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An investigation of acoustic environments in large and medium-sized open-plan offices in China

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Abstract

Few studies have investigated whether employees have different acoustic demands for various types of open-plan offices (OPOs), which can be subdivided into small, medium-sized and large OPOs depending on the number of employees sharing an office. In this study, an investigation of acoustic environment is carried out in 16 OPOs, aiming to 1) study how the design parameters of OPOs affect indoor acoustic environments, and 2) explore whether occupants' demands of acoustic environments are different between large open-plan offices (LOPOs) and medium-sized open-plan offices (MOPOs). Both objective measurement and subjective evaluation results that relate to the key aspects of the acoustic environment (noise level and speech privacy) are collected from 7 LOPOs and 9 MOPOs in China. The analysed results found that OPOs with the lower spatial density of workstations or higher storey height have the higher spatial decay rate of speech ($D_{2,S}$), lower speech level at 4 m distance ($L_{p,A,S,4m}$) and shorter comfort distance (r_C). The perceived noise level has the greatest influence on employees' acoustic satisfaction, and speech interference on employees' re-concentration is the main acoustic reason leading to work productivity decrease. In terms of the differences in acoustic environment between LOPOs and MOPOs, MOPO employees have higher acoustic satisfaction and lower disturbance levels of speech noises. Perceived speech privacy is a significant acoustic factor affecting work productivity in LOPOs, while it is not in MOPOs.

Keywords:

Noise level, speech privacy, work productivity, acoustic satisfaction, large open-plan offices (LOPOs), medium-sized open-plan offices (MOPOs)

1. Introduction

In the past decades, open-plan offices (OPOs) have been popular in office buildings for economic reasons, but also due to facilitating information flow and flexibility for layout changing [1, 2]. Increasing conflicts between good acoustic environments and convenient information communication in OPOs, however, become the main cause for employees' environment dissatisfaction. A large number of studies have demonstrated that poor acoustic environments in OPOs not only decrease employee's job satisfaction [3-5] but also exert adverse influences on employees' work productivity [6-8] and health status [9, 10]. Indoor uncontrollable noises, especially sudden speech noise, are the main reason for poor acoustic environments [11-14].

1.1 Noise level and speech privacy

Noise level and speech privacy are two important indices for assessing the acoustic environment in OPOs [10]. Both of them are correlated with employees' acoustic satisfaction [15-18] and work productivity [19-21].

A low noise level is a basic requirement for a comfortable environment and high work productivity [22-24]. Some studies [25, 26] have already demonstrated the negative relationship between perceived noise level and indoor environment satisfaction through questionnaire surveys. Kim and de Dear [27] suggested that noise levels in OPOs should be decreased to increase employees' environmental satisfaction. Kang et al. [6] also highlighted the importance of low noise levels on employees' acoustic satisfaction in open-plan research offices. In addition, a number of studies [28-30] have conducted acoustic measurements to explore how the noise level affects employees' perception of the acoustic environment and work productivity. Liu et al. [11] revealed that noise could increase annoyance when noise levels exceed 50 dBA. Jahncke et al. [19] found that participants could perform better and be more satisfied with the environment at a low noise level (39 dBA) in comparison to the condition with a high noise level (51 dBA). Tang et al. [29] reported that the increase of noise level in steps of 1dBA could result in a 0.177-point decrease of acoustic satisfaction score without the impacts of other environmental factors.

Speech privacy, a significant index in OPOs, is usually proposed to assess the adverse effects of speech noise on the acoustic environment and employees' work productivity [31]. High speech privacy commonly represents less speech disturbance on work productivity [32, 33] and job satisfaction [3, 15, 16]. Successful acoustic measurements are the foundation of acoustic environment evaluation [34-36]. Speech privacy-related parameters such as spatial decay rate of speech ($D_{2,S}$), distraction distance (r_D) and comfort distance (r_C) are provided by the international standard (ISO 3382-3) to evaluate the acoustic performance of OPOs. $D_{2,S}$ refers to the rate of spatial decay of A-weighted sound pressure level of speech per distance doubling in decibels. r_D indicates the distance from the sound source where the speech transmission index (STI) is below 0.5, and r_C describes the distance from the speaker where the SPL of speech is below 45 dB(A) [31]. Recent studies [37-39] have proven the validity of speech privacy-related parameters suggested in ISO DIS 3382-3:2021 [31] on predicting speech privacy and perceived noise disturbance.

1.2 Design parameters of OPOs

The office design parameters such as ceiling absorption, screen height, hanged baffles, spatial density, workstation size, ceiling height, masking sound signal and level are commonly considered by designers and acousticians when designing or improving the acoustic performance of OPOs [3, 40-42]. Among these parameters, ceiling absorption and screen height are more significant in increasing speech privacy. In 2012, an experimental study [43] conducted in an OPO showed that the surface of ceiling with high sound-absorbing material is important for improving acoustic performance. Another laboratory study [44] carried out in 2020 verified again that increasing ceiling absorption is the most effective way to increase the attenuation of speech and pointed out the importance of high screens for speech attenuation in OPOs. According to the international standard (ISO 22955:2021) [42], speech attenuation strengthens with the increase of screen height, and screens with a height of 1.1 m can cause

1.1 dB(A) speech attenuation. Workstation size is also an indispensable design parameter for acoustic performance. Newsham et al. [45] found that workstation size is positively correlated with employees' acoustic satisfaction. Moreover, some studies [41, 46] highlight the importance of low-spatial density in OPOs as high-density might increase disturbance by poor speech privacy and noise. Yadav et al. [47] found that OPOs with the low-spatial density of workstations have lower sound pressure levels for 500 Hz and 2000 Hz than the offices with high-spatial density.

1.3 Effects of different office types

Cell offices, shared-room offices, open-plan offices, flex offices and combi offices are five typical offices [48, 49]. Employees working in different office types have different requirements on the indoor environment. Kim and de Dear [27] revealed that low noise levels and high privacy are more important to employees in OPOs, whereas adequate lighting and comfortable furnishing receive higher priorities by cell offices. Danielsson and Bodin [50] investigated the influence of office types on employees' health status and job satisfaction. The results show that employees working in cell offices and flex offices have better health than employees in other office types.

OPOs can be subdivided into small (4-9 employees sharing a room), medium-sized (10-24 employees sharing a room) and large (over 24 employees sharing a room) OPOs [48, 50, 51], according to the number of employees sharing a room. Different types of OPOs also have influences on employees' work productivity, environment satisfaction and health [50, 52]. Seddigh et al. [53] in 2014 observed a dose-response tendency between perceived work productivity and the OPO types, implying that smaller OPOs may have more positive effects on employees in comparison to larger ones. In 2015, they [54] revealed that small OPOs are more suitable for employees to perform cognitive tasks compared with large OPOs. Danielsson [55] conducted a questionnaire survey to investigate the office types' effects on employees' feelings about noise and privacy. The results report that noise problems occurring in large OPOs (LOPOs) are more than those in medium-sized OPOs (MOPOs).

1.4 The purpose

To the authors' best knowledge, few studies explore the associations between speech privacy-related parameters and design parameters (e.g. floor area, the spatial density of workstations, etc.) in OPOs. In addition, it is not clear whether the effects of the acoustic environments in different types of OPOs on occupants' perceptions are different.

Hence, one of the main purposes of this study is to investigate the acoustic environment of OPOs and clarify how the design parameters affect acoustic indices (i.e. noise level and speech privacy) in OPOs. Another purpose of this paper is to investigate whether there are differences in occupants' perception and demands of acoustic environment (indoor noise level and speech privacy) between LOPOs and MOPOs. In this study, both acoustic measurements and questionnaire surveys are carried out in LOPOs and MOPOs. Small OPOs are excluded since the speech privacy-related measurement recommended in ISO 3382-3:2012 [56] is unsuitable for this office type.

2. Methodology

2.1 Offices

Shenzhen, the first Special Economic Zone of China, was selected as the case study city. It has a considerable number of OPOs. As given in Table 1, acoustic measurements and questionnaire surveys were carried out in 16 OPOs (offices A-P) from April to May 2021. Among those offices, 10 offices (offices B-K) are located within the same building (see Table 1). Offices B and C have the same layout, finishing materials, and workstation arrangement, although they are located on different floors. Offices D-F, which are located on different floors, also have the same layout and decorations.

7 LOPOs (offices A-G) and 9 MOPOs (offices H-P) were sampled. Some photos taken in these offices are given in Fig.1. Floor areas of 7 LOPOs range between 464 m^2 and 724 m^2, and the spatial density of workstations varies from 10.07% to 13.00% (see Table 1). Floor areas of 9 MOPOs range between 32 m^2 and 170 m^2, and the spatial density of workstations varies from 7.10% to 40.34% (see Table 1).

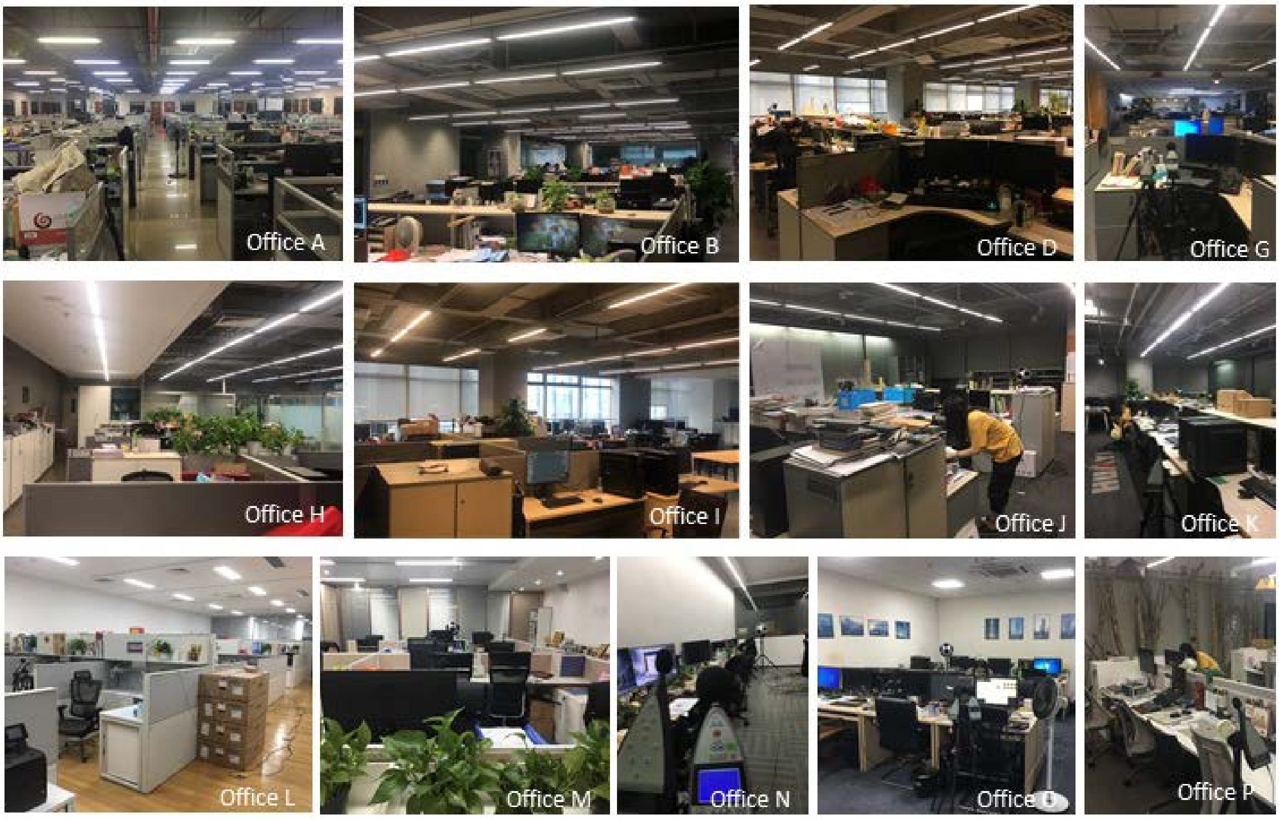

Fig. 1 Pictures of some offices (Offices A-G are LOPOs, and offices H-P are MOPOs. Offices B and C have the same layout and decorations. Similarly, offices D–E have the same layout and decorations)

Table 1 Basic information of the OPOs

Offices (building)	Area (m^2)	Number of workstations	Spatial density of workstations (%)	Screen height (m)	Ceiling type	Office length (m)	Office width (m)	Storey height (m)	Office type
A (1)	714.74	72	10.07	1.10	Concrete	31.5	22.7	2.6	LOPO
B (2)	723.23	94	13.00	1.15	Concrete	15.7~41.4	10.9~13.2	3.6	LOPO
C (2)	723.23	94	13.00	1.15	Concrete	15.7~41.4	10.9~13.2	3.6	LOPO
D (2)	670.17	83	12.38	1.15	Concrete	15.7~37.2	10.9~13.2	3.6	LOPO
E (2)	670.17	83	12.38	1.15	Concrete	15.7~37.2	10.9~13.2	3.6	LOPO
F (2)	670.17	83	12.38	1.15	Concrete	15.7~37.2	10.9~13.2	3.6	LOPO
G (2)	464.82	50	10.76	1.15	Concrete	15.7~25.7	10.9~13.2	3.6	LOPO
H (2)	89.32	10	11.20	1.15	Concrete	11.5	6.9	3.6	MOPO
I (2)	169.07	12	7.10	1.15	Concrete	16.0	10.7	3.6	MOPO
J (2)	82.78	14	16.91	1.15	Concrete	10.8	7.7	3.6	MOPO
K (2)	82.78	14	16.91	1.15	Concrete	10.8	7.7	3.6	MOPO
L (3)	142.7	14	9.81	1.69, 1.23	Suspended plasterboard	16.9	8.4	3.2	MOPO
M (4)	66.44	14	21.07	1.05	Suspended plasterboard	10.1	6.6	2.6	MOPO
N (5)	32.23	13	40.34	No screen	Concrete	8.4	3.8	2.9	MOPO
O (6)	49.45	16	32.36	No screen	Suspended ceiling	8.8	5.6	2.9	MOPO
P (7)	52.32	16	30.58	1.10	Concrete	7.7	6.8	3.4	MOPO

2.2 Acoustic measurement

Active noise levels were measured in occupied conditions using a sound level meter (AWA 6291). For LOPOs, office A has been divided into two equal zones considering its large area (714.7 m^2). The positions of the sound level meter were located in the centre of each zone. Since offices B-G have two working zones, two positions of the sound level meter were set in the centres of the two areas in offices B-G. For MOPOs, single measurements were carried out in the centre of MOPOs since the similar workstation arrangements. Every measurement position was at the height of 1.2 m from the floor and over 1.0 m away from office windows and walls. The measurements were performed for 1 hour on weekdays when employees were present (at 10:00 to 12:00 am or 2:30 to 5:30 pm). A-weighted equivalent sound pressure levels (L_{Aeq}) were utilised to present the sound pressure levels of the active noises in OPOs. Two statistical sound levels (L_{10} and L_{90}) were also considered.

Speech privacy-related measurements were conducted at night-time or weekend when employees were absent, as recommended in ISO DIS 3382-3:2021[31]. Since offices B and C have almost identical acoustic characteristics when not occupied, the speech privacy-related measurement was performed at one of the two offices. Similarly, the measurement was conducted at one of the offices D–F. During the measurements, the operation of air conditioners was the same as working hours. An omnidirectional source (B&K 4292) was used as a sound source and a sound level meter (B&K 2239) was utilised to record the signals. The software Dirac 6.05 was utilised to generate, play, record, and analyse the signals in OPOs. Measurement lines of measured OPOs, which indicate the path connecting the sound source and several successive measurement positions, were determined according to the ISO DIS 3382-3:2021 [31]. For LOPOs, as the plan of office A is a rectangle, the measurement line was set on the central axis of office A. Since offices B-G include two zones, one measurement line was determined in each zone of these offices. For MOPOs, only one measurement line was determined as each MOPO does not have more than one zone. In this study, two measurements were conducted in opposite directions along the selected measurement line. Apart from measurement lines in offices N and O, measurement lines in all the other offices included over 4 measurement locations. Measurement lines in offices N and O only contained three measurement positions due to their office layouts. Sound sources and measurement positions were placed at the height of 1.2 m from the floor and over 0.5m from tables. Based on the speech privacy-related measurements, spatial decay rate of speech ($D_{2,S}$), speech level at 4m distance ($L_{p,A,S,4m}$), distraction distance (r_D), comfort distance (r_C), and background noise level ($L_{p,A,B}$) were determined.

2.3 Questionnaire survey and respondents

The questionnaire consists of three parts. The first part is designed to collect the employees' individual information, including their gender and age. The second part involves the employees' perception of various acoustic factors and work productivity. Firstly, 2 questions in part 2 are used to assess perceived speech privacy: "How much do you think others can hear your conversation content?" and "How much do you hear the content of other's conversation?" Each question is answered on a 7-point scale from 1 (strongly high) to 7 (strongly low). Secondly, speech interferences on employees' abilities of re-concentration and problem-solving speed are assessed using 7-point scales (1 = "strongly low" ~ 7 = "strongly high"). Thirdly, perceived noise level is rated using 7-point scales (1 = "strongly low" ~ 7 = "strongly high"). Finally, acoustic satisfaction and the effects of acoustic interference on work productivity are evaluated. Question of acoustic satisfaction is evaluated from 1 (strongly dissatisfied) to 7 (strongly satisfied). The effects of acoustic interference on work productivity is evaluated from 1 (strongly low) to 7 (strongly large). The third part investigates the disturbance levels of 9 common noise sources (i.e. nearby conversation chatting, distant conversation chatting, speech from phone amplifier, telephone conversation, phone ringing, construction, machines, keyboard and traffic noises). Nearby conversation chatting refers to conversations from colleagues who sit near respondents (within a range of 3 workstations), and distant conversation chatting refers to conversations from colleagues sitting further away (beyond 3 workstations). Questions in this part are answered on a 7-point scale, from 1 (not at all) to 7 (strongly disturbing).

Full-time employees were randomly asked to answer the questionnaire during the measurement period of the active noise level. A total of 377 questionnaires were returned, out of which 348 were valid (a valid response rate of 92.3%). In these valid responses, 286 questionnaires (99 females and 187 males) were from LOPOs and 62 questionnaires (19 females and 43 males) were from MOPOs.

3. Results and analysis

3.1 Results of objective acoustic measurements

Results of active noise levels are given in Table 2. The measured L_{Aeq} values of OPOs range from 46.9 to 61.3 dBA, and the values of L_{10} and L_{90} are from 47.5 to 64.6 dBA and from 41.8 to 52.9 dBA, respectively.

The results of speech privacy-related measurements are also listed in Table 2. The $D_{2,S}$ values, ranging from 1.48 to 6.10 dBA, are small because few sound-absorbing materials are installed in each office. As recommended in annex C of ISO DIS 3382-3:2021 [31], the typical value of $D_{2,S}$ with poor acoustic conditions is $D_{2,S}$ < 5 dBA. So $D_{2,S}$ values in offices H-P are smaller than the limited value of poor acoustic conditions. $L_{p,A,S,4m}$ values vary from 48.8 to 56.2 dBA, which cannot satisfy the requirements of good acoustic conditions in annex C of ISO DIS 3382-3:2021 [31]. Offices M-O show pretty high values (54.9-56.2 dBA) than the others due to low screens between workstations and high reflective materials on walls. Results of r_C are between 7.15 and 194.42 m. Offices K-P show the much larger r_C because of the low $D_{2,S}$ and high $L_{p,A,S,4m}$. A classification scheme created by Hongisto and Keränen [37] shows that the ranges of r_C values for the medium class C and the worst class D are [7-9) m and [9-11) m, respectively. In other words, offices A-G measured in this study have acceptable comfort distances, although they do not satisfy the requirement of good office acoustic conditions in annex C of ISO DIS 3382-3:2021 [31]. Offices I, J and O showed smaller r_D values that satisfy the requirements of r_D for good office acoustic conditions (i.e. r_D < 5m) in ISO DIS 3382-3:2021 [31].

Table 2 Results of acoustic measurements in OPOs

Office	Active noise level			Speech privacy-related results				
	L_{Aeq}/dBA	L_{10}/dBA	L_{90}/dBA	$D_{2,S}$/dBA	$L_{p,A,S,4m}$/dBA	r_c/m	r_D/m	$L_{p,A,B}$/dBA
A	53.65	56.01	48.87	4.26[#]	51.20	10.97	5.30	47.93
B	51.85	54.16	45.80	5.94, 5.49	51.23, 51.90	8.38, 9.73	7.33, 6.90	43.38[@], 44.73[@]
C	54.44	56.84	48.87	--	--	--	--	--
D	51.71	53.41	47.68	5.55, 5.78	51.25, 51.40	8.76, 8.65	5.83,6.55	44.99[@], 45.00[@]
E	49.14	51.93	43.10	--	--	--	--	--
F	53.69	57.96	48.32	--	--	--	--	--
G	52.02	55.60	47.04	5.50, 6.10	51.25, 50.30	8.96, 7.30	9.10, 5.58	41.40[@], 42.95[@]
H	52.17	54.90	46.40	2.66[#]	48.80	10.77	5.05	44.15[@]
I	50.39	53.57	45.95	4.53[#]	48.80	7.15	3.85[@]	45.96
J	49.28	52.56	43.05	2.28[#]	49.55	15.95[#]	4.70[@]	44.99[@]
K	46.92	47.54	41.82	2.15[#]	51.50	32.52[#]	5.80	44.41[@]
L	55.27	59.25	44.33	3.64[#]	53.80[#]	21.37[#]	7.90	43.54[@]
M	50.82	53.73	42.65	2.80[#]	55.45[#]	53.16[#]	7.25	46.60
N	53.38	56.84	45.51	1.98[#]	54.95[#]	130.26[#]	8.60	44.02[@]
O	61.29	64.60	52.88	1.99[#]	56.15[#]	194.42[#]	4.43[@]	50.36[#]
P	54.61	57.30	46.02	1.48[#]	52.55[#]	137.32[#]	6.30	42.10[@]

[#]: "Poor" values based on the criteria in annex C of ISO DIS 3382-3:2021, in which typical values are $D_{2,S}$<5 dBA, $L_{p,A,S,4m}$>52 dBA, r_c>11 m, r_D>11 m and $L_{p,A,B}$<35 dBA or $L_{p,A,B}$>48 dBA.

[@]: "Good" values based on the criteria in annex C of ISO DIS 3382-3:2021, in which typical values are $D_{2,S}$>8 dBA, $L_{p,A,S,4m}$<48 dBA, r_c <5 m, r_D <5 m and 40 dBA < $L_{p,A,B}$<45 dBA.

Spearman rank correlation coefficients are calculated to determine whether there are significant correlations between acoustic parameters and design parameters (e.g. floor area, spatial density of workstation, screen height, and geometrical dimensions of OPOs). The calculation results are listed in Table 3 and Table 4.

As shown in Table 3, the L_{Aeq} values have significant correlations with the L_{10} values (P-value < 0.01) and the L_{90} values (P-value < 0.05). The r_D values significantly correlate with the values of $L_{p,A,B}$ (P-value < 0.05). However, other speech privacy-related parameters (i.e. $D_{2,S}$, $L_{p,A,S,4m}$ and r_D) do not show any significant correlation between each other (see Table 3).

Table 3 Spearman rank correlation coefficients of each acoustic parameter

	L_{Aeq}	L_{10}	L_{90}	$D_{2,S}$	$L_{p,A,S,4m}$	r_C	r_D	$L_{p,A,\mathrm{B}}$
L_{Aeq}	1							
L_{10}	**0.973****	1						
L_{90}	**0.560***	0.456	1					
$D_{2,S}$	-0.247	-0.275	0.220	1				
$L_{p,A,S,4m}$	0.487	0.547	-0.121	-0.435	1			
r_C	0.429	0.467	-0.187	**-0.868****	**0.798****	1		
r_D	0.225	0.291	-0.302	0.082	0.459	0.159	1	
$L_{p,A,\mathrm{B}}$	-0.129	-0.168	0.193	-0.044	0.072	0.094	**-0.605***	1

Note:
Coefficients values with – symbols represent negative correlations.
Significant findings are shown in bold.
* Correlation is significant at the 0.05 level (two-tailed).
** Correlation is significant at the 0.01 level (two-tailed).

As shown in Table 4, almost all the proposed design parameters have significant effects on the values of $D_{2,S}$ and r_C. More specifically: (1) floor area has a significantly positive correlation with $D_{2,S}$ (P-value < 0.01) and has a statistically negative correlation with r_C (P-value < 0.01), showing that increasing floor area is beneficial to increase $D_{2,S}$ and shorten r_C; (2) the spatial density of workstations is significantly correlated with $D_{2,S}$ (P-value < 0.01), $L_{p,A,S,4m}$ (P-value < 0.01) and r_C (P-value < 0.01). The results imply that OPOs with the smaller spatial density of workstations have larger $D_{2,S}$, smaller $L_{p,A,S,4m}$ and shorter r_C; (3) screen height has a significantly negative correlation with r_C (P-value < 0.05), implying that the higher screen, the shorter r_C; (4) office length and width have significantly positive correlations with $D_{2,S}$ (P-value < 0.01) and have statistically negative correlations with r_C (P-value < 0.01), indicating that OPOs with the larger length and width have larger $D_{2,S}$ and shorter r_C; (5) storey height has significantly negative correlations with L_{Aeq} (P-value < 0.01), L_{10} (P-value < 0.05), $L_{p,A,S,4m}$ (P-value < 0.01) and r_C (P-value < 0.01). These results show that increasing storey height is beneficial to reduce L_{Aeq}, L_{10}, $L_{p,A,S,4m}$ and shorten r_C. In addition, storey height is strongly correlated with $D_{2,S}$, which means the higher storey height is, the larger $D_{2,S}$ is; (6) office length-to-height ratio, which is used to represent the shape of the office, has a significantly positive correlation with $D_{2,S}$ and has a statistically negative correlation with r_C. The ratio of screen height and storey height, which describes the free area above the screen, has no significant correlation with any acoustic parameters.

Table 4 Spearman rank correlation coefficients of acoustic parameters and office design parameters

	L_{Aeq}	L_{10}	L_{90}	$D_{2,S}$	$L_{p,A,S,4m}$	r_C	r_D	$L_{p,A,\text{B}}$
Floor area	-0.162	-0.245	0.270	**0.922****	-0.446	**-0.809****	0.008	-0.037
Spatial density of workstation	0.148	0.176	-0.071	**-0.654***	**0.567***	**0.709****	0.137	-0.019
Screen height	-0.353	-0.392	-0.305	0.500	-0.539	**-0.598***	0.033	-0.407
Office length	-0.149	-0.250	0.355	**0.878****	-0.381	**-0.756****	0.187	-0.074
Office width	-0.150	-0.227	0.400	**0.839****	-0.475	**-0.770****	0.064	-0.137
Storey height	**-0.544****	**-0.605***	-0.019	**0.510***	**-0.687****	**-0.698****	-0.097	-0.376
Length/Height [1]	-0.033	-0.109	0.442	**0.858****	-0.237	**-0.670****	0.202	0.046
Screen height/Storey height [2]	0.051	0.059	-0.224	0.063	0.063	0.054	0.154	-0.051

Note:
Coefficients values with – symbols represent negative correlations.
Significant findings are shown in bold.
* Correlation is significant at the 0.05 level (two-tailed).
** Correlation is significant at the 0.01 level (two-tailed).
[1] Office length-to-height ratio.
[2] The ratio of screen height and storey height.

3.2 Results of subjective ratings

3.2.1 Reliability of the questions

Cronbach's alpha and Kaiser-Meyer-Olkin (KMO) measures are used to test the reliability and validity of the data collected from the questionnaires in this survey. As shown in Table 5, Cronbach's alpha ranges between 0.793 and 0.856, indicating internal consistencies of the questions [6, 57, 58]. KMO value is calculated as 0.871. Various studies have recommended that KMO values above 0.5 are acceptable [59]. The scale, thus, can be considered to show good reliability and validity.

Table 5 Reliability and validity of the questionnaire

Factors	Items	Cronbach's alpha	KMO
Speech privacy	Own conversation privacy	0.793	0.871
	Other's conversation privacy		
Speech interferences	Re-concentration	0.856	
	Problem-solving speed		
Noise level	Perceived noise level	--	
Satisfaction	Acoustic satisfaction	--	
Work productivity	The effects of acoustic interference with work productivity	--	
Noise disturbance	Nearby colleague chatting	0.803	
	Distant colleague chatting		
	Speech from phone amplifier		
	Telephone conversation		
	Phone ringing		
	Construction		
	Machines		
	Keyboard		
	Traffic		

3.2.2 Assessment of acoustic environment

The mean scores of respondents' perception of the acoustic environments are given in Table 6, and Table 7 shows how respondents' feelings about acoustic factors impact on acoustic satisfaction and work productivity by utilising Spearman rank correlation coefficients. The greater the absolute value of the Spearman correlation coefficients, the stronger the correlation between variables.

Table 6 Mean scores (SD) of respondents' perception of acoustic factors and noise sources

Factors	items	Mean scores (SD)
Speech privacy	Own conversation privacy	3.52 (1.411)
	Other's conversation privacy	3.08 (1.419)
Speech interferences	Re-concentration	4.00 (1.272)
	Problem-solving speed	4.19 (1.308)
Noise level	Perceived noise level	3.90 (0.952)
Satisfaction	Acoustic satisfaction	4.24 (0.973)
Work productivity	The effects of acoustic interference with work productivity	3.70 (1.114)
Noise disturbance	Nearby colleague chatting	3.20 (1.594)
	Distant colleague chatting	2.66 (1.444)
	Speech from phone amplifier	2.78 (1.554)
	Telephone conversation	3.05 (1.520)
	Phone ringing	3.47 (1.673)
	Construction	3.14 (1.876)
	Machines	2.82 (1.650)
	Keyboard	2.22 (1.250)
	Traffic	2.22 (1.468)

As seen in Table 7, all the acoustic factors have significant effects on acoustic satisfaction (P-value <0.05), which demonstrates the importance of high speech privacy, low speech interferences and small perceived noise levels to increase acoustic satisfaction in OPOs. The absolute correlation coefficient of the perceived sound level is the highest (0.517), which means the perceived noise level in OPOs has extremely significant influences on employees' acoustic satisfaction. In addition, all the acoustic factors are also significantly correlated with the effects of acoustic interference on work productivity (P-value<0.01), implying that poor qualities of these acoustic factors are the important causes of decreasing work productivity. The absolute correlation coefficient of speech interferences on re-concentration is the highest (0.622), followed by speech interference on problem-solving speed (0.591). These results indicate that the adverse effects of the acoustic environment on work productivity extremely stem from speech interferences on employees' abilities of re-concentration and problem-solving speed.

Table 7 Spearman rank correlation coefficients of acoustic factors, acoustic satisfaction and the effects of acoustic interference on work productivity

	Speech privacy		Speech interferences		
	Own conversation privacy	Other's conversation privacy	Re-concentration	Problem-solving speed	Perceived noise level
Acoustic satisfaction	0.162^{**}	0.260^{**}	-0.384^{**}	-0.304^{**}	-0.517^{**}
The effects of acoustic interference on work productivity	-0.184^{**}	-0.229^{**}	0.622^{**}	0.591^{**}	0.396^{**}

Note:
Coefficients values with – symbols represent negative correlations.
Significant findings are shown in bold.
** Correlation is significant at the 0.01 level (two-tailed).

4. Comparison of investigation results between LOPOs and MOPOs

4.1 Comparison of objective results

Mann-Whitney U Tests are utilised to compare the active noise levels in LOPOs and MOPOs, but the results show that there is no significant difference between the two office types in terms of L_{Aeq} , L_{10} and L_{90} (P-value >0.05).

Five acoustic parameters (i.e. $D_{2,S}$, $L_{p,A,S,4m}$, r_C, r_D and $L_{p,A,B}$) are provided by ISO DIS 3382-3:2021 [31] to assess speech privacy in OPOs and should be taken into account at the same time [31].

For better comparing the results of speech privacy between LOPOs and MOPOs, the objective results of speech privacy-related parameters are summarised in Table 8. As seen in Table 8, scores 1, -1 and 0.5 represent values meeting the requirements of good, poor and neutral acoustic conditions, respectively. A privacy score of each office, which is the sum of the five acoustic parameters' scores, is calculated to simplify the acoustic comparison of speech privacy-measured offices (see Table 8). The larger the privacy score, the higher the speech privacy of OPOs. As shown in Table 8, privacy scores of all LOPOs except for office A are much higher than MOPOs.

Table 8 Privacy scores of speech privacy-measured offices

Offices		$D_{2,S}$	$L_{p,A,S,4m}$	r_C	r_D	$L_{p,A,B}$	Privacy score
LOPOs	A	-1	0.5	0.5	0.5	0.5	**1**
	B	0.5	0.5	0.5	0.5	1	**3**
	D	0.5	0.5	0.5	0.5	1	**3**
	G	0.5	0.5	0.5	0.5	1	**3**
MOPOs	H	-1	0.5	0.5	0.5	1	**1.5**
	I	-1	0.5	0.5	1	0.5	**1.5**
	J	-1	0.5	-1	1	1	**0.5**
	K	-1	0.5	-1	0.5	1	**0**
	L	-1	-1	-1	0.5	1	**-1.5**
	M	-1	-1	-1	0.5	0.5	**-2**
	N	-1	-1	-1	0.5	1	**-1.5**
	O	-1	-1	-1	1	-1	**-3**
	P	-1	-1	-1	0.5	1	**-1.5**
Typical values with good acoustic condition		1	1	1	1	1	**5**
Typical values with poor acoustic condition		-1	-1	-1	-1	-1	**-5**

Note: Scores 1, 0.5 and -1 represent poor, neutral and good acoustic conditions, respectively, according to the typical values of the five acoustic parameters in ISO DIS 3382-3:2021. The neutral acoustic condition means a condition whose value of acoustic parameters is between the typical values standing for good and poor acoustic conditions. The privacy score is equal to the sum scores of the five parameters.

4.2 Comparison of subjective results

Mann-Whitney U Tests are used to explore whether there are significant differences in the assessment results of acoustic satisfaction and the effects of acoustic interference on work productivity between respondents in LOPOs and MOPOs. The results are shown in Table 9. Significant differences between LOPOs and MOPOs are found in terms of acoustic satisfaction and the effects of acoustic interference with work productivity, as seen in Table 9. The mean satisfaction score of acoustic environments (4.17) for LOPOs is significantly lower than that for MOPOs (4.56) (P-value < 0.05). The mean score of the effects of acoustic interference on work productivity (3.77) for LOPOs is significantly greater than for MOPOs (3.42) (P-value < 0.05), implying that employees' work productivity is more susceptible to acoustic interference in LOPOs in comparison to MOPOs.

Table 9 Mean scores (SD) of respondents' perception of acoustic satisfaction and acoustic interference on work productivity

	LOPOs	MOPOs	P-value[M]
Acoustic satisfaction	4.17 (0.92)	4.56 (1.15)	**0.034***
The effects of acoustic interference on work productivity	3.77 (1.04)	3.42 (1.37)	**0.038***

Note:
[M] Mann-Whitney U Tests.
Significant findings are shown in bold.
* Correlation is significant at the 0.05 level (two-tailed).

Mann-Whitney U Tests are also calculated to explore whether there are significant differences in the assessment results of speech privacy, speech interferences and perceived noise level between respondents in LOPOs and MOPOs (see Table 10). A significant difference is found between the two office types in the term of own conversation privacy (P-value < 0.05). The mean score of own conversation privacy (3.59) for LOPOs is statistically higher than for MOPOs (3.19).

Table 10 Mean scores (SD) of respondents' perception of acoustic environment and work productivity

	LOPOs	MOPOs	P-value[M]

Speech privacy	Own conversation privacy	3.59 (1.38)	3.19 (1.51)	**0.037***
	Other’s conversation privacy	3.10 (1.38)	3.00 (1.59)	0.426
Speech interferences	Re-concentration	4.03 (1.26)	3.89 (1.34)	0.234
	Problem-solving speed	4.23 (1.28)	4.02 (1.43)	0.135
Perceived noise level		3.93 (0.91)	3.74 (1.13)	0.406

Note:
Significant findings are shown in bold.
[M] Mann-Whitney U Tests.
[*] Correlation is significant at the 0.05 level (two-tailed).

Spearman rank correlation coefficients are utilised to explore how the acoustic factors affect acoustic satisfaction and work productivity. The results are listed in Table 11 and Table 12.

As seen in Table 11, the correlation coefficients of all the acoustic factors in MOPOs are much higher than those in LOPOs, implying that all the acoustic factors in MOPOs have much stronger correlations with acoustic satisfaction than those in LOPOs.

Table 11 Spearman rank correlation coefficients of acoustic satisfaction and factors of the acoustic environment in LOPOs and MOPOs

	Speech privacy		Speech interferences		
	Own conversation privacy	Other's conversation privacy	Re-concentration	Problem-solving speed	Perceived noise level
LOPOs	**0.143***	**0.243****	**-0.343****	**-0.222****	**-0.480****
MOPOs	**0.299***	**0.329****	**-0.549****	**-0.582****	**-0.660****

Note:
Significant findings are shown in bold.
Coefficients values with – symbols represent negative correlations.
[*] Correlation is significant at the 0.05 level (two-tailed).
[**] Correlation is significant at the 0.01 level (two-tailed).

As seen in Table 12, the effects of acoustic interference on work productivity in LOPOs have significantly negative correlations with speech privacy (i.e. own conversation privacy and other's conversation privacy) (P-value < 0.01), while these correlations cannot be found in MOPOs. In addition, the correlation coefficients of speech interferences and perceived noise level in MOPOs are larger than those in LOPOs.

Table 12 Spearman rank correlation coefficients of acoustic interference on work productivity and factors of the acoustic environment

	Speech privacy		Speech interferences		
	Own conversation privacy	Other's conversation privacy	Re-concentration	Problem-solving speed	Perceived noise level
LOPOs	**-0.189****	**-0.230****	**0.601****	**0.559****	**0.385****
MOPOs	-0.233	-0.229	**0.690****	**0.665****	**0.435****

Note:
Significant findings are shown in bold.
Coefficients values with – symbols represent negative correlations.
** Correlation is significant at the 0.01 level (two-tailed).

5. Discussion

5.1 Acoustic environment of OPOs

The active noise levels (L_{Aeq}) in 16 OPOs in China are between 46.9 and 61.3 dBA (see Table 2), showing good agreement with previous studies [15, 60]. The values of L_{90} in this study (41.8-52.9 dBA) are consistent with the findings of Tang [61], in which the L_{90} values of 26 offices in Hong kong ranged from 35 dBA to 59 dBA. However, these results are much higher than the findings of Yadav et al. [47], in which the L_{90} values of 43 Australian OPOs were between 27.1 and 38.7 dBA. As reported by previous studies [47, 62], the L_{90} values could be used to represent the OPOs background noise because of the operation of HVAC and other machinery. These results imply that the background noises due to operating HVAC and other machinery are higher in Chinese OPOs than in Australian OPOs. Lee et al. [15] also found similar results that noise levels from operating HVAC in China were louder than those in Korea. It is worth noting that the L_{Aeq} is significantly associated with the L_{90} (see Table 3). It is likely that due to the Lombard effect, the speech noise level increased with the high L_{90} and then the active noise levels increased. A previous study [63] showed that the Lombard effect could be initiated when the background noise level exceeds 43.3 dBA.

The $D_{2,S}$ values in 9 MOPOs (1.48-4.53 dBA) are much smaller compared to those in OPOs (4.0-12.4 dBA) in previous studies [12, 38, 64]. This inconsistency may stem from the little sound absorption of ceilings. The high absorption coefficiency of ceilings has great effectiveness to increase spatial decay of speech (i.e. $D_{2,S}$) in OPOs [42]. The materials of ceilings in measured OPOs, however, are concrete or suspended plasterboard with a very low sound absorption coefficiency (see Table 1).

The role of $L_{p,A,B}$ on r_D is demonstrated again by the finding that background noise level is negatively associated with distraction disturbance (see Table 3). This result is in agreement with previous studies [12, 38, 43]. Besides, this study does not find any significant correlations between $D_{2,S}$ and r_D nor between $D_{2,S}$ and $L_{P,A,S,4m}$, which are also in line with the findings of Haapakangas et al. [12].

Employees' acoustic satisfaction depends largely on perceived noise level, speech interferences, and speech privacy in OPOs (see Table 7). Among these factors, the perceived noise level has the highest negative correlation with acoustic satisfaction, which is in line with a previous study [6]. In addition, the speech interference on re-concentration is found to have the highest positive correlation with the effects of acoustic interference on work productivity (see Table 7), which demonstrates again previous findings [7, 16, 24, 65, 66] showing that speech noise is the main cause leading to the decrease in work productivity. It also reveals that the adverse effects of speech on work productivity result from its destructive effects on employees' re-concentration.

In OPOs, phone ringing is the most disturbing noise source (3.47), followed by nearby colleague chatting (3.20) (see Table 6), which are in line with the study of Banbury and Berry [13]. However, these results are not in agreement with the study of Kang et al. [6], in which conversation is the most disturbing noise in university open-plan research offices, while phone ringing is ranked at the 4th place. These differences may result from the difference in the primary workplace activities of offices. Surveys of this study and Ref. [13] were conducted in commercial OPOs in which information interchanges with each cooperative company by telephone are the common activity, while the survey of Kang et al. [6] was carried out in university research OPOs in which occupants' main activity is to complete complex mental work independently.

5.2 Relationships between acoustic parameters and office design parameters

The spatial density of workstations has a significantly positive correlation with $L_{p,A,S,4m}$ (see Table 4), implying that a smaller spatial density could give rise to lower $L_{p,A,S,4m}$. As reported by a previous study [12], small $L_{p,A,S,4m}$ is correlated with a smaller probability of high noise disturbance in OPOs. That is to say, the increase of spatial density has a disadvantage to reducing speech disturbance, which supports the idea of Gavhed and Toomingas [67] that high-density workstations may cause more disturbance from noises. In addition, low spatial density means a large personal workspace, which plays an important role in increasing employees' satisfaction with office layout [6, 8]. The low spatial density of workstations in OPOs, therefore, should be considered as a critical factor when improving environmental quality, which can not only increase workspace satisfaction but has a benefit to reduce noise disturbance.

Screen height does not have a significant correlation with $D_{2,S}$ which is not consistent with the findings of previous studies [44, 64] and the international standard (ISO 22955:2021) [42], in which screen height has significant effects on sound attenuation in OPOs. A possible explanation is the limited samples of screen heights in this study. The most of screens in measured OPOs are 1.15 m in height (see Table 1).

As shown in Table 4, the geometrical dimensions of OPOs (i.e., office length, width and storey height) have significant positive correlations with $D_{2,S}$ and negative correlations with r_C. Storey height has significantly negative correlations with L_{Aeq}, L_{10} and $L_{p,A,S,4m}$. These results imply that acoustic parameters of OPOs with large geometrical dimensions have great probabilities of being close to the targeted values for good acoustic environments. In particular, increasing storey height is beneficial to decrease the noise level of OPOs. Keränen and Hongisto [64] provided a model to predict $D_{2,S}$. In the model, the office length-to-height ratio, the ratio of the average height of screens and storage units and storey height, and sound absorption of ceilings and apparent furnishings were important independent variables. The importance of the length-to-height ratio on $D_{2,S}$ is also shown in the current study. However, the ratio of screen height and storey height is not associated with $D_{2,S}$ (see Table 4). This inconsistency may be because the height of storage units was not considered in the current study. A prediction model of $L_{p,A,S,4m}$ was also provided by Keränen and Hongisto [64], in which screen height, office width, and sound absorption of ceilings and apparent furnishings were significant variables. However, $L_{p,A,S,4m}$ is associated with storey height in this study, rather than screen height and office width. Further studies on the relationships between geometrical dimensions of OPOs and $L_{p,A,S,4m}$ are therefore recommended.

5.3 Comparison of acoustic environments between LOPOs and MOPOs

Poor speech privacy can increase acoustic interferences on work productivity [12, 31, 68, 69]. Privacy scores of all LOPOs except for office A are higher than that of MOPOs (see Table 8), and the mean scores of perceived speech privacy in LOPOs are larger than in MOPOs (see Table 10). These results imply that speech privacy in LOPOs is higher than in MOPOs; in other words, the effects of acoustic interference on productivity in LOPOs should be lower than in MOPOs. However, the subjective results show that acoustic interference on work productivity in LOPOs is significantly greater than in MOPOs (see Table 9). These conflict results may be because the relationships between speech privacy and work productivity in LOPOs and MOPOs are different. For LOPOs, speech privacy (including own conversation privacy and other's conversation privacy) is the important factor correlating with the effects of acoustic interference on work productivity in LOPOs, while this correlation cannot be found in MOPOs. As for why there is no significant correlation in MOPOs, a possible explanation is that, employees in MOPOs usually work for the same project, and the contents of their conversation are often related to their project. The employees do not care about the speech privacy levels in their offices. A weakness of this study is that the privacy score of each OPO is determined by simply adding scores of speech privacy-related parameters rather than adding the weighted score of each parameter based on its effects on perceived speech privacy. The weightings of speech privacy-related parameters on perceived speech privacy, generally, could be different. However, in the current study, no significant correlation has been found between perceived speech privacy and speech privacy-related parameters based on Spearman rank correlation coefficients. A possible explanation is that the sample of OPOs is not sufficient. Only 13 sets of data are utilised to explore the correlations between perceived speech privacy and speech privacy-related parameters. As mentioned in Section 2.2, several offices with the same layouts (i.e. offices B and C, offices D-F) have almost identical acoustic characteristics when not occupied. The speech privacy-related measurements were performed at one of those OPOs with the same layouts. More samples of OPOs are needed to determine the weightings of speech privacy-related parameters on perceived speech privacy for future studies.

6. Conclusion

In this study, both physical and subjective measurements were conducted to investigate the indoor acoustic environment in 16 occupied OPOs in China and compare the effects of acoustic environments between LOPOs and MOPOs. The main findings can be drawn as follows:

1) The spatial density of workstations and storey height show significant correlations with spatial decay rate of speech ($D_{2,S}$), speech level at 4 m distance ($L_{p,A,S,4m}$) and the comfort distance (r_C). Besides, distraction distance (r_D) is significantly correlated with the background noise level ($L_{p,A,B}$).
2) Both acoustic satisfaction and the effects of acoustic interference on work productivity significantly correlate with the perceived noise level, speech privacy (i.e. own and other's conversation privacy) and the effects of speech interferences on re-concentration and problem-solving speed. The perceived noise level is the most important criterion for acoustic satisfaction, and speech interferences on re-concentration are the main acoustic cause of work productivity decrease. Phone ringing has the highest disturbance to employees in OPOs in China.
3) MOPO employees have higher acoustic satisfaction and lower disturbance levels of speech noises. Speech privacy is an important factor affecting employees' work productivity in LOPOs, while it is not in MOPOs.

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