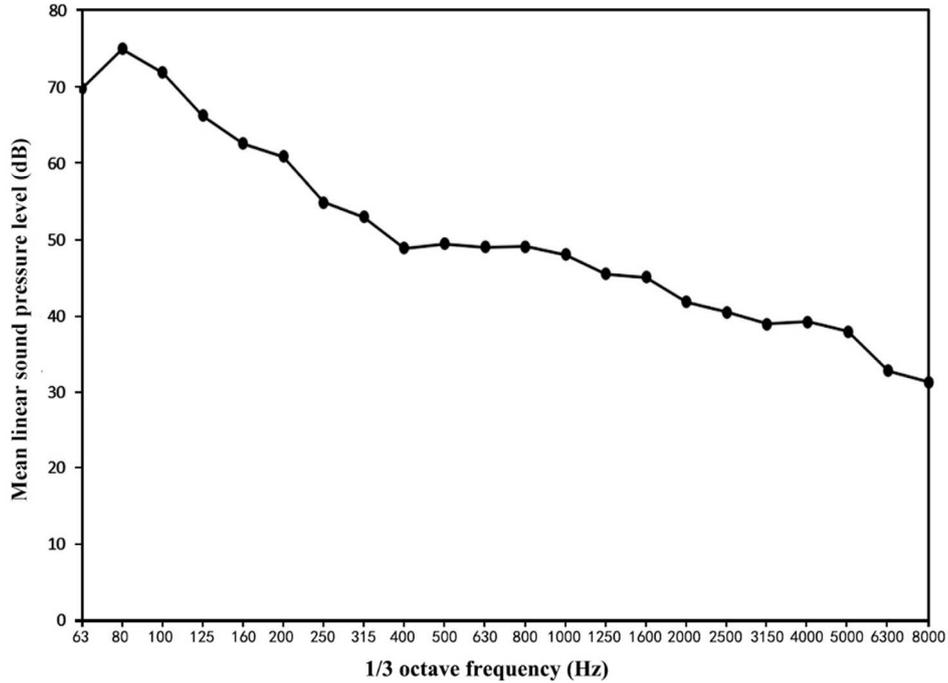


Figure 4. 1/3 octave spectra of metro noise.

Table 2. Spearman’s correlation coefficients between the acoustic parameters of metro noise samples.

	LA _{eq} (dBA)	LAF _{max} (dBA)	N (sone)	R (asper)	S (acum)	F (vacil)
LA _{eq} (dBA)	–	0.903**	0.830**	0.207	0.903**	0.770**
LAF _{max} (dBA)	0.903**	–	0.661*	0.390	0.903**	0.673*
S _n (sone)	0.830**	0.661*	–	0.317	0.770**	0.758*
R (asper)	0.207	0.390	0.317	–	0.561	0.256
S (acum)	0.903**	0.903**	0.770**	0.561	–	0.709*
F (vacil)	0.770**	0.673*	0.758*	0.256	0.709*	–

* Significant at the 0.05 level (two-tailed test).

** Significant at the 0.01 level (two-tailed test).

Note: N, loudness; R, roughness; S, sharpness; F, fluctuation strength.

Table 3. Spearman’s correlation coefficients between the personal characteristics of interviewees and their multi-dimensional perception ratings due to metro noise.

Non-acoustic factors	A		D		P	
	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>
Metro noise sensitivity	0.805**	0.000	0.768**	0.000	0.813**	0.000
Metro noise attitude	0.709**	0.000	0.637**	0.000	0.708**	0.000
Gender	0.289**	0.002	0.268**	0.004	0.236*	0.013
Being office staff or not	0.858**	0.000	0.803**	0.000	0.848**	0.000

* Significant at the 0.05 level (two-tailed test).

** Significant at the 0.01 level (two-tailed test).

Note: A, metro noise annoyance rating; D, metro noise dissatisfaction rating; P, metro noise unpleasantness rating; Metro noise sensitivity: 1 as “not at all”, 5 as “extremely sensitive”; Metro noise attitude: 1 as “not at all”, 5 as “extremely noisy”; Gender: 1 as “male”, 2 as “female”; Being office staff or not: 1 as “office staff”, 2 as “non-office staff”.

of the target building or not, followed by metro noise sensitivity and metro noise attitude, and gender was the least important influencing factor in comparison with the other non-acoustic factors. In addition, the significant and

positive relationships between multi-dimensional metro noise perception ratings and being the staff of the target building or not suggested that the non-office staff rated higher level on metro noise annoyance, dissatisfaction and

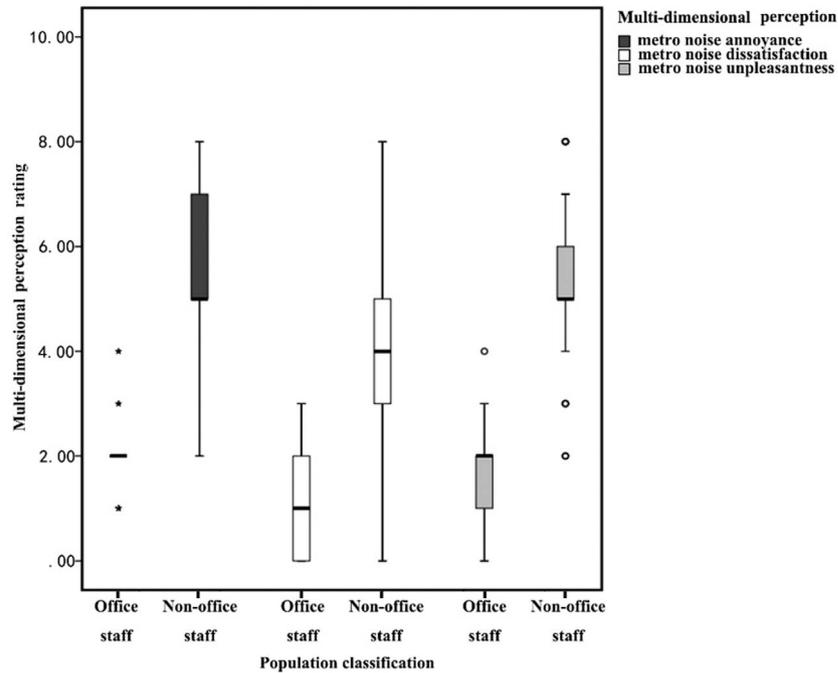


Figure 5. The distributions of multi-dimensional perception ratings due to metro noise.

unpleasantness ratings than the office staff, and relatively higher correlation coefficients were found between being office staff or not and the ratings of annoyance ($p = 0.858$) and unpleasantness ($p = 0.848$) than that of dissatisfaction ($p = 0.803$), indicating that the office staff and non-office staff expressed more differences on annoyance and unpleasantness ratings, while expressed less differences on dissatisfaction ratings. The above results demonstrate that the office staff and non-office staff showed significant differences in multi-dimensional metro noise perceptions, and therefore we divided the interviewees in the underground commercial spaces into office staff and non-office staff groups and studied their metro noise reactions separately.

The multi-dimensional perception (annoyance, dissatisfaction and unpleasantness) ratings of office staff and non-office staff due to metro noise were analyzed in the form of box-plot in Figure 5, with the information on median and distribution. With regard to both the office and non-office staff, the widest distributed perception rating was dissatisfaction, indicating both the office and non-office staff rated most variedly in this regard. For the office staff and non-office staff, respectively, their medians of annoyance and unpleasantness ratings were higher than their dissatisfaction ratings by 1 unit. In addition, the medians of annoyance, dissatisfaction and unpleasantness ratings of non-office staff were all higher than those of office staff by three units, respectively, which proves that the non-office staff expressed obviously more intense multi-dimensional negative emotions to metro noise than the office staff.

Table 4 shows the Spearman's correlation coefficients of three multi-dimensional perception variables of office staff

and non-office staff due to metro noise. For the office staff and non-office staff respectively, no significant differences were found in correlation coefficients between three multi-dimensional perception variables, and compared with the annoyance and dissatisfaction, the correlations between unpleasantness with other variables were slightly stronger, with relatively higher correlation coefficients. In addition, in contrast to those of the office staff, the correlation coefficients between three multi-dimensional perception variables of non-office staff were much higher, indicating the correlations between the three perception variables of non-office staff were stronger.

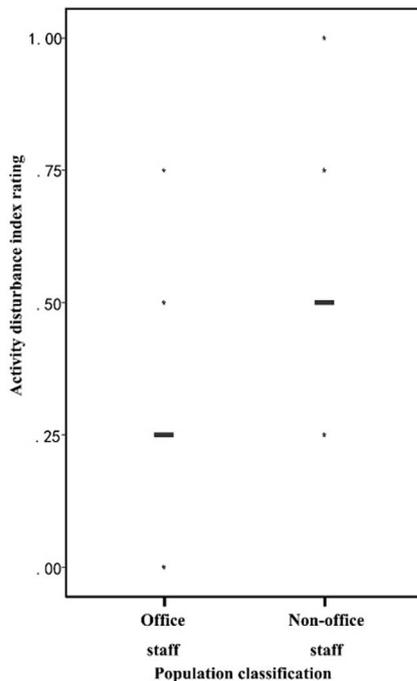
3.3 Multi-dimensional perception ratings and activity disturbance index rating

As the interviewees were asked to identify the disturbance degree of metro noise to their four types of activities (conversation, entertaining, eating and concentrating), the disturbed status was defined when the disturbance rating was 3 or more than 3, and an activity disturbance index rating was computed by summing affirmative responses [48]. In particular, if the interviewee rated three or more for none of the four activities, then the activity disturbance index rating was defined as 0. In a similar manner, if the interviewees rated 3 or more for 1, 2, 3 and 4 activities, then the activity disturbance index ratings were defined as 0.25, 0.5, 0.75 and 1, respectively. The activity disturbance index ratings expressed by office staff and non-office staff were analyzed by means of box-plot. In Figure 6, it can be seen that the median of activity disturbance index ratings of non-office staff ($ADI = 0.5$) was higher than that of the

Table 4. Spearman's correlation coefficients between 3 multi-dimensional perception variables.

	A		D		P	
	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>
Office staff						
A	–	–	0.360*	0.007	0.445*	0.001
D	0.360*	0.007	–	–	0.382*	0.004
P	0.445*	0.001	0.382*	0.004	–	–
Non-office staff						
A	–	–	0.768*	0.000	0.822*	0.000
D	0.768*	0.000	–	–	0.806*	0.000
P	0.822*	0.000	0.806*	0.000	–	–

* Significant at the 0.01 level (two-tailed test).

**Figure 6.** The distributions of activity disturbance index ratings due to metro noise.

office staff ($ADI = 0.25$), which means the metro noise induced more disturbances to the activities of non-office staff than those of the office staff. According to Job's study [48], the validity of perceptual evaluation index could be examined based on the correlation coefficient between perception ratings and activity disturbance index ratings, and the optimal subjective evaluation index could be selected based on the higher correlation coefficient between these two variables. The Spearman's correlation coefficients between the activity disturbance index rating with three multi-dimensional perception ratings (annoyance, dissatisfaction and unpleasantness) due to metro noise are shown in Table 5. In terms of the office staff, annoyance ($p = 0.472$) and unpleasantness ($p = 0.418$) ratings showed similar, significant and positive correlations with activity

disturbance index ratings at the 0.01 level, whereas a statistically significant relationship was not found between dissatisfaction ratings ($p = 0.261$), indicating annoyance and unpleasantness showed higher validity than dissatisfaction. For the non-office staff, the correlation coefficients between activity disturbance index ratings and ratings of annoyance ($p = 0.426$) and dissatisfaction ($p = 0.485$) were similar and higher than that of unpleasantness ($p = 0.288$), representing that dissatisfaction and annoyance were more valid than unpleasantness, thus in this study, annoyance-unpleasantness and annoyance-dissatisfaction were determined as optimal subjective indexes for evaluating the metro noise reactions of office staff and non-office staff, respectively.

With respect to both the office and non-office staff, the annoyance was one of their optimal subjective indexes. Thus, to reveal the influence mechanism between optimal perception rating with activity disturbance degree rating based on the same subjective indexes, the metro noise annoyance ratings of office staff and non-office staff under each activity disturbance index rating were averaged and plotted as shown in Figure 7, and the fitted equations are as follows:

$$\text{Office staff : } MAR = 2.428 \text{ ADI} + 1.302 \quad (R^2 = 0.924), \quad (1)$$

$$\begin{aligned} \text{Non - office staff : } MAR &= 3.216 \text{ ADI} \\ &+ 4.030 \quad (R^2 = 0.971). \end{aligned} \quad (2)$$

In Figure 7, when the activity disturbance index rating varied from 0.25 to 0.75, the mean metro noise annoyance ratings of non-office staff were all much higher than those of office staff, showing that in contrast to the office staff, the non-office staff felt more annoyed under the same activity disturbance degrees. In addition, due to the stronger adaptability to metro noise of office staff, even if the activity disturbance index rose significantly, the mean annoyance level of office staff still remained at lower levels. While in terms of the non-office staff, who did not work in the offices affected by frequent metro noise and were more sensitive to the change of activity disturbance degree, their mean metro noise annoyance ratings went up more significantly with the increase of activity disturbance level.

3.4 Optimal perception ratings and acoustic parameters

According to the previous studies, six acoustic parameters (LA_{eq} , LAF_{max} , loudness, roughness, sharpness and fluctuation strength) which are commonly used to evaluate the perceptions of low-frequency noise [54, 73, 74] were chosen as quantitative standards to explore the acoustic parameters responsible for the optimal perceptions of office and non-office staff, and the relationships between the selected acoustic parameters of metro noise and the optimal perception ratings of office staff and non-office staff due to metro noise were firstly analyzed based on Spearman's correlation analysis, and the results are shown in Table 6.

Table 5. Spearman’s correlation coefficients between multi-dimensional perception ratings and activity disturbance index rating due to metro noise.

	A		D		P	
	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>
ADI of office staff	0.472**	0.000	0.261	0.057	0.418**	0.002
ADI of non-office staff	0.426**	0.001	0.485**	0.000	0.288*	0.030

* Significant at the 0.05 level (two-tailed test).

** Significant at the 0.01 level (two-tailed test).

Note: ADI, activity disturbance index rating.

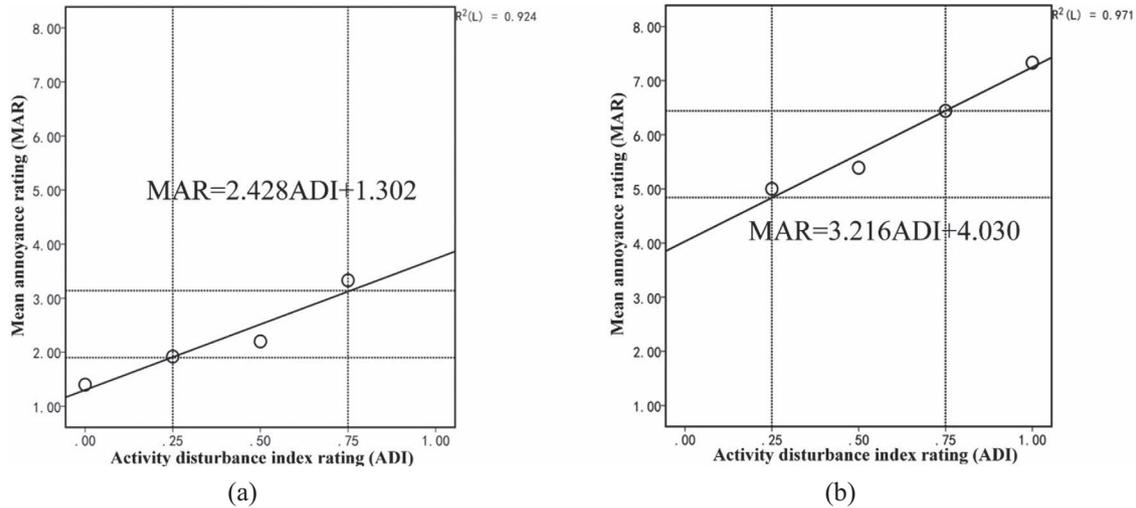


Figure 7. Relationship between mean annoyance rating (MAR) with activity disturbance index rating (ADI). (a) Office staff, (b) Non-office staff.

With respect to the office staff, only loudness showed significant and positive correlations with their annoyance ratings at the 0.05 level, whereas statistically significant relationships were not found between their annoyance and unpleasantness ratings and other acoustic parameters, indicating the negative mood level of office staff did not rise regularly with the increase of most acoustic parameters. In terms of the non-office staff, much stronger correlations were found between their optimal perception ratings and the selected acoustic parameters, demonstrating that the non-office staff were more sensitive to the change of metro noise environments than the office staff. In addition, as for the non-office staff, the LA_{eq} and LAF_{max} had strong correlations with their annoyance and dissatisfaction ratings caused by metro noise; among psychoacoustic measures, the loudness and sharpness were dominant factors in determining their annoyance and dissatisfaction perceptions, indicating that apart from the average energy of noise, the rapid temporal variation in sound might also contribute to the perceptions of metro noise in commercial areas.

For the second step, the acoustic parameters which showed significant correlations with the optimal perception ratings of office staff and non-office staff were chosen as optimal acoustic parameters to identify whether perceptual

evaluation models could be established based on these indexes. Following the previous studies [54, 75], the mean optimal perception ratings of office and non-office staff under each optimal acoustic parameter were calculated, and the fitted formulas between these two variables are listed in Table 7. For the office staff, the R^2 of mean annoyance prediction model based on loudness was 0.289, indicating that all acoustic parameters including loudness were not adequate to well predict the mean annoyance ratings of office staff in this study. In terms of the non-office staff, R^2 more than 0.5 or close to 0.5 were found for all mean perception prediction equations based on the optimal acoustic parameters except for the mean dissatisfaction and annoyance prediction equations based on roughness, showing their mean annoyance and dissatisfaction ratings due to metro noise could be well evaluated based on the LA_{eq} , LAF_{max} , loudness, sharpness and fluctuation strength, among these, higher R^2 and Beta, as well as less Std. Err. values were found for the mean perception regression equations based on loudness and sharpness, demonstrating that compared with the other single acoustic parameters, it seemed that the mean perception ratings were more affected by the psychoacoustic metrics of loudness and sharpness, which could be used to better estimate the

Table 6. Spearman's correlation coefficients between the acoustic parameters of metro noise and optimal perception ratings.

	LA _{eq} (dBA)		LAF _{max} (dBA)		N (sone)	
	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>
A of office staff	0.222	0.106	0.013	0.924	0.276*	0.043
P of office staff	0.232	0.092	0.050	0.720	0.158	0.253
D of non-office staff	0.599**	0.000	0.556**	0.000	0.660**	0.000
A of non-office staff	0.571**	0.000	0.520**	0.000	0.561**	0.000
	R (asper)		S (acum)		F (vacil)	
	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>
A of office staff	-0.106	0.444	0.018	0.899	0.012	0.932
P of office staff	0.040	0.773	0.095	0.494	0.138	0.318
D of non-office staff	0.390**	0.003	0.582**	0.000	0.292*	0.027
A of non-office staff	0.411**	0.001	0.569**	0.000	0.270*	0.042

* Significant at the 0.05 level (two-tailed test).

** Significant at the 0.01 level (two-tailed test).

Table 7. Prediction models for the mean optimal perception ratings based on the optimal acoustic parameters.

Group	Linear regression equations for the mean optimal perception ratings due to metro noise	R^2	Std. Err.	Beta
Office staff	MAR = 0.038N + 1.560	0.289	0.262	0.537
Non-office staff	MDR = 0.353LA _{eq} - 17.761	0.798	0.617	0.894
	MDR = 0.235LAF _{max} - 11.389	0.782	0.642	0.885
	MDR = 0.236N + 0.250	0.913	0.406	0.955
	MDR = 12.906R + 1.048	0.163	1.258	0.403
	MDR = 2.816S - 1.045	0.894	0.449	0.945
	MDR = 2.084F + 1.872	0.586	0.885	0.765
Non-office staff	MAR = 0.242LA _{eq} - 9.620	0.608	0.676	0.779
	MAR = 0.159LAF _{max} - 5.163	0.585	0.696	0.765
	MAR = 0.165N + 2.663	0.720	0.571	0.848
	MAR = 15.373R + 1.758	0.375	0.853	0.612
	MAR = 2.123S + 1.473	0.824	0.452	0.908
	MAR = 1.500F + 3.743	0.493	0.768	0.702

Note: R^2 , the coefficient of determination; Std. Err., the standard error of the estimate; Beta, standard regression coefficient; MDR, mean dissatisfaction rating; MAR, mean annoyance rating.

mean dissatisfaction and annoyance ratings of non-office staff. In addition, stepwise regression was conducted to obtain optimal regression equations which could best predict the mean perception ratings of non-office staff, and the results seemed to show that using the sharpness to predict annoyance and using the loudness to predict dissatisfaction could yield the highest coefficients of determination, in view of the limited amount of data in this study, a greater size would likely to produce more accurate prediction models of mean perception ratings.

As shown in Table 6, the mean dissatisfaction ratings of non-office staff were lower than their mean annoyance ratings under the same metro noise environments. The reasons for this could be that compared with annoyance, dissatisfaction showed a stronger correlation with psychological factors, thus although the metro noise environments had caused a certain degree of annoyance, the interviewees believed the commercial areas should be noisy and voted

lower dissatisfaction ratings. Furthermore, as Table 6 shows, it seems that compared with the mean annoyance ratings of non-office staff, the mean dissatisfaction ratings of non-office staff were more sensitive to the change of metro noise environments, with relatively higher slopes for regression equations based on all acoustic parameters.

4 Discussion

1. By summarizing these results and comparing them with the research results focusing on the perceptual evaluation of metro noise, it is found that the previous studies have proposed some objective influencing factors of metro noise perceptions in different spaces. For instance, Walker put forward that the LA_{eq} correlated well with the negative perception ratings of metro noise in dwellings [3]. Steinbach pointed out that the

LA_{eq} , loudness and sharpness were found to play important roles in influencing the metro interior noise perceptions [13]. Hou et al. believed that the LAF_{max} should be regarded as one influencing factor of metro noise perceptions at underground station platforms [15]. The results of this study have shown that all of the above acoustic parameters – LA_{eq} , LAF_{max} , loudness and sharpness – would contribute to the metro noise perceptions of non-office staff in the commercial spaces along metro lines. For people like the office staff, who are frequently exposed to metro noise environment during working hours, the effect of the above acoustic parameters is much milder. Only loudness seems effective, with a slight influence on the individuals' annoyance ratings but not the mean value, and their negative perception ratings of metro noise seemed to remain at lower levels no matter how much the metro noise level increased.

2. Compared with the non-office staff, the office staff were less affected by metro noise and expressed significantly lower annoyance, dissatisfaction and unpleasantness ratings to the same metro noise in the two underground commercial spaces, demonstrating that due to the long-term impact of metro noise, the hearing system of office staff impaired and became less sensitive to the change of metro noise, which should draw the attention of urban planners to carefully design the buildings near metro lines with the aim of reducing the influence of metro noise on the auditory systems of people in indoor environments.
3. To better control the negative moods induced by metro noise, this study investigated the factors responsible for the perceptions of metro noise. In particular, the results of this study revealed that the multi-dimensional negative perception ratings of office staff due to metro noise were much lower than those of non-office staff, indicating that noise adaptability is an important factor influencing the negative moods induced by metro noise. Besides, the LA_{eq} , LAF_{max} , loudness and sharpness of metro noise were found to significantly affect the metro noise perceptions of non-office staff. Furthermore, the LAF_{max} , loudness, sharpness and roughness showed significant and positive correlations with the dissatisfaction and annoyance ratings of non-office staff at 0.01 levels, indicating that rapid temporal variation in sound might contribute to their perceptions of metro noise.
4. Taking into account that the non-office staff tended to feel more annoyed, dissatisfied, unpleasant, and disturbed under the same metro noise environments than the office staff and that compared with those of the office staff, the multi-dimensional negative perceptions of non-office staff were more sensitive to the change of metro noise, it becomes evident that a small optimization could result in a great drop in the negative moods of non-office staff, therefore the architects should pay greater attention to the non-office staff's perceptions to metro noise in their commercial space designs of buildings along metro lines, which could be easily satisfied based on optimization

strategies and would contribute to the satisfaction of the overall acoustic demands of both office and non-office staff.

5. One of the limitations is the sample size (54 office staff and 57 non-office staff), that is, considering that the population characteristics of surveyed groups in this study were relatively scattered, a greater sample size would be likely to draw more accurate conclusions, even if the previous study has proved that more than 30 questionnaires were enough for representative results [75]. Furthermore, except for adaptability and tolerance, which influence people's reactions to metro noise, there are other population characteristics which might also affect people's responses, such as gender, age, educational attainment etc., considering the socio-demographic characteristics of the studied groups, the findings may only be applicable for young people aged between 20 and 40 years, and a big database is required to make a detailed analysis of these factors, which should contain enough samples for men and women as well as people of different age and education level. Therefore, a great number of studies need to be carried out in the future. Furthermore, the results of this study such as acoustical influence factors responsible for metro noise perceptions were related to the acoustical characteristics of studied metro noise sources, specifically, for the investigated metro noise samples in this study, their LA_{eq} , LAF_{max} , loudness, sharpness and fluctuation strength correlated well with each other, while their roughness showed relatively weak correlations with other acoustic parameters, for other types of metro noise, these correlation relationships might be different, which could contribute to different conclusions, thus more metro noise samples ought to be collected in the future to investigate the universal acoustic characteristics of metro noise.
6. For further studies, there is a need to collect more subjective and objective data, and more subjective and objective factors influencing metro noise perceptions should be selected, which should be regarded as input parameters to establish a more accurate evaluation system or prediction models of metro noise perception based on an appropriate data analysis method such as structural equation model (SEM) and artificial neural network. This model could be used to evaluate people's perceptions of metro noise before the completion of buildings, which could provide architects with references for better acoustic design and afford users of the spaces better acoustic experiences.

5 Conclusions

In this study, questionnaire surveys related to multi-dimensional metro noise perceptions were conducted in the underground commercial spaces of a high-rise office building near the metro line 5 in Guangzhou, China, accompanied with on-site metro noise environment measurements. Metro noise perception differences were determined between the

office staff and non-office staff, and the acoustic influencing factors of their perceptions due to metro noise were proposed. Some conclusions could be drawn:

1. The non-office staff expressed significantly more intense multi-dimensional negative emotions (annoyance, dissatisfaction and unpleasantness) to metro noise than the office staff (Fig. 5), and the metro noise induced more disturbances to the activities of non-office staff than those of the office staff (Fig. 6). In addition, the non-office staff tended to feel more annoyed than office staff under the same activity disturbance indexes. When the increase of metro noise level led to the increase of activity disturbance degree, the mean metro noise annoyance ratings of non-office staff went up significantly, while those of the office staff remained at lower levels (Fig. 7).
2. Compared with those of the non-office staff, much weaker correlations were found between the optimal perception (annoyance and unpleasantness) ratings of office staff with the selected six acoustic parameters including the LA_{eq} , LAF_{max} , loudness, roughness, sharpness and fluctuation strength of metro noise (Tab. 6), indicating that in contrast to the non-office staff, the office staff were less sensitive to the change of metro noise environments. Furthermore, compared with those of the office staff, the correlations between the three perception variables (annoyance, dissatisfaction and unpleasantness) of non-office staff were much stronger.
3. For the non-office staff, their annoyance and dissatisfaction perceptions due to metro noise correlated well with LA_{eq} and LAF_{max} ; among the psychoacoustic measures, loudness and sharpness were found to significantly influence their annoyance and dissatisfaction perceptions (Tab. 6). In addition, their mean annoyance and dissatisfaction ratings could be well estimated based on the acoustic parameters of LA_{eq} , LAF_{max} , loudness, sharpness and fluctuation strength, and it seems that in contrast to other acoustic parameters, the psychoacoustic indexes of loudness and sharpness could better predict their mean annoyance and dissatisfaction ratings (Tab. 7).
4. In terms of the non-office staff, their mean annoyance ratings were higher than their mean dissatisfaction ratings under the same metro noise environments (Tab. 7), the reason of which might be that although the metro noise environments had caused a certain degree of annoyance, the non-office staff believed the commercial areas should be noisy and voted lower levels of metro noise dissatisfaction ratings, which might reveal that compared with annoyance, dissatisfaction is more related to people's psychological factors. Possibly due to the psychological acceptance for noisy commercial space environments, compared with annoyance and unpleasantness ratings, the office staff and non-office staff expressed least differences on metro noise dissatisfaction rating (Tab. 3). Since people might have different psychological expectations for metro noise environment, for the office staff and non-office staff alike, the most varied results were found in metro noise dissatisfaction ratings (Fig. 5).

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Conflict of interest

The authors declare that they have no conflicts of interest in relation to this article.

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