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Effects of speech intelligibility and reverberation time on the serial recall task in Chinese open-plan offices: a laboratory study

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Abstract:

Speech intelligibility is an essential index for evaluating acoustic performance in open-plan offices. Both speech-to-noise ratio (SNR) and reverberation time (RT) are critical parameters for determining the Speech Transmission Index (STI). STI is an important parameter for the objective prediction of speech intelligibility. Many studies explored the effects of speech intelligibility on work performance and acoustic environmental perceptions in open-plan offices by changing the SNR to obtain various STI conditions. However, few studies research how RT affects speech intelligibility and then influences work performance and perceptions of acoustic environments in open-plan offices. This study conducted a laboratory experiment to identify the changing trends of work performance and acoustic environment perceptions with the increase in STI under different RT conditions and to explore how room RT affects work performance and perceptions of the acoustic environment under the same STI condition. The acoustic conditions tested in this study varied in speech intelligibility (STI of 0.21, 0.42, and 0.61) and reverberation time (RT of 0.4s and 1.4s). The main outcome of this study is that occupants have less mental workload, faster task completion speed, and higher acoustic adaptability in a long RT environment compared to a short RT environment at an STI of 0.42. Furthermore, the data show a decreased work performance and an increased speech disturbance with the increase in STI in the short RT environment, while that trend was not observed in the long RT environment. The effects of STI conditions on occupants may differ by gender and noise sensitivity.

Keywords: Open-plan Offices, Speech Transmission Index, Reverberation Time, Work Performance, Speech Disturbance

1. Introduction

1.1 Speech disturbance in open-plan offices

Large spaces without partition walls are a typical feature of open-plan offices. This feature allows noise to transmit throughout the office space with few obstacles, resulting in a poor acoustic environment. Speech is one of the most annoying noises in open-plan offices [1-3]. Clear semantic content is one of the main reasons for the high disturbance of speech noise [4, 5]. Thus, speech intelligibility is regarded as a critical acoustic index for evaluating room acoustic quality levels in open-plan offices. Unlike other rooms where high speech intelligibility is required (e.g., classrooms, meeting rooms, and lecture halls), lower intelligibility of irrelevant speech is desirable in open-plan offices. This is because lower speech intelligibility in an open-plan office is associated with higher work performance [6-8] and acoustic satisfaction [9-11]. The recent standard, ISO 22955:2021 [12], proposes an important criterion between workstations in open-plan offices that speech intelligibility should be reduced to increase discretion.

1.2 Acoustic parameters affecting speech intelligibility

The Speech Transmission Index (STI) is an objective parameter for evaluating room speech intelligibility [13]. Speech intelligibility can be classified into 11 qualification scales from U ($STI < 0.36$) to A+ ($STI > 0.76$) based on the value of STI, according to the revised standard IEC 60268-16:2020 [13]. An STI above 0.76 implies excellent speech intelligibility, and an STI below 0.36 means nearly unintelligible speech [13]. Both speech-to-noise ratio (SNR) and reverberation time (RT) are key acoustic parameters affecting speech intelligibility in an environment [13, 14].

A high SNR will result in high speech intelligibility (i.e., a large STI value) [15]. Changing the SNR value by introducing masking sounds is a common method for exploring the effects of STI values on work performance and acoustic environmental perceptions. For instance, Haka et al. [11] adjusted the relative levels of speech and masking sound to study the effects of STI conditions (STI=0.10, 0.35, and 0.65) on work performance and subjective speech disturbance. Kang and Ou [9] changed the SNR values to explore the effects of STI conditions (STI = 0.32, 0.50, and 0.67) on the work performance of different task types in Chinese environments. Lou and Ou [10] studied the effects of speech intelligibility on English scientific literature reading by changing the SNR to obtain different STI conditions (STI= 0.08, 0.16, 0.23, 0.34, and 0.78). Jahncke et al. [16] researched the effects of speech intelligibility and office-task characteristics by changing the sound pressure levels of speech and masking sound to determine 5 STI conditions (0.08, 0.16, 0.23, 0.34, and 0.71). The STI value in the studies mentioned above was determined based on Hongisto's method [15] or Houtgast and Steeneken's method [14] by using the values of SNR and early decay times (EDT). The EDT for determining STI values in these studies was very low (approximately 0.31s on average from the 500 to 1000 Hz range), representing an office environment with high sound absorption. It is worth mentioning that few laboratory studies exploring the effects of STI values have been carried out in low absorption environments (i.e., rooms with a long RT) based on the authors' best knowledge. However, not all open-plan offices have high room absorption and a short RT. According to the acoustic measurement results of real open-plan offices in previous studies [17-23], the RT value of real open-plan offices is between 0.2s and 1.5s. Thus, it is necessary to explore the effects of speech intelligibility on work performance and acoustic environmental perceptions in different reverberant environments.

RT is one of the critical acoustic parameters for assessing room acoustic performance. A long RT will reduce speech intelligibility because the speech signal in reverberant environments is covered with multiple reflections, resulting in a smooth waveform profile [24]. Beaman and Holt [24] showed that environments with longer RTs could decrease the speech disturbance of occupants. However, Braat-Eggen et al. [25] revealed that a longer RT could increase the perceived disturbance of speech noise. As mentioned above, RT could affect perceived speech disturbance, but the relationship between RT and perceived speech disturbance is unclear. Moreover, Meng et al. [26] revealed that with the increase in RT of speech, the reaction time for completing visual cognitive work decreases, and the memory accuracy of graphics increases. However, laboratory studies on the effects of the same speech intelligibility (i.e., the same STI value) on work performance and acoustic environment perceptions in different reverberant environments are still lacking.

1.3 Individual factors

The individual factor is a critical non-acoustic factor that affects work performance and perceptions of acoustic environments [27]. The noise sensitivity of occupants is one of the critical individual factors. Lee et al. [28] reported a significant relationship between speech privacy and noise sensitivity. Ellermeier and Zimmer [29] found that participants with high noise sensitivity had lower serial recall performance in a noise environment than participants with low noise sensitivity. The study of Zhang et al. [30] indicated that occupants with low noise sensitivity tend to feel more comfortable with certain masking environments in open-plan offices. However, some studies [25, 31] reported that there was a weak or no correlation between noise sensitivity and work performance and sound disturbance. Other than noise sensitivity, gender has been shown the moderating roles in the effects of acoustic environments on occupants [1, 30, 32]. Pellerin and Candas [33] showed that males prefer less noisy environments than females. Meng et al. [26] reported that gender could affect participants' visual cognitive performance.

1.4 Aim of this study

Against this background, the present study carried out an experiment to investigate the impacts of speech intelligibility in different reverberant environments on work performance and perceptions of acoustic environments. This study also compares the effects of speech environments with the same STI value on participants under different reverberant environments and analyses the impacts of individual factors. The hypothesis of this study can be summarized as follows:

1) The increase in STI values will increase speech disturbance and decrease work performance and acoustic satisfaction, regardless of the room RT.
2) At the same STI condition, participants will be easier affected by speech noise in offices with a short RT than in offices with a long RT.
3) Differences in individual factors (i.e., noise sensitivity and gender) affect work performance and acoustic environment perceptions.

2. Research methods

2.1 Participants

In total, 32 students (14 females and 18 males) aged between 18 and 30 years (mean = 25.91, SD = 3.0) were recruited from the Hong Kong Polytechnic University, Hong Kong. All participants were native Chinese speakers and reported no known hearing problems. Participants were paid 150 Hong

Kong dollars for their participation. The characteristics of the participants are given in Table 1.

Table 1 Characteristics of participants

Characteristics	Group	Number
Gender	Male	18
	Female	14
Noise sensitivity [1]	Low sensitivity [2]	14
	High sensitivity [3]	18

[1]: collected by a questionnaire recommended in ISO 22955:2021 (see Section 2.6);
[2]: Noise-sensitivity score is below the mean score (50.9) of all participants;
[3]: Noise-sensitivity score is over the mean score (50.9) of all participants.

2.2 Laboratory room

A 4.2 (length) x 3.2 (width) x 2.8 m (height) test laboratory was used (Figure 1). As shown in Figure 1, workstations R and E were arranged as the test position and the control console, respectively. There was a 1.5 m high partition between workstations R and E.

During each test session, the room temperature varied between 23 °C and 26 °C. The CO_2 concentrations were maintained at approximately 718-956 ppm. The vertical illumination level of the workstation surface was approximately 534 lx. No glare problems were observed at the testing workstation R (see Figure 1). The background noise level in the laboratory was around 33.3 dBA.

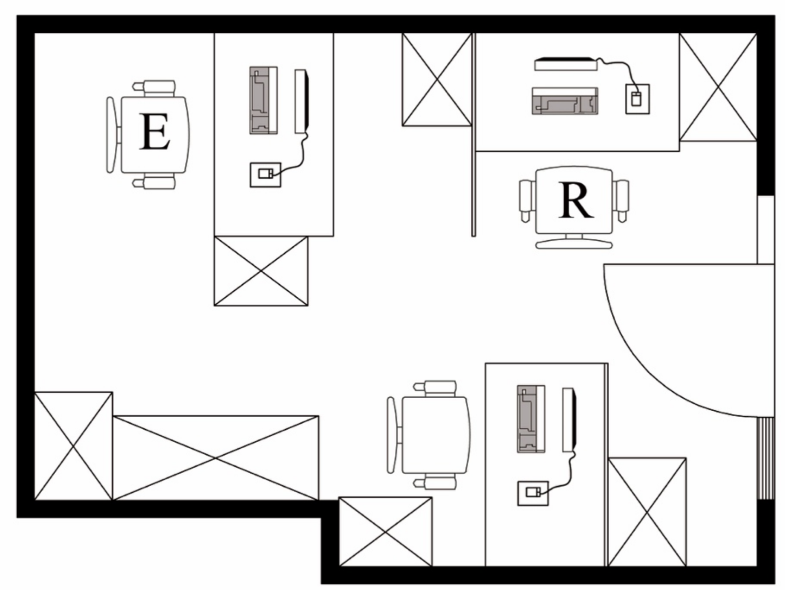

Figure 1 Layout of the test laboratory (Crossed out squares refer to lockers. E and R represent the position of the control console and the test position, respectively).

2.3 Computer simulation

An open-plan office was modelled using Auto CAD and SketchUp software, according to the in-situ measurement results of our recent study [17]. This office (16.9 x 8.4 m^2) for engineers was furnished with a small number of absorption materials in the interior. A 1.7 m high partition was installed between two workstations. The physical acoustic properties and layout of this office space are given in Table 2 and Figure 2, respectively. According to the in-situ measurement results conducted in accordance with ISO 3382-3:2022 [34], the values of the A-weighted sound pressure level at 4 m ($L_{p,A,S,4m}$) and spatial decay rate of speech ($D_{2,S}$) were 53.8 dBA and 3.6 dBA (see Table 2), respectively. Furthermore, the reverberation time (T_{30}) of the office was 0.77s on average over 250 to 4000 Hz octave bands.

Table 2 Physical acoustic properties of the open-plan office.

	$L_{p,A,S,4m}$ /dBA	$D_{2,S}$ /dBA	T_{30} /s
Measurement	53.8	3.6	0.77
Simulation	50.9	3.4	0.76
T_{30} averaged over 250 to 4000 Hz octave bands			

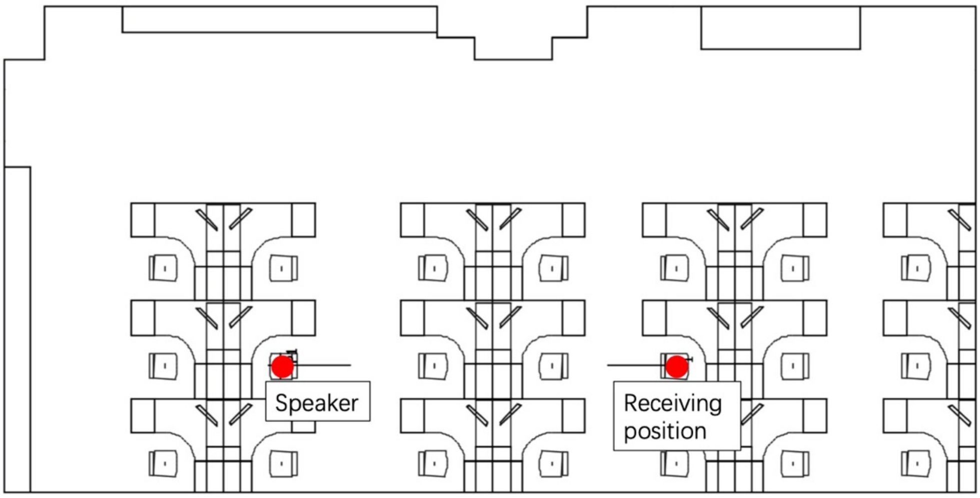

Figure 2 Layout of the simulated open-plan office.

The acoustic simulation was performed using the Odeon software. The acoustic parameters measured in the real office were calculated for the simulated office by specifying the same speaker position and speaker-receiving points as those in the in-situ measurements. Table 2 shows the comparison results of in-situ measurements and simulation. The values of all acoustic parameters differed by 8% or less when compared with the in-situ measurement results.

According to previous studies [17-21, 23, 35-38], which measured acoustic performance in real open-plan offices, the RT of open-plan offices is between 0.2s and 1.5s (see Figure 3). As shown in Figure 3, most open-plan offices have RTs between 0.2s and 0.8s, with a few exceeding 1.0s. This study chose two extreme RTs (i.e., 0.4s and 1.4s) to explore how STI affects work performance and acoustic environment perceptions under different reverberant environments. Considering the objective of auralization, two virtual environments were created by modifying the materials of the walls, ceiling, floor, and furniture. One office model was calculated with sound-absorbing walls, ceiling, floor, and partitions between workstations, resulting in an absorbing environment (reverberation time T_{30}=0.4 s). Another model was calculated with reflecting walls, ceiling, floor, and partitions, resulting in a reverberant environment (T_{30} = 1.4 s). The first model is named the absorbing model, and the latter is called the reverberant model in this study.

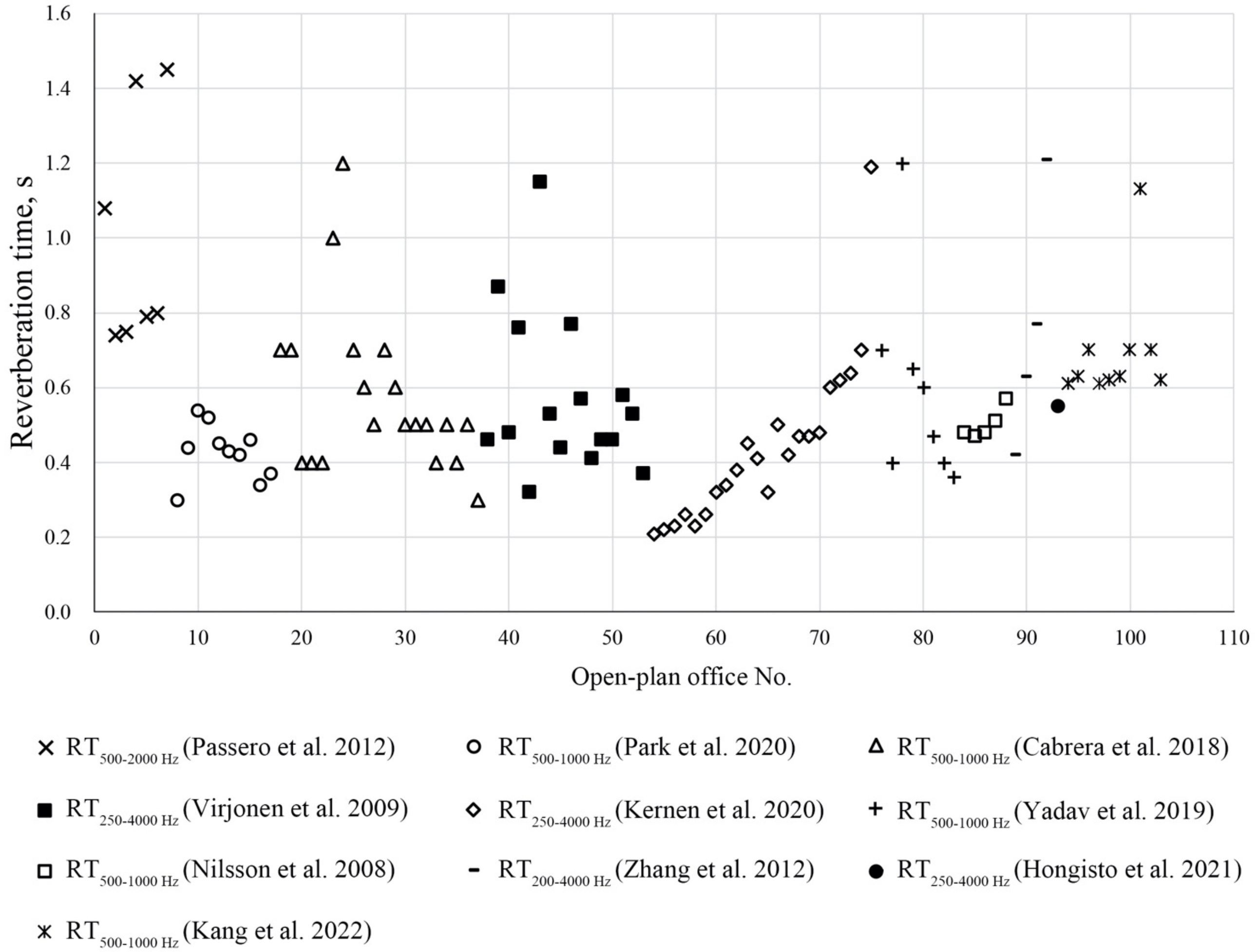

Figure 3 Reverberation time of open-plan offices

2.4 Acoustic conditions

Three STI conditions (i.e., STI of 0.21, 0.42, and 0.61) were created using the absorbing model. Two STI conditions (i.e., STI of 0.21 and 0.42) were created using the reverberant model. The condition of STI 0.61 at RT 1.4s was not made because the STI value cannot exceed 0.60 in the environment with RT 1.4s based on the STI prediction graph shown in Ref. [8, 15]. In this study, the STI was calculated based on the method described by Hongisto et al. [15], which was frequently used in previous studies [10, 11, 30]. Furthermore, a silence condition without playing any sounds was added as a reference. Thus, a total of six acoustic conditions were considered in this study.

The speech materials used in this study were from 14 dry recordings made by female and male native Chinese speakers in an anechoic room before the experiment. These 14 recordings were cut into full-sentenced samples ranging from 10 to 30 seconds long. Five single-speaker speech signals were constructed by randomly inserting a 3- to 10-second-long silence between every two full-sentenced samples. Finally, these five single-speaker speech signals were convolved with the calculated impulse responses between the speaker and receiving positions (Figure 2). In addition, ventilation sound recorded in the field was utilized to change the STI value. These speech and ventilation sounds have been used in our previous studies [9, 10, 30]. Details on speech materials and ventilation sounds were shown in the study of Zhang et al.[30].

The schematic drawing of playing and measuring the test materials is shown in Figure 4. An in-ear microphone (B&K 4101-B) was used to measure the sound pressure level from the headphone (Sennheiser HD 600). All signals were collected from pulse hardware (B&K 3160-B-042) into the computer and analyzed by the Pulse LabShop. The Sennheiser HD 600 was not equalized before the experiment, as Odeon could compensate for its non-linear frequency response. Table 3 shows the acoustic parameters of each acoustic condition. Figure 5 shows the sound levels of the speech at the receiver position in each acoustic condition and the sound level of the ventilation noise in Abs_0.61. "Abs" refers to absorbing environments, and "0.61" refers to the STI value in Abs_0.61. Figure 6 shows the T_{30} values by 1/1 octave bands for the absorbing and reverberant models.

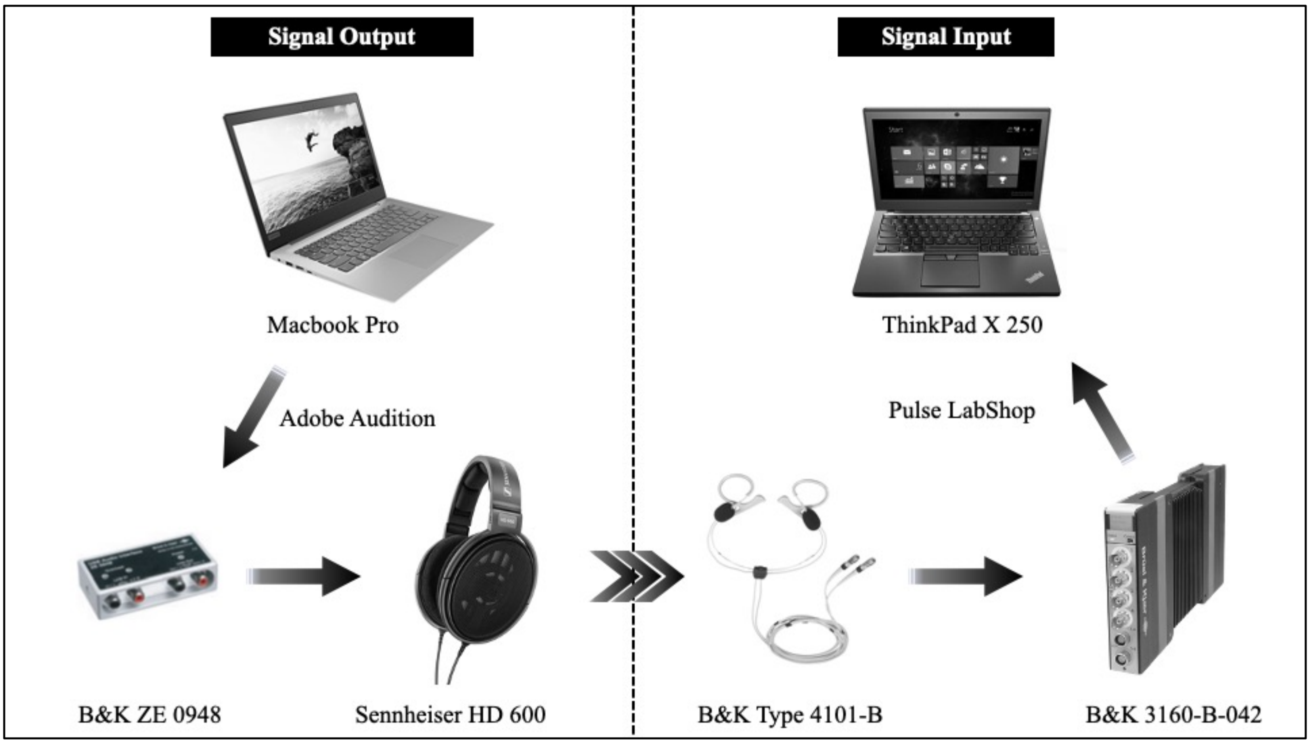

Figure 4 Schematic drawing of measuring the test material

Table 3 Acoustic parameters of each acoustic condition depended on two models. Abs and Rev refer to the absorbing and reverberant environments, respectively.

Model	Office conditions	$L_{A,S}$[1] dBA	$L_{p,A,B}$[2] dBA	$L_{Aeq,total}$[3] dBA	SNR[4] dBA	EDT[5] s	T_{30}[6] s	STI[7]
Absorbing model	Abs_0.21	49.2	51.1	51.8	-1.9	0.36	0.40	0.21
	Abs_0.42	50.8	45.4	52.4	5.4	0.36	0.40	0.42
	Abs_0.61	54.2	35.7	54.5	18.5	0.36	0.40	0.61
	Rev_0.21	50.0	49.3	52.8	0.7	1.40	1.37	0.21

Reverberant model	Rev_0.42	49.6	35.4	50.1	14.2	1.40	1.37	0.42
Silence[8]		--	33.3	33.3	--	--	--	--

Note:
[1] The A-weighted sound pressure level of speech;
[2] The A-weighted sound pressure level of ventilation noise;
[3] The total sound pressure level;
[4] Speech-to-noise ratio;
[5] EDT averaged over 250 to 4000 Hz octave bands of the receiving position (see Figure 2);
[6] T_{30} averaged over 250 to 4000 Hz octave bands of each office model;
[7] STI was determined based on the method described by Hongisto et al. [15] using EDT values and SNR.
[8] $L_{p,A,B}$ in silence refers to the ambient noise of the laboratory test room.

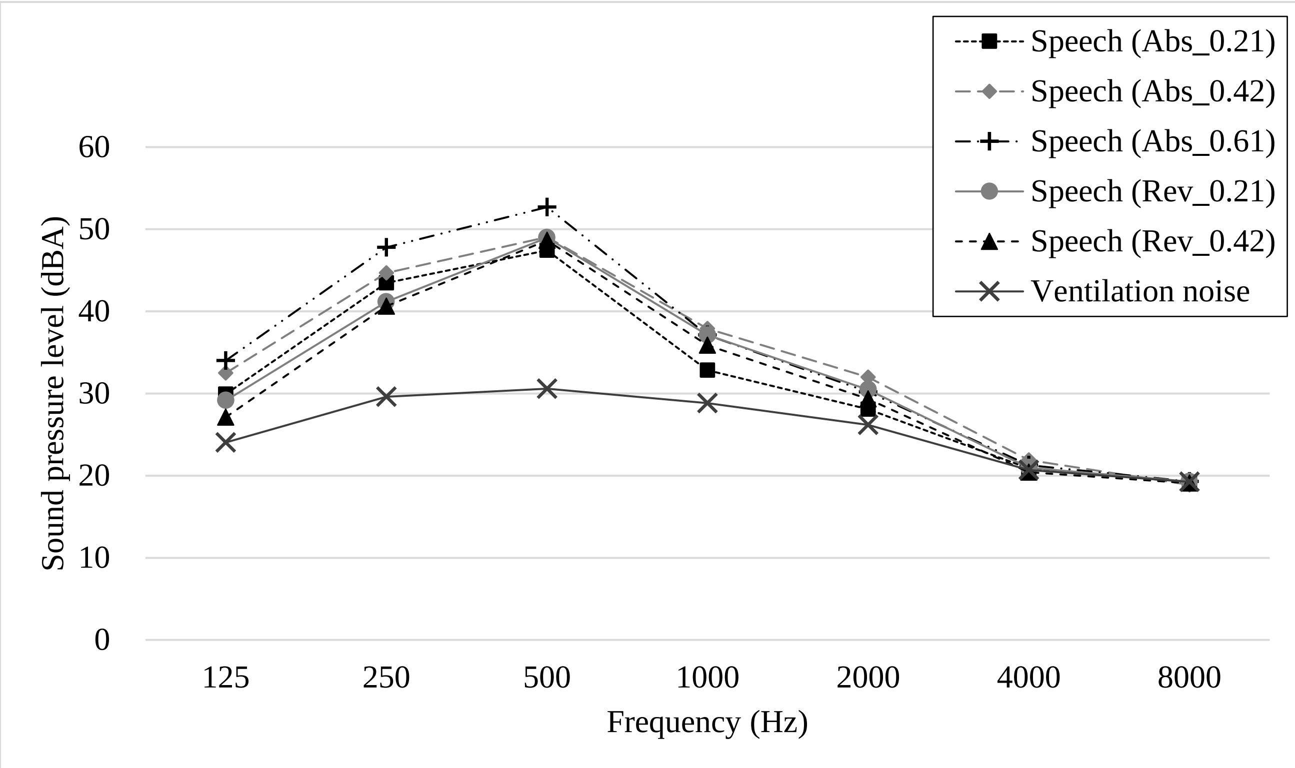

Figure 5 Average sound pressure levels of speech and ventilation noises.

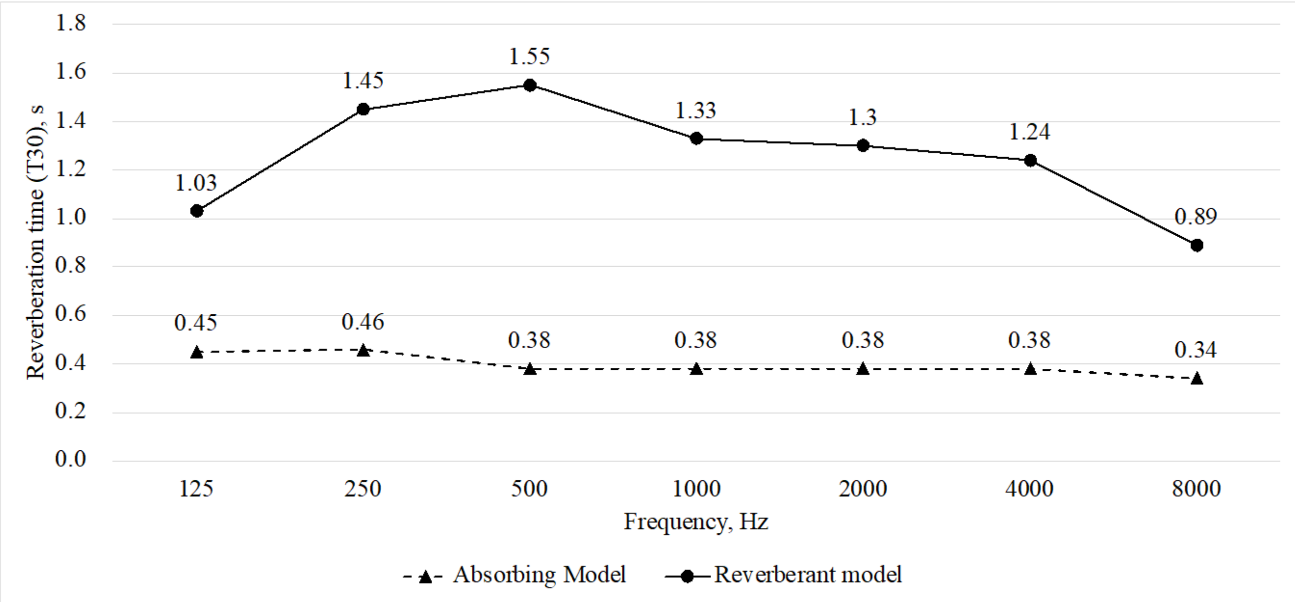

Figure 6 T_{30} values by 1/1 octave bands for the absorbing and reverberant models

2.5 Cognitive task

The serial recall task is a common cognitive task which is frequently used to study work performance in offices [11, 39, 40]. It was utilized in this study. In the current study, each serial recall task included ten number sequences. For each sequence, nine numbers from 0 to 9 were sequentially displayed on the computer screen (0.5s on and 0.5s off) in random order. After all numbers were displayed, participants were asked to recall and type the nine numbers they saw in order of appearance within 19 seconds on the keyboard. A Chinese exam website (you kao shi) was used to complete the serial recall task. The following two scores were considered: (1) accuracy rate (%); and (2) reaction time (i.e., the mean response time in seconds for recalling all numbers). Reaction time was calculated by subtracting the display time for all numbers from the total completion time recorded on the exam website.

2.6 Questionnaire

In this study, two questionnaires were used to collect the basic information on participants and the self-rating scores of subjective variables about participants' experiences during the serial recall task. Questionnaire 1 (Q1) collected the individual information of the participants, such as age, gender, noise sensitivity, and whether they had hearing problems or not. The self-rated noise sensitivity was evaluated by a questionnaire suggested by ISO 22955:2021[12]. The noise sensitivity was assessed on the basis of twelve statements in which the participants needed to indicate to what extent they agreed with these statements (see supplemental Appendix A.). All statements were responded on a 6-point Likert scale ranging from 1 (strongly disagree) to 6 (strongly agree).

Questionnaire 2 (Q2) was designed to collect subjective work performance, acoustic environment perceptions (i.e., speech disturbance, adaptability to the acoustic condition, and acoustic satisfaction), and the mental workload during the testing. Subjective work performance and speech disturbance were evaluated using questions answered on a 5-point Likert scale from 1 (very low) to 5 (very high), adaptability to the acoustic condition (i.e., acoustic adaptability) from 1 (unable to adapt) to 5 (easy to adapt), and acoustic satisfaction from 1 (very dissatisfied) to 5 (very satisfied). The mental workload of the serial recall task under each acoustic condition was measured using the NASA task load index (NASA-TLA) [41], which is a common scale used for measuring the participants' workload during testing and was frequently utilized in previous studies [40, 42-44]. The six items of NASA-TLA (i.e., mental and physical demands, time pressure (i.e., temporal demand), overall performance, effort, and frustration) were evaluated on a 10-point scale ranging from 1 (very low) to 10 (very high). The sum of all the item scores was calculated to show the mental workload of the participants.

2.7 Experimental procedure

The experiment was carried out in a Hong Kong Polytechnic University laboratory from August to September 2022. The experiment consisted of two stages: preparation and formal testing, which is similar to our recent study [45]. Figure 7 shows the experimental procedure.

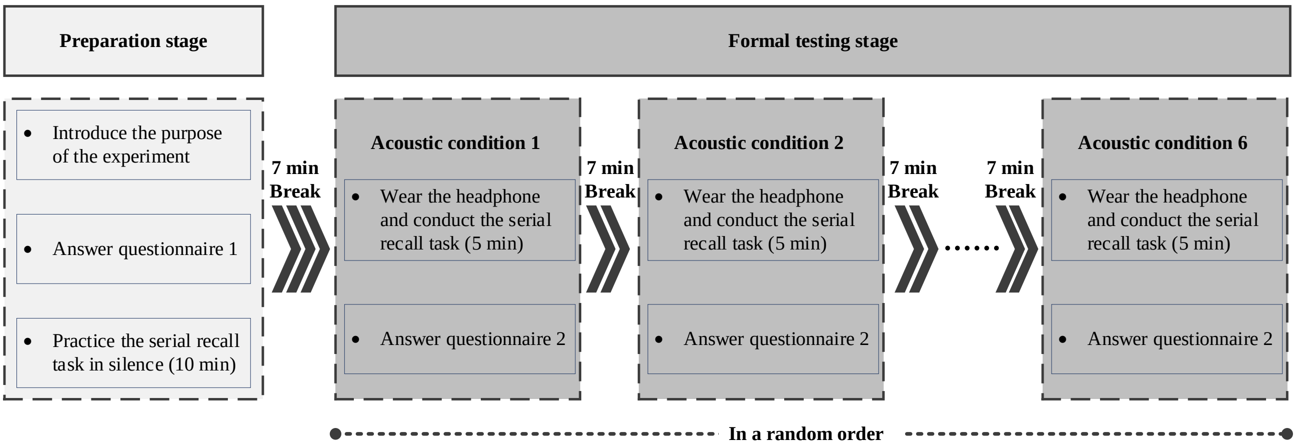

Figure 7 Experimental procedure

During the preparation stage, participants were told the goal of this experiment, but no details of acoustic conditions were given. They then completed a basic questionnaire (Q1). Finally, they practised the tasks in silence for ten minutes, becoming familiar with the test requirements.

During the formal testing stage, all STI conditions were played back through headphones (Sennheiser HD 600). In silence, participants were asked to wear headphones even though no sounds were played. Participants conducted the serial recall tasks under six acoustic conditions (silence and 5 STI conditions) in random order and then completed a questionnaire (Q2). The tests for each acoustic condition lasted approximately 8 minutes, with a seven-minute break between each test.

The experiment lasted approximately 1 hour and 40 minutes. All the acoustic conditions were controlled by the researcher seated in workstation E (see Figure 1). One participant was tested at a time. After the experiment was over, participants were given more information about this study.

2.8 Statistical analysis

SPSS Statistics software was used to analyze the data. The normality of objective results (i.e., accuracy rate and reaction time) was calculated using the Shapiro–Wilk test, which demonstrated that the accuracy rate and reaction time obeyed a normal distribution under all acoustic conditions. The serial recall task was analyzed using repeated measures of analysis of variance (RM ANOVA) tests with objective results (accuracy rates and reaction time) as within-subject variables and acoustic conditions as between-subject variables. F (F-ratio [46]) is calculated by dividing the mean square between groups by the mean square within groups. Partial η^2 is a measure of the effect size, representing the ratio of the sum of squares of the effect to the sum of squares of the effect and the error sum of squares [47]. Moreover, a follow-up pairwise comparison was carried out by using the post-hoc test with Bonferroni correction to determine in which significant differences occur. Two-way Friedman tests were performed on the participants' subjective rating results, followed by paired comparisons with Bonferroni correction. Paired-sample t-tests and Wilcoxon tests were utilized to determine the differences between the absorbing and reverberant environments concerning work performance, reaction time, and perceptions of acoustic conditions.

Participants were divided into two groups using the mean noise-sensitivity score of all participants (50.9) as the cut-point. There are 14 low-sensitivity and 18 high-sensitivity participants (see Table 1). Independent-sample T-tests and Mann-Whitney U-tests were performed to determine the effects of individual factors (gender and noise sensitivity) on participants' objective results (accuracy rate and reaction time) and subjective results (subjective work performance, mental workload, time pressure, speech disturbance, acoustic adaptability and satisfaction).

3. Results

3.1 Effects of STI in the absorbing environment (RT = 0.4 s)

3.1.1 Objective and subjective performance

The objective performance (accuracy rates) and subjective performance of participants under the silence and three STI conditions (i.e., STI = 0.21, 0.42, and 0.61) in the absorbing environment (i.e., RT = 0.4 s) are shown in Figure 8. Figure 8 also shows the mean score of the mental workload in each condition. A higher score means a higher mental workload.

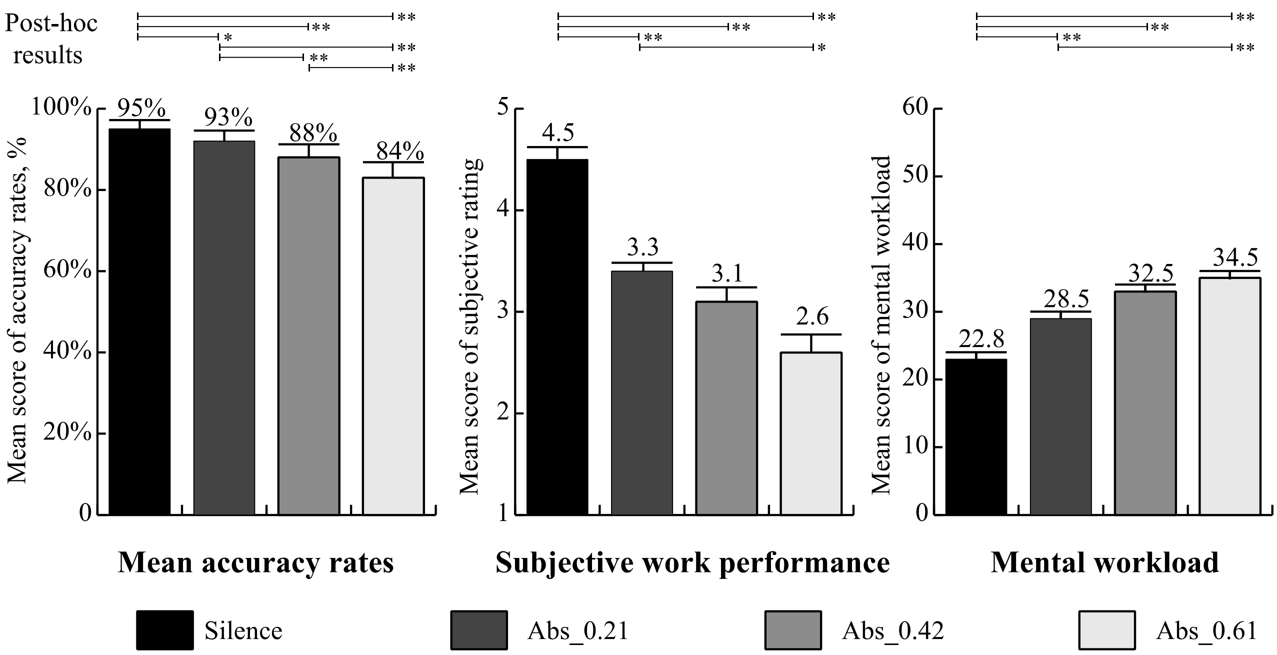

Figure 8 Mean score of objective performance and subjective evaluation results of participants in the silence and 3 STI conditions in the absorbing environment (error bars define standard errors. * refers to Bonferroni P-value<0.05. ** refers to Bonferroni P-value<0.01).

For the objective performance, as expected, the average accuracy rates decrease with increasing STI values (Figure 8). Mauchly's test for sphericity was not significant (P-value>0.05). RM ANOVA test revealed a significant main effect of acoustic condition on accuracy rates of the serial recall task

($F_{3,93}$=39.927, P-value=0.000, and partial η^2=0.563). Moreover, post-hoc tests (Bonferroni) showed that 1) The average accuracy rate in silence was significantly higher than that in Abs_0.21 (P-value<0.05), Abs_0.42 (P-value<0.01) and Abs_0.61 (P-value<0.01). 2) The average accuracy rate in Abs_0.21 was significantly higher than that in Abs_0.42 (P-value<0.01) and Abs_0.61 (P-value<0.01). 3) The average accuracy rate in Abs_0.42 was significantly greater than that in Abs_0.61 (P-value<0.01).

For subjective perceptions, with the increase in the STI, the subjective work performance of participants decreases, and the mental workload increases (Figure 8). Friedman tests showed that the STI condition had significant effects on subjective work performance (P-value<0.01) and mental workload (P-value<0.01). Subsequently, pairwise comparisons were performed, and the results can be summarised as follows: 1) The mean score of subjective work performance was significantly higher in silence than in the three STI conditions (P-value<0.01 for all comparisons) and statistically higher in Abs_0.21 than in Abs_0.61 (P-value<0.05). 2) The mean mental workload score was statistically lower in silence than in the three STI conditions (P-value<0.01 for all comparisons) and significantly lower in Abs_0.21 than in Abs_0.61 (P-value<0.01).

3.1.2 The reaction time

The mean reaction time and subjective time pressure results under the silence and three STI conditions (i.e., STI=0.21, 0.42, and 0.61) in the absorbing environment (RT=0.4 s) are displayed in Figure 9. As shown in Figure 9, the mean reaction time and subjective time pressure increase with the increase in STI values. A significant main effect of STI condition on the reaction time to complete the serial recall task ($F_{3,93}$=10.466, P-value=0.000, partial η^2=0.252) was revealed by RM ANOVA tests.

Additionally, post-hoc tests (Bonferroni) revealed that the mean reaction time was significantly higher in silence than in Abs_0.21 (P-value<0.05), Abs_0.42 (P-value<0.01), and Abs_0.61 (P-value<0.01). Friedman tests showed significant differences in subjective time pressure (p-value<0.01) among the four conditions (silence, Abs_0.21, Abs_0.42, and Abs_0.61). Subsequently, pairwise comparisons were carried out, and the results revealed that the mean score of subjective time pressure was statistically lower in silence than in Abs_0.21 (P-value<0.05), Abs_0.42 (P-value<0.01) and Abs_0.61 (P-value<0.01).

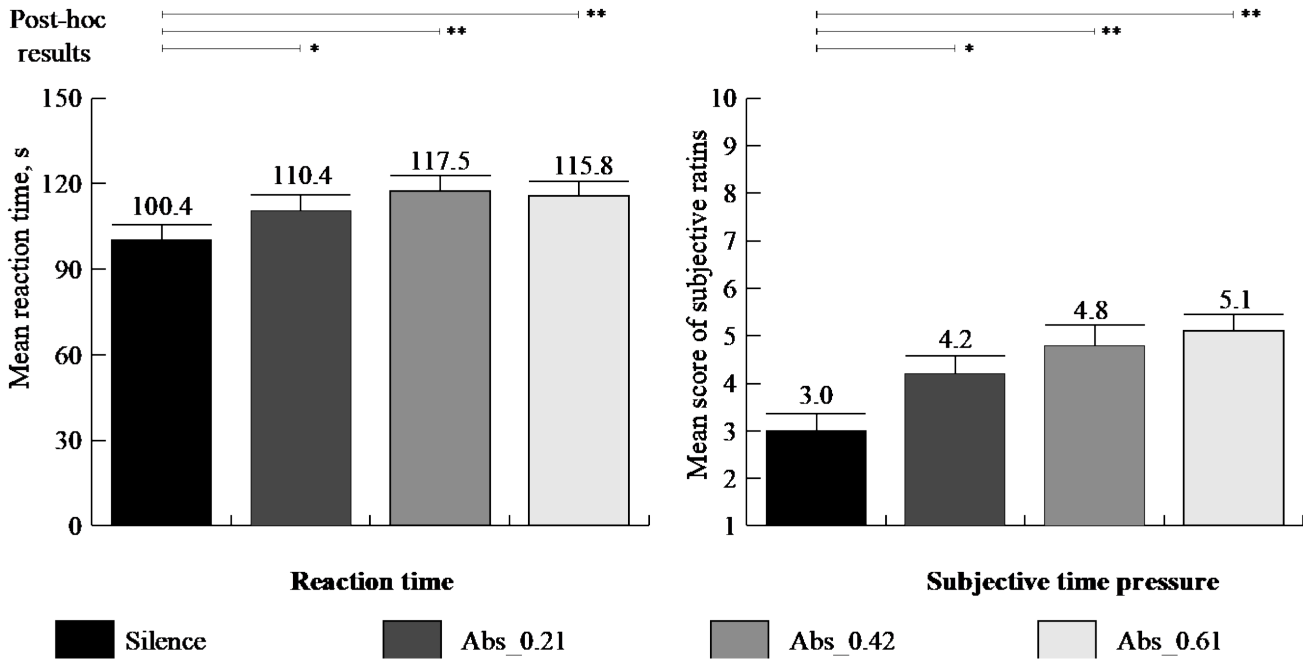

Figure 9 Mean reaction time and the mean score of the subjective time pressure in the silence and 3 STI conditions in the absorbing environment (error bars define standard errors. * refers to Bonferroni P-value<0.05. ** refers to Bonferroni P-value<0.01).

3.1.3 Perceptions of acoustic conditions

The subjective condition evaluations (acoustic adaptability, acoustic satisfaction, and speech disturbance) of participants in the four conditions are shown in Figure 10. With the STI increasing, the mean scores of acoustic adaptability and satisfaction decrease, and the mean scores of speech disturbance increase (see Figure 10). Friedman tests revealed that the STI condition had significant effects on acoustic adaptability (P-value<0.01), acoustic satisfaction (P-value<0.01), and speech disturbance (p-value<0.01). Subsequently, pairwise comparisons were performed. The mean scores of subjective acoustic evaluations, displayed in Figure 10, and the analysis of post-hoc tests can be summarised as follows: 1) The mean score of acoustic adaptability was statistically higher in silence than in the three STI conditions (i.e., Abs_0.21, Abs_0.42, and Abs_0.61) (P<0.01 for all comparisons). 2) The mean score of acoustic satisfaction was statistically higher in silence than in the three STI conditions (P<0.01 for all comparisons). 3) The mean speech disturbance score was significantly lower in silence than in the three STI conditions (P<0.01 for all comparisons) and significantly lower in Abs_0.21 than in Abs_0.42 (P-value<0.05) and Abs_ 0.61 (P-value<0.01).

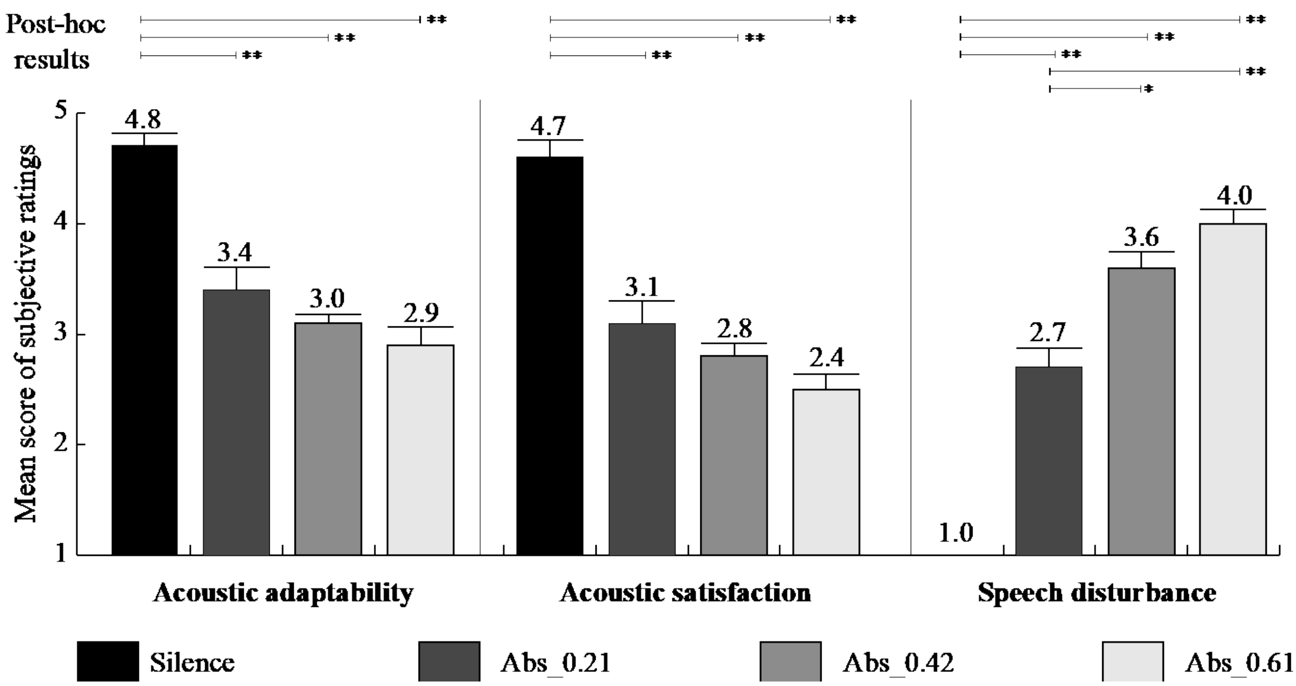

Figure 10 Subjective condition evaluations of participants in the silence and 3 STI conditions in the absorbing environment (error bars define standard errors. * refers to Bonferroni P-value<0.05. ** refers to Bonferroni P-value<0.01).

3.2 Effects of STI in the reverberant environment (RT = 1.4 s)

3.2.1 Objective and subjective performance

The objective performance (accuracy rates) and subjective work performance of participants under the silence and two STI conditions (i.e., Rev_0.21 and Rev_0.42) in the reverberant environment (RT = 1.4 s) are shown in Figure 11. Furthermore, the mean score of the mental workload, measured with the NASA-TLX, in each condition is also displayed in Figure 11.

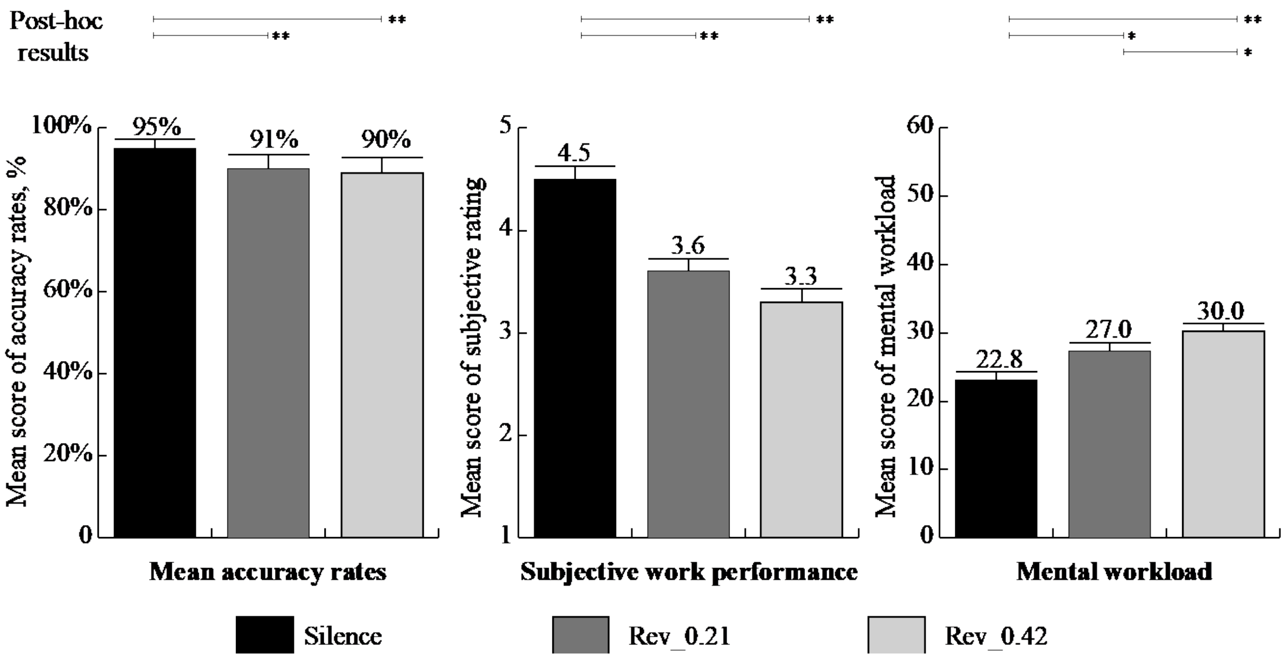

Figure 11 Mean score of objective performance and subjective evaluation results of participants in the silence and two STI conditions in the reverberant environment (error bars define standard errors. * refers to Bonferroni P-value<0.05. ** refers to Bonferroni P-value<0.01).

For the objective performance, the accuracy rates decrease when the STI increases (Figure 11). Mauchly's test for sphericity was not significant (P-value>0.05). RM ANOVA test revealed a significant main effect of acoustic condition on accuracy rates of the serial recall task ($F_{2,62}$=11.627 P-value=0.000, and partial η^2=0.273). Moreover, post-hoc tests (Bonferroni) showed that the average accuracy rate in silence was significantly higher than that in Rev_0.21 (P-value<0.01) and Rev_0.42 (P-value<0.01). However, no significant differences were observed between Rev_0.21 and Rev_0.42 (P-value>0.05).

For subjective perceptions, as expected, with the increase in the STI, the subjective work performance of participants decreases, and the mental workload increases (Figure 11). Friedman tests showed that the STI condition had significant effects on subjective work performance (P-value<0.01) and mental workload (P-value<0.01). Subsequently, pairwise comparisons were conducted, and the results can be summarised as follows: 1) The mean score of subjective work performance was significantly higher in silence than in the two STI conditions (P-value<0.01 for all comparisons). 2) The mean mental workload score was statistically lower in silence than in the Rev_0.21 (P-value<0.05) and Rev_0.42 (P-value<0.01) and significantly lower in Rev_0.21 than in Rev_0.42 (P-value<0.05).

3.2.2 The reaction time

The mean reaction time and subjective time pressure results under the silence and two STI conditions (i.e., Rev_0.21 and Rev_0.42) in the reverberant environment (RT =1.4 s) are displayed in Figure 12. The mean score of subjective time pressure increases with the increase in STI values (see Figure 12). A significant main effect of STI condition on the reaction time to complete the serial recall task ($F_{2,62}$=8.24, P-value=0.001, partial η^2=0.210) was revealed by RM ANOVA tests. Additionally, post-hoc tests (Bonferroni) revealed that the mean reaction time was significantly higher in silence than in Rev_0.21 and Rev_0.42 (P-value<0.01 for all comparisons). Friedman tests showed significant differences in subjective time pressure (p-value<0.01) among the three conditions (silence, Rev_0.21, and Rev_0.42). Subsequently, pairwise comparisons revealed that the mean score of subjective time pressure was statistically lower in silence than in Rev_0.42 (P-value<0.01).

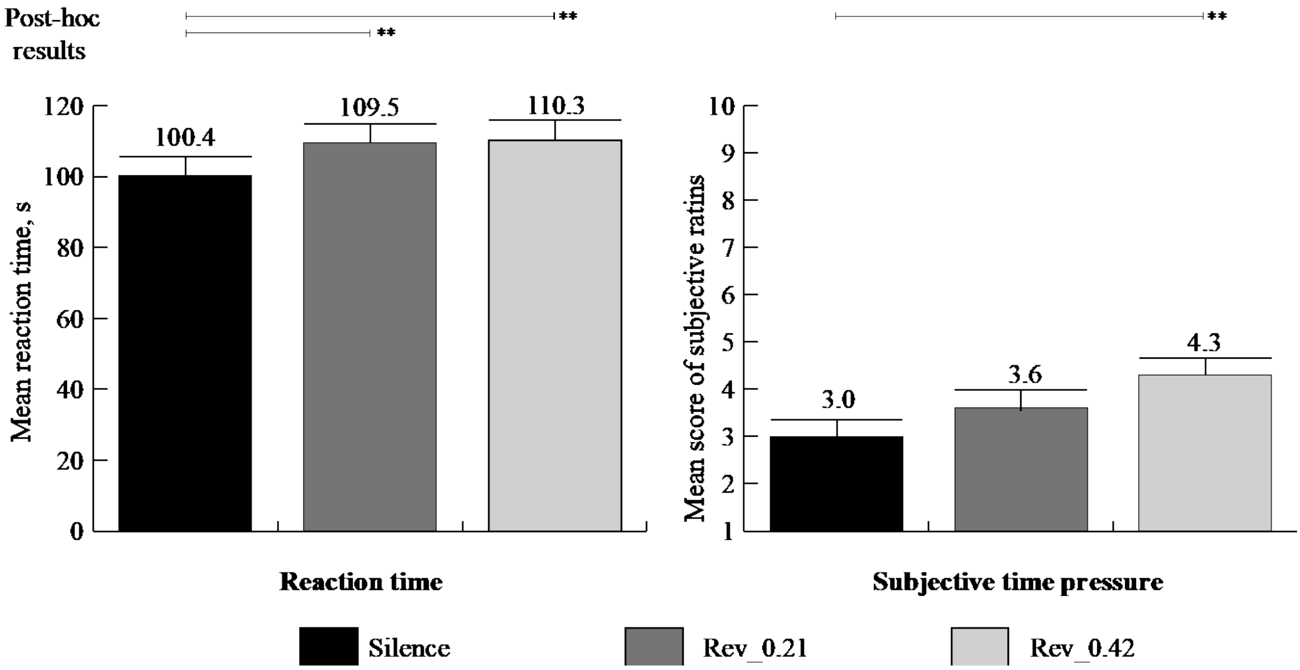

Figure 12 Mean reaction time and the score of the subjective time pressure of participants in the silence and two STI conditions in the reverberant environment (error bars define standard errors. ** refers to Bonferroni P-value<0.01).

3.2.3 Perceptions of acoustic conditions

The subjective condition evaluations (acoustic adaptability, acoustic satisfaction, and speech disturbance) of participants in the three conditions are shown in Figure 13. With the STI increasing, the mean score of acoustic satisfaction decreases, and the mean score of speech disturbance increases (see Figure 13). Friedman test revealed that the STI condition had significant effects on acoustic adaptability (P-value<0.01), acoustic satisfaction (P-value<0.01), and speech disturbance (p-value<0.01). Subsequently, pairwise comparisons were performed. The mean scores of subjective acoustic evaluations, displayed in Figure 13, and the analysis of post-hoc tests can be summarised as follows: 1) The mean score of acoustic adaptability was statistically higher in silence than in Rev_0.21 and Rev_0.42 (P<0.01 for all comparisons). 2) The mean score of acoustic satisfaction was statistically higher in silence than in Rev_0.21 and Rev_0.42 (P<0.01 for all comparisons). 3) The mean speech disturbance score was significantly lower in silence than in Rev_0.21 and Rev_0.42 (P<0.01 for all comparisons) and was lower in Rev_0.21 than in Rev_0.42 at marginally significant levels (P-value=0.086).

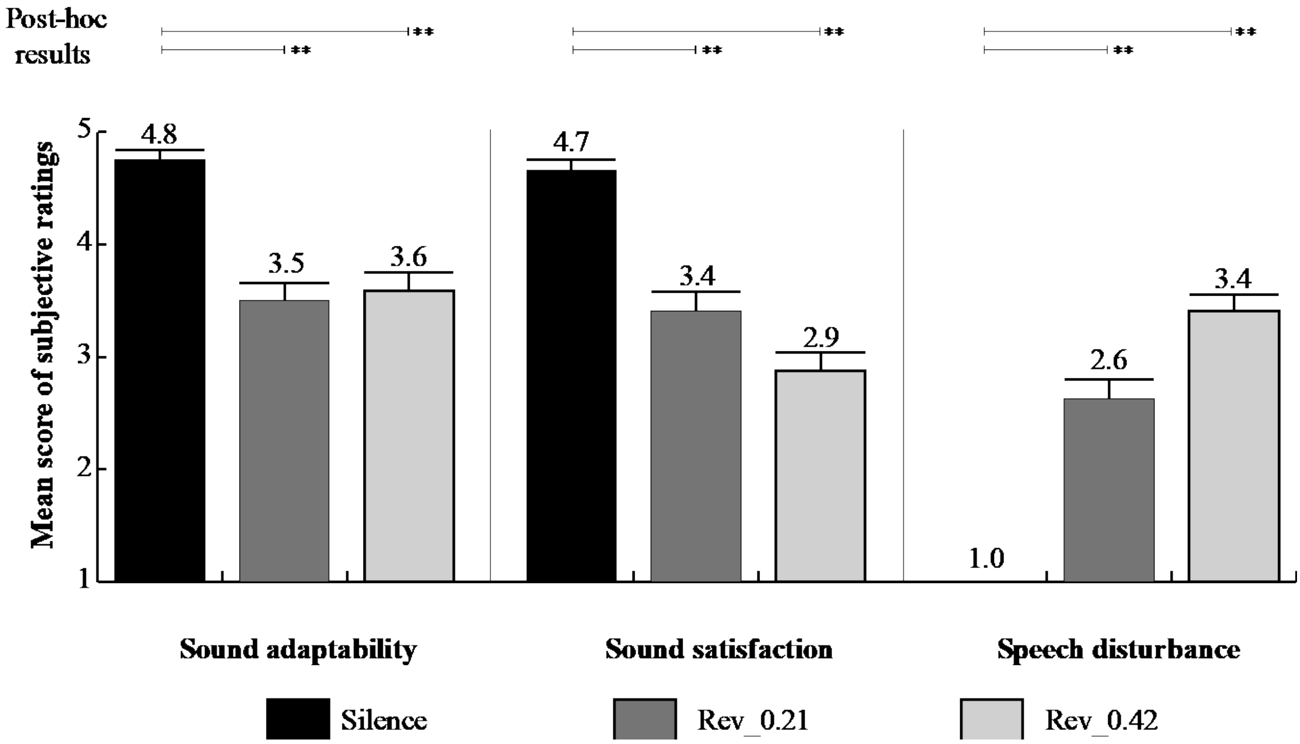

Figure 13 Subjective condition evaluations of participants in the silence and two STI conditions in the reverberant environment (error bars define standard errors. ** refers to Bonferroni P-value<0.01).

3.3 Comparison of work performance and acoustic environment perceptions between the absorbing and reverberant environments

Paired-sample t-tests and Wilcoxon tests were conducted to determine the effects of reverberation time at the same STI level concerning objective results (i.e., accuracy rates and reaction time) and subjective evaluations. The comparative results are given in Table 4.

Table 4 Comparative results (P-values) between two RT conditions

Items	STI=0.21		P-value	STI=0.42		P-value
	Abs_0.21	Rev_0.21		Abs_0.42	Rev_0.42	
Accuracy rate [1]	93%	91%	0.289	88%	90%	0.222
Subjective work performance[2]	3.3	3.6	0.207	3.1	3.3	0.138
Mental workload[2]	28.5	27.0	0.121	32.5	30.0	**0.019***
Reaction time[1]	110.4	109.5	0.662	117.5	110.3	**0.041***
Subjective time pressure[2]	4.2	3.6	**0.084**	4.8	4.3	**0.057**
Acoustic adaptability[2]	3.4	3.5	0.875	3.0	3.6	**0.001****
Acoustic satisfaction[2]	3.1	3.4	0.128	2.8	2.9	0.378
Speech disturbance[2]	2.7	2.6	0.913	3.6	3.4	0.319

Note:
[1]: Paired-samples t-tests;
[2]: Wilcoxon tests;
*: P<0.05;
**:P<0.01;
P-values<0.09 are presented in bold.

Both at STI of 0.21 and 0.42, the mean scores of the mental workload, reaction time, subjective time pressure, and speech disturbance were higher in the absorbing environment (RT=0.4s) than in the reverberant environment (RT=1.4s), while the mean scores of subjective work performance, acoustic adaptability and satisfaction were lower in the absorbing environment (see Table 4). According to the results of paired-samples t-tests and Wilcoxon tests in Table 4, it can finally be summarized as follows: 1) The mean score of the mental workload in Abs_0.42 (32.5) was significantly higher than that in Rev_0.42 (30.0) (P-value<0.05). 2) The mean reaction time in Abs_0.42 (117.5 s) was significantly larger than that in Rev_0.42 (110.3 s) (P-value<0.05). 3) The mean scores of subjective time pressure in Abs_0.21 and Abs_0.42 were higher than those in Rev_0.21 and Rev_0.42, respectively, at marginal significance levels (P-value<0.09). 4) The mean score of acoustic adaptability was significantly lower in Abs_0.42 (3.0) than in Rev_0.42 (3.6) (P-value<0.01). These results imply that under the STI of 0.42, participants in the long reverberant environment had lower mental workload, faster completion speed of tasks, less subjective time pressure and higher acoustic adaptability.

3.4 Effects of individual factors

Independent-Sample T-tests and Mann-Whitney U-tests were used to show the effects of noise sensitivity and gender. The calculated results are given in Table 5, but only outcome measures for which significant differences were found (P-value<0.05) are shown. In silence, no significant differences were found between different noise sensitivities and between genders in all outcome measures. In the STI conditions, the effects of noise sensitivity and gender can be summarized as follows:

For different noise sensitivity, low-sensitivity participants tend to have higher acoustic adaptability and satisfaction than high-sensitivity participants (see Table 5). Significant differences between low- and high-sensitivity were found in acoustic adaptability and satisfaction under the condition of Abs_0.61 (P-value<0.05, table 5). Concerning other outcome measures (e.g., accuracy rate, reaction time, mental workload, speech disturbance, etc.), the analyses revealed no statistically significant difference between low- and high-sensitivity groups both in the absorbing and reverberant environments.

For different genders, female participants had higher acoustic adaptability and satisfaction than male participants, but male participants' serial recall task was completed faster than female participants (see Table 5). There were significant differences between males and females concerning the reaction time under the condition of Abs_0.61 (P-value<0.01) and acoustic adaptability under the condition of Abs_0.21(P-value<0.05). In addition, borderline-significant differences were shown between different genders concerning the reaction time under the condition of Rev_0.42 (P-value=0.052), acoustic adaptability under the condition of Abs_0.42 (P-value=0.054), and acoustic satisfaction under the condition of Abs_0.21 (P-value=0.056).

Table 5 Mean scores for reaction time, acoustic adaptability and satisfaction in the noise sensitivity and gender groups

		Absorbing environments			Reverberant environments	
		Abs_0.21	Abs_0.42	Abs_0.61	Rev_0.21	Rev_0.42
Mean scores of the reaction time	Low-sensitivity	109.9	110.5	111.6	118.3	121.4
	High-sensitivity	110.8	108.7	119.3	116.9	111.3
	P-value [1]	0.936	0.863	0.838	0.901	0.326
	Male	104.4	111.7	103.5	102.0	101.1
	Female	118.0	125.0	131.5	119.1	122.1
	P-value [1]	0.232	0.100	**0.004****	0.212	**0.052**
Mean scores of the acoustic adaptability	Low-sensitivity	3.7	3.3	3.3	3.4	3.9
	High-sensitivity	3.2	2.8	2.6	3.6	3.4
	P-value [2]	0.202	0.133	**0.035***	0.800	0.164
	Male	3.1	2.8	2.8	3.4	3.4
	Female	3.9	3.4	2.9	3.6	3.9
	P-value [2]	**0.018***	**0.054**	0.721	0.311	0.164
Mean scores of the acoustic satisfaction	Low-sensitivity	3.3	2.8	2.9	3.4	3.1
	High-sensitivity	2.9	2.7	2.1	3.4	2.7
	P-value [1]	0.409	0.749	**0.035***	0.627	0.397
	Male	2.8	2.5	2.3	3.2	2.6
	Female	3.5	3.1	2.6	3.7	3.2
	P-value [2]	**0.056**	0.093	0.454	0.085	0.121

Note:
[1] Independent-Sample T-test;
[2] Mann-Whitney U test;
* P-value<0.05;
P-values<0.06 are presented in bold.

4. Discussion

One purpose of this study was to determine the effects of STI on work performance and perceptions of acoustic environments under absorbing and reverberant environments (RT=0.4s and 1.4s). Thus, participants conducted a serial recall task while exposed to silence and five STI conditions.

4.1 Effects of STI in different RT environments

The results show that silence was the most appreciated condition regarding all the objective and self-estimated variables. In the absorbing environment (RT=0.4s), as expected, the increase in STI values increases speech disturbance and decreases work performance. The accuracy rate of participants significantly decreased when the STI increased from 0.21 to 0.61, which is in agreement with previous studies [10, 11, 16] in which experiments exploring the impact of speech intelligibility on task performance were carried out under absorbing environments (RT<0.4s).

In the reverberant environment (RT=1.4s), when STI increased from 0.21 to 0.42, a significant increase was only observed in perceived mental workload, while significant differences were not found in other outcome measures. These results are inconsistent with our expectations. In particular, no significant differences were found in the accuracy rate between Rev_0.21 and Rev_0.42. It seems a little surprising because the differences in STI values are the same under absorbing and reverberant environments. However, significant differences were observed in the accuracy rate of the serial recall task between Abs_0.21 and Abs_0.42. Moreover, the SNR difference between Abs_0.21 and Abs_0.42 was smaller than that between Rev_0.21 and Rev_0.42 (see Table 3). According to the study of Ranz et al. [48], a high SNR will result in low work performance and increased sound annoyance. A possible explanation for this could be the effects of room reverberation time. Some previous studies [49, 50] found that the listening effort of speech will increase with the increase in room reverberation. Moreover, according to the experimental results of Rennies et al. [51], even under the same STI condition, the listening effort does not decrease with increasing SNR due to the impacts of RT. That is, it may be more difficult for participants to understand speech content in a long reverberant environment, especially when concentrating on completing tasks. Thus, the accuracy rate of the serial recall task in Rev_0.42 (90%) was not significantly lower than that in Rev_0.21 (91%).

4.2 Effects of reverberation time on the dependent variables

Both RT and SNR are key factors affecting the STI value and thus could impact work performance and acoustic environment perceptions. A longer reverberation time in a room or a smaller SNR value can reduce speech intelligibility [15]. As shown in Table 4, significant differences were found between the absorbing and reverberant environments in terms of mental workload, reaction time, and acoustic adaptability in the STI of 0.42. In this study, the SNR of Abs_0.42 was 8.8 dBA lower than that of Rev_0.42, but participants in Rev_0.42 had lower mental workload and were easier to adapt to the sound environment compared with Abs_0.42 (Table 4). This implies that a longer reverberant environment could reduce some of the negative effects of speech at an STI of 0.42. As recommended in IEC 60268-16:2020 [13], an STI of 0.42 means that speech intelligibility is at level I. That is to say, a long RT is beneficial for reducing mental workload and increasing sound adaptability when room speech intelligibility is at level I.

4.3 Effects of the individual factors

Pierrette et al. [2] found that noise sensitivity significantly affects occupants' noise annoyance in open-plan offices. Zimmer and Ellermeier [52] showed a weak relationship between noise sensitivity and work performance in noisy environments. Haapakangas et al. [42] showed that high-sensitivity occupants are more impacted by speech than low-sensitivity occupants concerning work performance and subjective reactions to noise. Similarly, the results of this study indicate that the low-sensitivity participants have higher acoustic satisfaction both in the absorbing and reverberant environments compared to the high-sensitivity participants, although significant differences were only found under the condition of Abs_0.61. However, no influence of noise sensitivity on work performance was found in this study, which is consistent with previous studies [11, 53]. Concerning different gender groups, this study shows that male participants in STI conditions show lower acoustic satisfaction and adaptability than females (Table 5), which is in agreement with Pellerin and Candas [33].

4.3 Limitations

One of the limitations of the present study is that measurement points between RT 0.4 s and 1.4 s were not included. One of the main objectives was to explore whether the reverberation time could affect work performance and acoustic environmental perceptions under the same STI condition. Thus, two extreme sound-absorbing models (RT=0.4 s and 1.4 s) were built. According to the findings in this study, changing the room RT could alter the influence of speech intelligibility on occupants. However, this effect of RT does not seem to happen in the condition with low speech intelligibility. As shown in Figure 3, the RTs of most open-plan offices are between 0.4s and 0.8s. It is necessary to add measurement points ranging from RT 0.4 s to 1.4 s at different speech intelligibility levels to determine the effects of speech intelligibility on occupants under common office RT conditions. Additionally, adding RT measurement points facilitates finding the appropriate office RT range where the negative effects of speech on occupants could be significantly reduced. Another limitation is that only the serial recall task was tested in this study. Task type is a key factor that affects the effects of speech intelligibility on work performance. Therefore, more research is needed on the effects of speech intelligibility on the work performance of other tasks in different reverberant environments. Finally, the total speech level of Abs_0.61 was 54.5 dBA, which is higher than Abs_0.21 (51.8 dBA). Although some studies [54-56] consider 3 dB as the just noticeable difference (JND) of sound pressure level, the higher total sound pressure level of Abs_0.61 may have slight effects on the results of this study. Despite such limitations, this study is meaningful and unique because it is one of the first experimental studies to compare the effects of RTs on occupants in open-plan offices at different levels of speech intelligibility. The findings of this study also indicate that although speech can rapidly decay in a very absorbing environment, its disturbance on occupants in open-plan offices is not always less than that in a long reverberant environment.

5. Conclusion

This study examined the effects of STI conditions on serial recall performance and acoustic environmental perceptions under two RT environments. The results show that an increase in STI values will increase speech disturbance and decrease work performance and acoustic satisfaction in a short reverberation environment, while this trend is not observed in a long reverberation environment. At the STI of 0.42, occupants will be easier affected by speech noise in offices with a short RT than in offices with a long RT. Furthermore, individual factors affected participants' perceptions of STI conditions. Low-sensitivity participants were easier to adapt to acoustic environments in open-plan offices with a short RT. Female participants had higher acoustic satisfaction in all STI conditions regardless of the RT of open-plan offices.

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Appendix A. Details of the noise-sensitivity scale

Table A1 Noise-sensitivity scale

No.	Statements
1	“I need an environment that is completely quiet to get a good night’s sleep.”
2	“I need a quiet environment to be able to perform new tasks.”
3	“When at home, I quickly get used to noise.”
4	“I become very distressed, if I hear someone talking when I am trying to sleep.”
5	“I am very sensitive to noise from my neighbours.”
6	“When people around me are noisy, I have trouble completing my work.”
7	“I am much less efficient in noisy environments.”
8	“I do not feel well-rested after a noisy night.”
9	“It would not bother me to live in a noisy street.”
10	“I am willing to accept the disadvantages of living in a quiet place.”
11	“I need peace and quiet to perform a difficult task.”
12	“I can fall asleep even when it is noisy.”

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