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The effect of room acoustic quality levels on work performance and perceptions in open-plan offices: a laboratory study

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Abstract:

A laboratory experiment was performed to explore the effects of acoustic quality levels on work performance and perceptions in open-plan offices. The accuracy rate of the serial recall task and the reported perceptions of the 41 participants were tested at two receiving positions in four office scenarios. According to the revised international standard for measuring room acoustic parameters in open-plan offices, ISO 3382-3:2022, the room acoustic qualities of the four office scenarios were classified into four levels (good, high-medium, low-medium, and poor). The results confirm the validity of the acoustic classification criteria in ISO 3382-3:2022 and highlight that people working in offices with good acoustic quality have significantly higher work performance and acoustic satisfaction than those working in offices with poor acoustic quality. Moreover, comparisons of objective and subjective results between the two receiving positions imply that maintaining a greater distance from people speaking improves work performance and acoustic satisfaction in offices with poor acoustic quality. However, this improvement is insignificant when working in offices with good acoustic quality.

Keywords: open-plan offices, acoustic quality levels, work performance, acoustic satisfaction, sound pressure level of speech

1. Introduction

1.1 Effects of speech noise in open-plan offices

Noise disturbance in open-plan offices has become a major acoustic problem because noise can be transmitted with few obstacles in large office spaces without partition walls. Irrelevant conversation noise (or irrelevant speech noise) is a common noise type in open-plan offices and has a strong negative impact on work performance [1-3], job satisfaction [1, 4, 5], environmental satisfaction [6, 7] and mental health [8, 9]. Several studies have explored why speech noise can result in decreased work performance and acoustic dissatisfaction. For example, Sörqvist et al. [10] found that the semanticity of irrelevant speech is the main cause of distraction in the workplace. Marsh et al. [11] revealed that the detrimental effects of speech noise on work performance are higher when the semanticity of irrelevant speech is related to work. Speech privacy has been proposed as an acoustic index for the evaluation of acoustic quality in open-plan offices [5]. The index is a measure of how well speech noise is audible and understandable by unintentional listeners [12].

1.2 Physical parameters for acoustic performance in open-plan offices

Speech privacy is usually viewed as the opposite of speech intelligibility. Several studies [2, 13-15] have assessed the effects of the speech transmission index (STI), a fundamental physical parameter for evaluating speech intelligibility, on work performance and acoustic environment perceptions in open-plan offices [16, 17]. In 2005, Hongisto [18] presented a model of the relationship between the performance of office workers and STI. In the Hongisto's model, work performance begins to decrease when the STI increases beyond 0.2, and performance reaches a minimum when the STI increases to

0.5. This model provides a scientific background for defining an acoustic parameter (i.e., distraction distance) to describe speech privacy in open-plan offices. In 2020, Haapakangas et al. [15] revised Hongisto's model based on a systematic literature review. The revised model shows that the performance decrease begins at an STI of 0.12, rather than at an STI of 0.20, as in Hongisto's model.

Successful acoustic measurements are key to evaluating acoustic quality [19-21]. A measurement standard for acoustic environments in open-plan offices, ISO 3382-3:2012 [22], was published in 2012. Three single-number quantities, namely spatial decay rate of speech ($D_{2,S}$), speech level at a 4 m distance ($L_{p,A,S,4m}$), and distraction distance (r_D), have been recommended for evaluating acoustic environments in open-plan offices. Among these single-number quantities, $D_{2,S}$ describes the rate of spatial decay of the A-weighted sound pressure level (SPL) of speech per distance doubling in decibels, $L_{p,A,S,4m}$ indicates the A-weighted speech SPL in decibels at a distance of 4 m from the speaker, and r_D refers to the distance in metres from the speaker beyond which the STI falls below 0.5. The revised standard ISO 3382-3:2022 introduced comfort distance (r_C) as a physical parameter to evaluate acoustic environments [23]. The distance from the speaker in which the speech SPL falls below 45 dBA is represented by r_C, which is used to determine the effect of spatial attenuation in open-plan offices [23]. These four parameters, namely $D_{2,S}$, $L_{p,A,S,4m}$, r_D, and r_C are related to the spatial decay of speech in open-plan offices [23].

1.3 Evaluation of room acoustic quality

Room acoustic quality is a key factor affecting the indoor environment quality and has a significant impact on the performance and acoustic satisfaction of office workers [6, 24]. Hongisto et al. [25] conducted a quasi-field experiment in an open-plan office with 135 employees to determine the relationship between indoor environmental quality and environmental satisfaction. They provided evidence that the disturbance caused by poor speech privacy decreased with increased acoustic quality. Lou and Ou [13] found that improving acoustic environments by reducing speech intelligibility increased the acoustic comfort of occupants in open-plan offices.

An acoustic classification criterion is important for predicting and evaluating indoor acoustic quality based on the acoustic parameter values. Several studies have proposed classification criteria for acoustic environments regarding speech decay-related parameters to guide acoustic design and evaluation of open-plan offices. For instance, in 2009, Virjonen et al. [26] proposed an acoustic classification method and corresponding target values of speech decay-related parameters based on the data obtained from 16 open-plan offices. Accordingly, room acoustic quality can be classified into four levels based on the three speech decay-related parameters, namely $D_{2,S}$, $L_{p,A,S,4m}$, and r_D. In 2021, Hongisto and Keränen [27] proposed four acoustic quality levels of r_D based on data from 26 open-plan offices. However, the acoustic classification criteria of Virjonen et al. [26] and Hongisto and Keränen [27] were determined according to the distribution of the values of speech decay-related parameters without considering work performance and perceptions of the acoustic environment. In 2022, Jo et al. [28] proposed four acoustic quality levels of $L_{p,A,S,4m}$ based on the relationship between $L_{p,A,S,4m}$ and the acoustic satisfaction of participants. However, the effects of room acoustic quality levels on work performance were not considered. The 2022 revised ISO 3382-3 provides two examples of room acoustic quality levels; one good and one poor. More specifically, typical values of speech decay-related parameters indicating the good room acoustic quality 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, and those indicating the poor acoustic quality 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. However, it is still unclear whether office workers in good acoustic environments, as defined in ISO 3382-3:2022, perform better and are more satisfied with their acoustic environment.

1.4 Aim of this study

To the best of our knowledge, laboratory studies analysing the effects of acoustic quality levels on work performance and reported perceptions in open-plan offices are still limited. Therefore, in this study, a laboratory study was conducted to determine the effects of room acoustic quality levels on work performance and perceptions of acoustic environments in open-plan offices. Four office scenarios were considered in this study. The acoustic quality level of each office scene was determined according to ISO 3382-3:2022, Annex C. In addition, speaker-receiver distance is a non-negligible factor that affects the subjective evaluation of speech interference in open-plan offices [1]. Thus, two receiving positions were selected in each office scene to assess how the distance from the speaker affects the performance of office workers and their perceptions of different room acoustic qualities. The following three research questions were addressed:

1) Do office workers perform better, and is their acoustic satisfaction higher in open-plan offices with good acoustic qualities than in open-plan offices with poor acoustic qualities?

2) Do the effects of speaker-receiver distances on work performance, and perceptions of acoustic environments decrease when the room acoustic quality level rises from poor to good?

2. Research methods

2.1 Participants

In this study, 41 students (20 men and 21 women) aged between 18 and 31 years (mean = 22.41, SD = 3.79) were recruited from Huaqiao University, Xiamen City, China. All were native speakers of Chinese and reported no known hearing problems. Participants were compensated for their involvement in the study.

2.2 Laboratory room

A 6.6 (length) x 6.5 (width) x 3.0 m (height) test laboratory was used (Figure 1). The early decay times (EDT) of this laboratory, which is measured by Dirac 6.0, were 0.70, 0.56, 0.50, 0.56, 0.56, 0.56, and 0.54 s in the octave bands 125, 250, 500, 1000, 2000, 4000, and 8000 Hz, respectively. As shown in Figure 1, workstation E was used as the control console. Two workstations, R1 and R2, were arranged as test positions and were separated by a 1.5 m high partition to avoid visual contact during the testing.

During each test session, the room temperature and relative humidity remained within a comfortable range between 21 °C and 23 °C and 51 % and 66 %, respectively. The concentrations of CO_2 were maintained at approximately 407–969 ppm. The vertical illumination level was approximately 530 lx for each workstation surface. Glare problems were not observed at any of the workstations. The background noise in the laboratory was approximately 35.6 dBA.

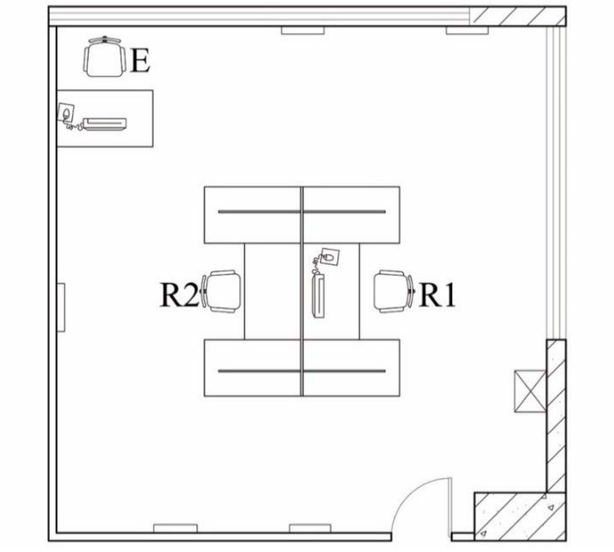


Figure 1 Layout of the test laboratory (E represents the position of the control console, and R1 and R2 represent the test positions).

2.3 Open-plan offices

Based on the in situ measurement results of our recent study [3], an open-plan office was modelled using Auto CAD and SketchUp software. The layout of the simulated open-plan office is shown in Figure 1. The computer simulation model dimensions were 37.2 x 10.9 x 3.6 m^3, and the partition height between workstations was 1.5 m.

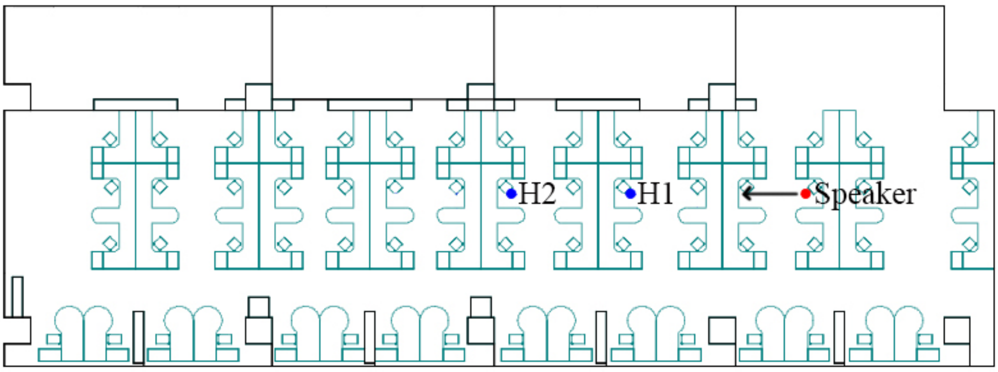


Figure 2 Layout of the simulated open-plan office (H1 and H2 present receiving positions).

Odeon simulation software (version 13) was used for the acoustic simulation. This study created four office scenes by modifying the sound absorption at each surface. Detailed information for each office scene is presented in Table 1. According to Annex C of ISO 3382-3:2022 [23], Scene 1 had good room acoustic quality (Table 1). Due to the impact of the background noise in the laboratory (35.6 dBA), the background noise level of Scene 4 was 35.8 dBA, which was slightly above the threshold for poor room acoustic quality (35 dBA). The room acoustic quality level of Scene 4 was still poor, as the values of speech decay-related parameters (i.e., $D_{2,s}$, $L_{p,A,S,4m}$, r_C, and r_D) were in the poor acoustic quality range (Table 1). As indicated in Table 1, although the values of speech decay-related parameters of scenes 2 and 3 were both between good and poor acoustic quality range, the acoustic quality of Scene 2 was better than that of Scene 3 because, according to previous studies [25, 29], occupants in open-plan offices with low $L_{p,A,S,4m}$ and short r_D have a low probability of being disturbed by speech noise. Therefore, the acoustic conditions of the four office scenes could be classified as good, high-medium, low-medium, and poor acoustic qualities.

All office scenes had a speaker location and two receiving positions (Figure 2). As shown in Table 1, the r_D of the four office scenes varied from 3.5 to 13.5 m, which means sites with an STI of 0.5 in office scenes 1, 2, 3, and 4 were positioned in proximity to the first, second, fourth, and sixth workstations from the speaker, respectively (Figure 2). The third (7 m) and fifth workstations (11 m) from the speaker were selected as the receiving positions (i.e., H1 and H2) to explore the effects of the speaker-receiver distance at different acoustic quality levels. Thus, the open-plan office possessed eight acoustic conditions. The sound pressure level of speech ($L_{A,S}$) and total sound pressure level ($L_{Aeq,total}$) changed in the ranges of 35.8–46.4 dBA and 40.7–46.8 dBA (Table 1), respectively.

Table 1 Acoustic parameters of sound stimuli depended on different sound absorption conditions. Abbreviations are used to describe the tested acoustic conditions and are defined as follows: 1) GO_H1 and GO_H2 describe acoustic conditions of receiving positions H1 and H2 in scene 1, respectively; 2) MH_H1 and MH_H2 describe acoustic conditions of receiving positions H1 and H2 in scene 2, respectively; 3) ML_H1 and ML_H2 describe acoustic conditions of receiving positions H1 and H2 in scene 3, respectively; and 4) PO_H1 and PO_H2 describe acoustic conditions of receiving positions H1 and H2 in scene 4, respectively.

Office scenes	Receiving positions	Office conditions	$D_{2,S}$ dBA	$L_{p,A,S,4m}$ dBA	r_C m	r_D m	$L_{A,S}$ dBA	$L_{p,A,B}$ dBA	$L_{Aeq,total}$ dBA	EDT/s	Acoustic quality level
1	H1	GO_H1	8.5	44.5	3.8	3.5	37.1	40.1	41.9	0.13	Good
	H2	GO_H2	8.5	44.5	3.8	3.5	31.6	40.1	40.7	0.13	Good
2	H1	MH_H1	7.3	47.7	5.2	5.6	39.2	39.1	42.2	0.24	High-medium
	H2	MH_H2	7.3	47.7	5.2	5.6	35.7	39.1	40.7	0.24	High-medium
3	H1	ML_H1	6.5	49.9	6.7	9.9	44.6	37.0	45.3	0.34	Low-medium
	H2	ML_H2	6.5	49.9	6.7	9.9	38.9	37.0	41.1	0.34	Low-medium
4	H1	PO_H1	4.7	52.4	11.9	12.3	46.4	35.8	46.8	0.69	Poor
	H2	PO_H2	4.7	52.4	11.9	12.3	42.2	35.8	43.1	0.69	Poor

Note:
"Poor" values are 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 are 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.
EDT averaged over 250 to 4000 Hz octave bands of each office scene.

2.4 Sound stimuli

The sound stimuli for the auditory assessment were using the room impulse responses generated using computer simulations and background noise. First, single-speaker speech sounds and background noise were convolved with a binaural room impulse. Second, the $L_{A,S}$ and $L_{p,A,B}$ values were adjusted using a sound card (Fireface UC) and Adobe Audition software to ensure that the values of speech decay-related parameters were consistent with those in Table 1. Figure 3 shows the schematic drawing of measuring sound materials. The convolved speech and background noise were played back through a sound card (Fireface UC) and headphones (Sennheiser HD 600 and 650), and recorded for analyzing the sound levels using an in-ear microphone (B&K 4101-A) and the pulse system (B&K

3160-B-042 and Pulse LabShop). The amplification of the head was not compensated since most of the sound energy was located under 1000 Hz. The effect of correction on the A-weighted speech pressure level is under 0.5 dB for the speech sounds. All sound stimuli were intended to represent the acoustic environment of four office scenes when a single person was speaking in a natural tone.

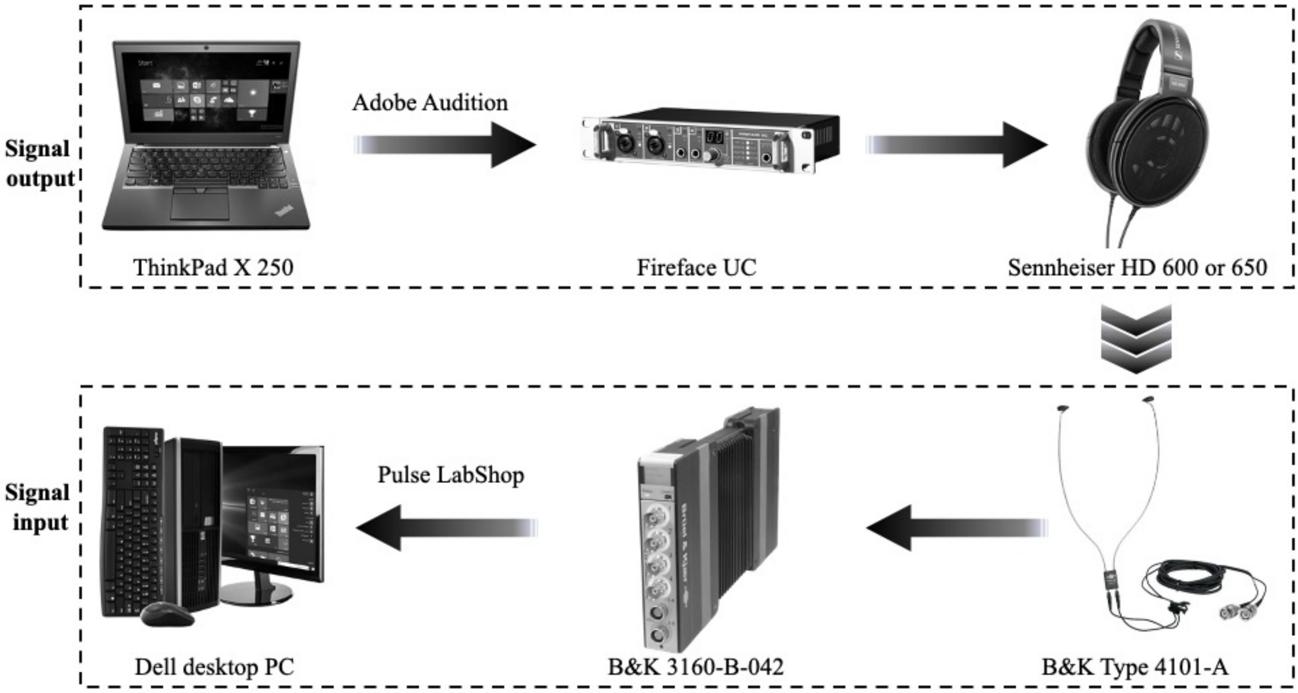


Figure 3 Schematic drawing of playing and measuring the test material

The sound materials used in this study comprised 14 speech recordings of female and male native Mandarin speakers in an anechoic room before the experiment. In addition, ventilation sounds were recorded in the field for background noise. Our previous studies have also used these speech and ventilation sounds [2, 13, 30]. More information on the speech materials and ventilation sounds can be found in Zhang et al. [30].

2.5 Cognitive task

The serial recall task, which is widely used to study work performance in offices [31-33], was used in the experiment. In the current study, each serial recall task consisted of ten Chinese word sequences. For each sequence, seven words were displayed consecutively on a computer screen for 1 s each with a 0.5 s blank screen interval between each change. After the word display, participants were asked to recall all the words they had seen in order of appearance within 47 seconds. Additional information on this task can be found in Zhang et al. [30]. Moreover, mute keyboards were used in this study to minimize the keyboard sounds produced by participants during the testing.

2.6 Questionnaires

Questionnaires were utilized to collect background information on participants and measure the effects of acoustic quality levels on the acoustic preferences of participants and their work performance. Questionnaire 1 (Q1) gathered basic information on participants' age, gender, and whether they had hearing problems or not. Questionnaire 2 (Q2) collected the subjective performance and speech disturbance of participants, which were evaluated using questions answered on a 5-point Likert scale from 1 = very low to 5 = very high. Acoustic satisfaction from 1 = very dissatisfied to 5 = very satisfied was also included in Q2. In addition, the NASA task load index (NASA-TLA) was included in Q2 to measure the mental workload of the serial recall tasks. Mental, physical, and temporal demands and performance, effort, and frustration were the six items assessed on an 11-point scale, from 0 = very low to 10 = very high. The mental workload of the participants was the sum of all the item scores.

2.7 Experimental procedure

The experiment was conducted in a Huaqiao University laboratory from December 2021 to January 2022. The experiment took place in two stages, namely preparation and formal testing.

In the preparation stage, participants were informed of the purpose of the experiment, but details of acoustic conditions were not provided. Subsequently, they were requested to complete Q1. Finally, they were given ten minutes to practice the tasks in silence and familiarise themselves with the test requirements.

In the formal testing stage, participants performed the given tasks under eight acoustic conditions in random order. They performed a serial recall task for each acoustic condition and completed one questionnaire (Q2). Tests of each acoustic condition lasted approximately 12 min, and a four-minute break was provided between each test. All acoustic conditions were presented by Sennheiser HD 600 or 650 headphones, an RME Audio Fireface UC sound card, and a ThinkPad X250 laptop (see Figure 3).

The experiment lasted for approximately 2 h 20 min. A researcher was present in the laboratory to control all the acoustic conditions. One or two participants were tested at a time. After the experiment, participants were provided with more information on their role in the study and the overall objectives.

2.8 Statistical analysis

The data were analysed using SPSS Statistics. The normality of the serial recall task accuracy rates was checked using the Shapiro–Wilk test. The results demonstrate a normally distributed accuracy rate for each acoustic condition. The serial recall task was analysed using repeated measures of analysis of variance (RM ANOVA) tests with accuracy rates as dependent variables and room acoustic quality levels as independent variables. The RM ANOVAs were followed up with paired comparisons of the adjusted means. Two-way Friedman tests were conducted on the subjective rating results of the participants. The Friedman tests were followed up with paired comparisons with adjustments for multiple comparisons using the Bonferroni correction. Paired-samples t-tests and Wilcoxon tests were performed to evaluate the differences between the two receiving positions, H1 and H2, regarding work performance and perceptions of room acoustic quality levels. The mean values were calculated as descriptive statistics for all dependent variables.

3. Results

3.1 Effects of acoustic conditions at a close receiver (H1)

The objective performance (accuracy rates) and subjective evaluation results (subjective performance, speech disturbance, and acoustic satisfaction) of participants at a close distance (H1) to the speaker in the four office scenes are displayed in Figure 4. In addition, the mean score of the mental workload, measured with the NASA-TLX, in each office scene is provided in Figure 4. A higher score indicates a higher mental workload.

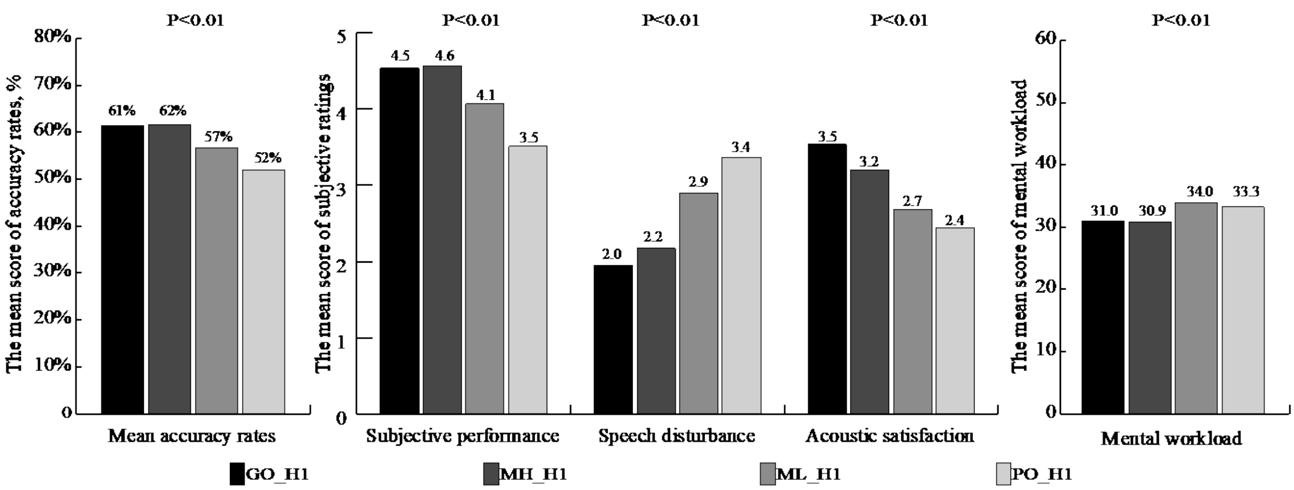
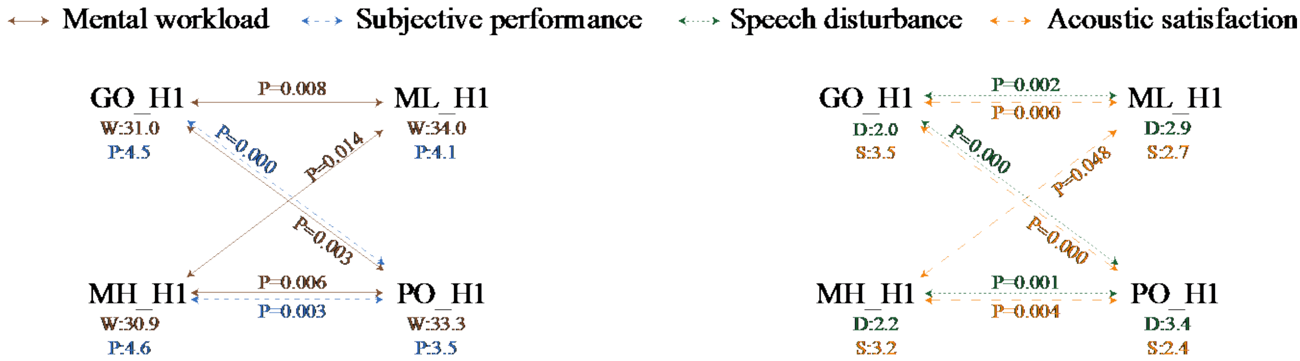


Figure 4 Mean results of objective performance and subjective evaluation of participants at the receiving position H1 in different office scenes. Room acoustic quality levels in scenes 1, 2, 3, and 4

are described by GO, MH, ML, and PO, respectively, and H1 refers to the position at 7 m from the speaker.

For the objective performance, the average accuracy rates follow the expected pattern; the accuracy rates decrease when the room acoustic quality worsens (Figure 4). Mauchly's test for sphericity was not significant (P-value>0.05). A significant main effect of room acoustic quality on accuracy rates was revealed by the RM ANOVA tests at the receiving position H1 ($F_{3,120}$=15.474, P-value=0.000, and partial η^2=0.279). Moreover, post hoc tests (Bonferroni) indicated that the average accuracy rate in GO_H1 was significantly higher than that in ML_H1 (P<0.05) and PO_H1 (P<0.01). The average accuracy rate in MH_H1 was also significantly higher than that in ML_H1 (P<0.05) and PO_H1 (P<0.01).

For subjective perceptions, Friedman tests revealed that the room acoustic quality level had significant effects on mental workload (P<0.01), subjective performance (P<0.05), speech disturbance (P<0.01), and acoustic satisfaction (P<0.01) when sitting at position H1 (Figure 4). Subsequently, pairwise comparisons were conducted, and the results are provided in Figure 5. The average scores of subjective evaluations, provided in Figure 4, and the analysis of post hoc tests, provided in Figure 5, can be summarised as follows: 1) The mean mental workload score was significantly lower in GO_H1 than in ML_H1 (P<0.01) and PO_H1 (P<0.01) and significantly lower in MH_H1 than in ML_H1 (P<0.05) and PO_H1 (P<0.01); 2) the mean subjective performance score was significantly lower in PO_H1 than in GO_H1 (P<0.01) and MH_H1 (P<0.01); 3) the mean speech disturbance score was statistically lower in GO_H1 than in ML_H1 (P<0.01) and PO_H1 (P<0.01) and significantly lower in MH_H1 than in PO_H1 (P<0.01); and 4) the mean acoustic satisfaction score was significantly higher in GO_H1 than in ML_H1 (P<0.01) and PO_H1 (P<0.01) and similarly, was significantly higher in MH_H1 than in ML_H1 (P<0.05) and PO_H1 (P<0.01).



(a) Pairwise comparisons regarding mental workload and subjective performance

(b) Pairwise comparisons regarding speech disturbance and acoustic satisfaction

Figure 5 Pairwise comparisons of room acoustic quality levels at receiving position H1 in terms of mental workload, subjective performance, speech disturbance, and acoustic satisfaction. Room acoustic quality levels in scenes 1, 2, 3, and 4 are described by GO, MH, ML, and PO, respectively, H1 refers to the position at 7 m from the speaker, and W, P, D, and S refer to the mean mental workload scores, subjective performance, speech disturbance, and acoustic satisfaction, respectively.

3.2 Effects of acoustic conditions at a far receiver (H2)

The objective performance (accuracy rates) and subjective evaluation results (subjective performance, speech disturbance, acoustic satisfaction, and mental workload) of participants at a greater distance (H2) from the speaker in the four office scenes are displayed in Figure 6.

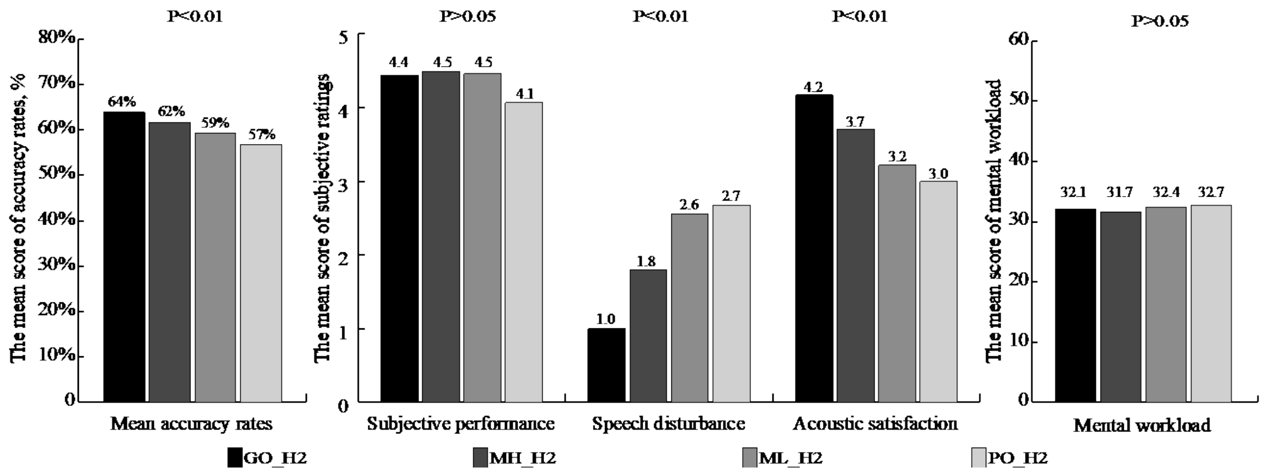


Figure 6 Mean results of objective performance and subjective evaluation by participants at the receiving position H2 in different office scenes. Room acoustic quality levels in scenes 1, 2, 3, and 4 are described by GO, MH, ML, and PO, respectively, and H2 refers to the position at 11 m from the speaker.

For the objective performance, the average accuracy rates decreased when the room acoustic quality worsened (Figure 6). A significant main effect of room acoustic quality on the accuracy rates of the serial recall task ($F_{3,120}$=8.654, P-value=0.000, and partial η^2=0.178) at the receiving position H2 was revealed by RM ANOVA tests. Moreover, post hoc tests (Bonferroni) revealed that the average accuracy rate was significantly higher in GO_H2 than in ML_H2 (P<0.05) and PO_H2 (P<0.01). The average accuracy rate was significantly higher for MH_H2 than for PO_H2 (P<0.01).

For subjective perceptions, Friedman tests revealed significant differences in speech disturbance (P<0.01) and acoustic satisfaction (P<0.01) among the four office scenes when sitting at the receiving position H2 (Figure 6). However, no significant differences were observed in either subjective performance (P>0.05) or mental workload (P>0.05). The mean scores of subjective evaluations, shown in Figure 6, and the results of pairwise comparisons, shown in Figure 7, can be summarised as follows:1) the mean score of speech disturbance was significantly lower in GO_H2 than in MH_H2

(P<0.01), ML_H2 (P<0.01), and PO_H2 (P<0.01); 2) the mean score of speech disturbance was significantly lower in MH_H2 than in ML_H2 (P<0.05) and PO_H2 (P<0.05); 3) the mean score of acoustic satisfaction was significantly higher in GO_H2 than in ML_H2 (P<0.01) and PO_H2 (P<0.01); and 4) the mean score of acoustic satisfaction was significantly higher in MH_H2 than in PO_H2 (P<0.01).

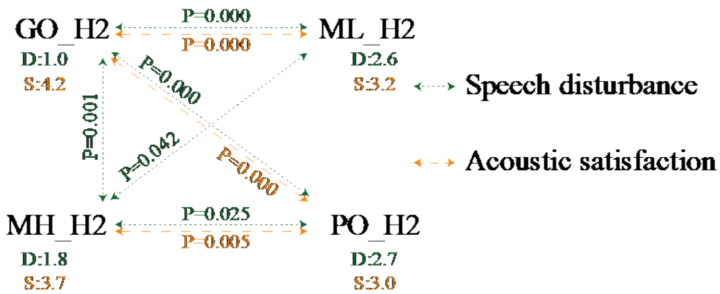


Figure 7 Pairwise comparisons of room acoustic quality levels at the receiving position H2 in terms of speech disturbance and acoustic satisfaction. Room acoustic quality levels in scenes 1, 2, 3, and 4 are described by GO, MH, ML, and PO, respectively, H2 refers to the position at 11 m from the speaker, and D and S refer to the mean scores of speech disturbance and acoustic satisfaction, respectively.

3.3 Effects of the speaker-receiver distance

As shown in Figures 4 and 6, the average accuracy rates and acoustic satisfaction of participants were generally lower at position H1 than at position H2 in all office scenes. Similarly, the mean score for speech noise disturbance was higher at position H1 than at position H2. In addition, the mean score of subjective performance at position H1 was higher than that at position H2 in scenes 1 and 2, whereas the opposite was observed for scenes 3 and 4. Similarly, the mean mental workload scores were lower at position H1 than at position H2 in scenes 1 and 2, whereas the opposite was observed for scenes 3 and 4 (Figures 4 and 6).

Paired-samples t-tests and Wilcoxon tests were performed to explore the differences between the two receiving positions, H1 and H2, regarding objective performance and subjective evaluations. The results are presented in Table 2. The average results, shown in Figures 4 and 6, and the pairwise comparison results, shown in Table 2, can be summarised as follows: 1) Paired-samples t-tests revealed that the average accuracy rate was significantly lower at position H1 than at position H2 in scene 4 (P<0.01) and marginally lower at position H1 than at position H2 (P=0.076) in scene 3; 2) Wilcoxon tests demonstrated that the mean score of subjective performance was lower at position H1 than at position H2 at the marginal significance level (P=0.054) in scene 4 and no significant differences were observed in subjective performance between the two positions in the other three scenes; 3) based on the Wilcoxon test results, the mean mental workload score was significantly higher at position H1 than at position H2 in office scene 3 (P<0.05); 4) the mean speech disturbance scores were significantly higher at position H1 than at position H2 in scenes 1 and 4 (P<0.01) and were higher at position H1 than at position H2 at marginal significance levels (P=0.052) in scenes 2 and 3; and 5) the mean acoustic satisfaction scores were significantly lower at position H1 than at position H2 in all office scenes (P<0.05).

Table 2 Comparative results (P-values) between receivers H1 and H2

Items	Scene 1	Scene 2	Scene 3	Scene 4
Accuracy rate[1]	+0.102	+0.978	**+0.076**	**+0.009**[**]
Subjective performance[2]	-0.806	-0.567	+0.162	**+0.054**
Mental workload[2]	+0.325	+0.219	**-0.033**[*]	-0.634
Speech disturbance[2]	**-0.000**[**]	**-0.052**	**-0.052**	**-0.004**[**]
Acoustic satisfaction[2]	**+0.000**[**]	**+0.001**[**]	**+0.000**[**]	**+0.001**[**]
Note: [1]: Paired-samples t-tests; [2]: Wilcoxon tests; [*]: P<0.05;				

**:P<0.01;
-: the results at position H1 are higher than at position H2;
+: the results at position H1 are lower than at position H2;
P-values<0.08 are presented in bold.

4. Discussion

4.1 Comparisons among different office scenes

The analysis presented in Section 3 demonstrates that the effects of room acoustic quality levels on work performance and reported perceptions differed for different office scenes and receiving positions. The room acoustic quality levels at the two receiving positions were compared and ranked according to each objective and subjective item (Table 3). Perceptions of mental workload and subjective performance were not considered when ranking because no significant differences were observed among four acoustic quality levels at position H2 concerning these two subjective items. The ranking principles were as follows: 1) Two acoustic quality levels share the same rank order if no statistical differences were observed; 2) The mean score of each item (Table 3) could be used as an auxiliary evaluation index if there was a problem with the room acoustic quality level ranking when considering only statistical significance. For instance, significant differences were observed in speech disturbance between GO_H1 and ML_H1, GO_H1 and PO_H1, and MH_H1 and PO__H1, but not found between GO_H1 and MH_H1, and ML_H1 and PO_H1. Thus, the mean score of speech disturbance was considered for the room acoustic quality level ranking. As shown in Table 3, the accuracy rate and acoustic satisfaction are ranked from high (A) to low (B^-), and the speech disturbance is ranked in reverse order from low (A) to high (C). Thus, the lower the ranking, the lower the quality of the acoustic condition. Considering rankings in the three items (accuracy rate, speech disturbance, and acoustic satisfaction), it is evident that the acoustic quality of office scenes 1 and 2 are much higher than that in 2 and 4, regardless of the receiving positions (Table 3). As recommended in ISO 3382-3:2022 Annex C [23], the acoustic quality level was set from high to low in scenes 1, 2, 3, and 4, based on the acoustic parameter values of each office scene. These results demonstrate the validity of the acoustic classification in Annex C of ISO 3382-3:2022 [23]. More specifically, 1) open-plan offices with good acoustic quality (i.e., $D_{2,S}$>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) are beneficial for maintaining high performance and acoustic satisfaction of workers; and 2) open-plan offices with poor acoustic quality (i.e. $D_{2,S}$<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) could impair performance and decrease acoustic satisfaction of workers. However, it is unclear whether there are significant differences in acoustic quality between scenes 1 and 2 because of the small differences in the accuracy rate and acoustic satisfaction of participants (Figures 4 and 6).

Table 3 Ranking of the room acoustic quality levels. Acoustic conditions in scenes 1, 2, 3, and 4 are described by GO, MH, ML, and PO, respectively, and H1 and H2 refer to positions at 7 m and 11 m from the speaker, respectively.

Items	Acoustic conditions at the position H1				Acoustic conditions at the position H2			
	GO_H1	MH_H1	ML_H1	PO_H1	GO_H2	MH_H2	ML_H2	PO_H2
Accuracy rate	A-	A	B	B	A	A-	B	B-
Speech disturbance [R]	A	A-	B	B-	A	B	C	C-
Acoustic satisfaction	A	A-	B	B-	A	A-	B	B-

Note:
[R]: the items ranked in reverse order (i.e., ranked from low to high);
"-" was used to show the lower rank of two conditions when no significant differences were found between them.

Pairwise comparisons were conducted to determine the impacts of source-receiver distances on work performance and perceptions of acoustic environments at different acoustic quality levels. For work performance, no significant differences were detected between the two receiving positions (H1 and H2) in terms of accuracy rate and subjective performance in scenes 1 and 2 (Table 2), implying that the increase in source-receiver distance does not result in a significant improvement in work performance (both objective and subjective performance) in offices with good and high-medium acoustic qualities. In scene 4, a significant difference was observed in accuracy rate between the two receiving positions but not in subjective performance, indicating that the farther the speaker is, the higher the objective performance in offices with poor acoustic quality. Regarding perceptions of room acoustic quality levels, the results in Table 2 indicate that the farther away from the speaker, the higher the acoustic satisfaction of participants. Interestingly, perceptions of speech noise disturbance showed statistically significant differences between different receiving positions in both good and poor acoustic environments. In all office scenes, positions H1 and H2 are 7 m and 11 m from the speaker, respectively. For office scene 1, the privacy distance (r_P), which is the distance from the speaker where the STI is decreased to 0.2 [22], is 9.96 m. The disturbance of speech on work performance disappears when STI falls below 0.2 [18, 22]. In other words, speech noise in office scene 1 causes little disturbance to work performance if the speaker-receiver distance exceeds 9.96 m. In this study, the mean speech disturbance score at H2 (1.0) demonstrates that the negative effect of speech is negligible when the speaker-receiver distance exceeds r_P (i.e., STI < 0.2). For office scene 4, r_D is 12.3 m, implying that the distraction effects of speech noise are high within 12.3 m of the speaker. Moreover, in the range of 12.3 m, as the speaker-receiver distance increases, speech intelligibility reduces, resulting in fewer distraction effects of speech noise on workers in open-plan offices [15, 18].

4.2 Limitations

The experimental findings of this study are expected to be utilised as references for designing pleasant acoustic environments in open-plan offices. Despite these findings, this study had several limitations. First, only one open-plan office size was considered. The distance from the receiving position H2 to the speaker position (11 m) in this study is typical for large-sized open-plan offices based on previous studies [26, 34]. In contrast, the speaker-receiver distance of 11 m could be large or even non-existent for small-sized open-plan offices [3]. Thus, follow-up studies could explore the effects of the different acoustic quality of open-plan offices at closer speaker-receiver distances. Second, acoustic simulation was used to generate sound stimuli like those of actual open-plan offices. However, the visual environment of an actual open-plan office could not be reconstructed because of the limited space in the laboratory. Third, background noise was convolved with a binaural impulse response. The azimuth separation of sources (e.g. speech, background noise, and etc.) is an important factor for binaural interaction in auralization experiments [35]. The convolved background noise of this study may weaken the interpretation of the relationships between parameters and their effects since it came from the same location as the speech source. Finally, the background noise level of office scene 4 was slightly high. As recommended in ISO 3382-3:2022 Annex C, the background noise level of poor acoustic quality should be above 48 dBA or below 35 dBA. In this study, the background noise level of office scene 4 was 35.8 dBA as the impact of background noise in the laboratory.

5. Conclusion

This work was among the first experimental laboratory studies which explored the effects of room acoustic quality levels proposed by ISO 3382-3:2022 standard in open-plan offices. Both the work performance and perceptions of the acoustic environment were examined at two receiving positions in four office scenes corresponding to different acoustic quality levels. The findings of this study can be summarised as follows:

1) The comparisons among the four office scenes largely demonstrate higher work performance and acoustic satisfaction in open-plan offices with good or high-medium acoustic quality based on the acoustic classification in Annex C of ISO 3382-3:2022.
2) The effects of speaker-receiver distance on work performance and the acoustic environment perception decrease when the acoustic quality level increases from poor to good. In poor room acoustic quality, the objective performance of workers and their acoustic environment perception significantly improved with increasing distance from the speaker. However, a large speaker-receiver distance was not significantly better in good room acoustic quality.

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