A STUDY ON ACOUSTIC ENVIRONMENTAL EVALUATION OF OPEN-PLAN OFFICES IN MAINLAND CHINA

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A Study on Acoustic Environmental Evaluation of Open-plan Offices in Mainland China

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A thesis submitted in partial fulfillment of the requirements for the

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CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

___________________________ (Signed)

KANG Shengxian (Name of student)

DEDICATION

To Xinxin, Zhou, my dear husband, for your care and love at this stage of our lives.

To Xiu’e, Yang, my kind mother, for your encouragement and continuous support.

ABSTRACT

Abstract of thesis entitled : A study of acoustic environmental evaluation in Chinese open-plan offices

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An open-plan office is a typical type and has been favoured by architects and builders for ease of information flow, flexibility for layout changes and economic reasons. Noise, especially irrelevant speech, can transmit with few obstacles in large office spaces due to the spatial characteristics of the open-plan office (i.e., without partition walls). This acoustic characteristic results in some acoustic problems, such as poor speech privacy and a noisy environment. For employees who spend long periods of time in open-plan offices, these acoustic problems can lead to poor indoor environment satisfaction, low work productivity, and high job dissatisfaction. Thus, the contradiction between convenient information communication and good acoustic quality requirements of open-plan offices has become a pressing acoustic issue in open-plan offices. This thesis systematically investigated the acoustic environment of real open-plan offices, the impacts of acoustic quality levels, work performance prediction, the impacts of reverberation time and speech intelligibility in Chinese open-plan offices by means of acoustic measurements, objective experiments, subjective questionnaires, and acoustic simulation of open-plan offices. In order to achieve the above research objectives, a number of sub-studies have been carried out: (1) An investigation of acoustic environments in large and medium-sized open-plan offices in China; (2) The effect of room acoustic quality levels on work performance and perceptions in open-plan offices; (3) A prediction model that evaluates how much work performance is decreased by speech noise with different intelligibility in Chinese open-plan offices; (4) The effects of speech intelligibility and reverberation time on the serial recall task in Chinese open-plan offices.

Open-plan offices can be subdivided into small, medium-sized and large open-plan offices depending on the number of employees sharing an office. An investigation of acoustic environment was carried out in 16 Chinese open-plan offices, aiming to (1) study how the design parameters of open-plan offices 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 critical aspects of the acoustic environment (noise level and speech privacy) were collected from seven LOPOs and nine MOPOs in China. The analysed results found that open-plan offices with a lower spatial density of workstations or higher storey height have a 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 a work productivity decrease. In terms of the differences in acoustic environment between LOPOs and MOPOs, employees in MOPOs 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.

A laboratory experiment was carried out 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 locations 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 locations 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.

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 STI. 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. A laboratory experiment was carried out to determine the changing trends of work performance and acoustic environment perceptions with the increase in STI under different RT conditions. In addition, this experiment also explored how room RT affects work performance and perceptions of the acoustic environment under the same STI condition. The acoustic conditions tested in this experiment 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 experiment is that occupants working in a long reverberant environment have less mental workload, faster task completion speed, and higher acoustic adaptability than those working in a short reverberant 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 reverberant environment, while that trend was not observed in the long reverberant environment. The effects of STI conditions on occupants may differ by gender and noise sensitivity.

Speech noise can reduce occupants' work performance in open-plan offices. Some models have been created to predict the effect of speech of different intelligibility on work performance. However, few of them consider the effects of speech intelligibility in Chinese environments. Thus, a model was developed to evaluate how much work performance is decreased by speech noise with different intelligibility in Chinese open-plan offices. The data from the abovementioned two laboratory experiments and two previous studies were collected and analysed. These two studies researched the effects of the Speech Transmission Index (STI) on serial recall performance in Chinese environments. STI is an important parameter for the objective prediction of speech intelligibility. A sigmoidal curve shape was used to develop a prediction model to explain the relationship between STI and the performance decrease of serial recall tasks (DP). A comparison of curves between STI and DP with previous studies shows that the STI range for serial recall performance variation in Chinese environments is narrower than in non-Chinese language environments.

PUBLICATIONS ARISING FROM THIS THESIS

Journal Papers

2022 **Kang, S.**, Mak, C.M., Ou, D., and Zhang, Y., 2022. An investigation of acoustic environments in large and medium-sized OPOs in China. Applied Acoustics, 186, p. 108447-.

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Conference Papers

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Table of Content

Nomenclature

Abbreviation	Description
LOPO	Large OPO
MOPO	Medium-sized OPO
OPO	OPO
MLS	Maximum length sequence
IEQ	Indoor environment quality
DP	Decrease in performance
GO_H1	Acoustic conditions of receiving position H1 in the good room acoustic quality
GO_H2	Acoustic conditions of receiving position H2 in the good room acoustic quality
MH_H1	Acoustic conditions of receiving position H1 in the high-medium room acoustic quality
MH_H2	Acoustic conditions of receiving position H2 in the high-medium room acoustic quality
ML_H1	Acoustic conditions of receiving position H1 in the low-medium room acoustic quality

ML_H2	Acoustic conditions of receiving position H2 in the low-medium room acoustic quality
PO_H1	Acoustic conditions of receiving position H1 in the poor room acoustic quality
PO_H2	Acoustic conditions of receiving position H2 in the poor room acoustic quality
Abs	Absorption condition
Rev	Reverberant condition

Terms	**Description**
$D_{2,S}$	Spatial decay rate of speech
L_{10}	The sound pressure level exceeded for 10% of the time
L_{90}	The sound pressure level exceeded for 90% of the time
L_{Aeq}	A-weighted noise pressure level
$L_{p,A,S,4m}$	Speech level at 4m distance
$L_{p,A,B}$	A-weighted background noise level
$L_{A,\mathrm{S}}$	A-weighted speech level

$L_{Aeq,\mathrm{total}}$	A-weighted total noise level of acoustic conditions
r_C	Comfort distance
r_D	Distraction distance
SNR	Signal to noise ratio
SPL	Sound pressure level
STI	Speech transmission index
L	Office length (m)
W	Office width (m)
h	Screen height (m)
H	Storey height (m)
W/H	The office width-to-height ratio
h/H	The ratio of screen height and storey height

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Chapter 1

Introduction

1.1. Research Background

In the past decades, open-plan offices (OPOs) have been popular in office buildings due to advantages such as economic reasons, the flexibility to facilitate information flow and layout changes (Pejtersen, Allermann, Kristensen, & Poulsen, 2006; Shafaghat, Keyvanfar, Ferwati, & Alizadeh, 2015). However, as the room characteristics of OPOs (i.e., large office spaces without partition walls), there are few sound obstacles to noise transmission, resulting in a poor acoustic environment. Numerous studies have shown that a poor acoustic environment in OPOs not only reduces employees' job satisfaction (Park, Lee, Lee, Roskams, & Haynes, 2020; Veitch, Charles, Farley, & Newsham, 2007; M. Zhang, Kang, & Jiao, 2012) but also adversely impact employees' work productivity (S. Kang, Ou, & Mak, 2017; Lou & Ou, 2019; C. M. Mak & Lui, 2011) and health status (Kaarlela-Tuomaala, Helenius, Keskinen, & Hongisto, 2009; Seddigh, Berntson, Jonsson, Danielson, & Westerlund, 2015). Uncontrollable indoor noise, especially sudden conversation noise, is a major cause of bad acoustic environments (Banbury & Berry, 2005; Annu Haapakangas, Hongisto, Eerola, & Kuusisto, 2017; Liu, He, & Qin, 2021; Poll, Ljung, Odelius, & Soerqvist, 2014, Mak, Ma, & Wong, 2023).

Both noise level and speech privacy are two critical indices for evaluating the acoustic environment in OPOs (Kaarlela-Tuomaala et al., 2009). They are strongly related to the acoustic satisfaction of employees (Frontczak et al., 2012; Annu Haapakangas, Hongisto, Hyönä, Kokko, & Keränen, 2014; Pyoung Jik Lee, Lee, Jeon, Zhang, & Kang, 2016; Navai & Veitch, 2003) and work productivity (Jahncke, Hygge, Halin, Green, & Dimberg, 2011; Liebl, Assfalg, & Schlittmeier, 2016; Lou & Ou, 2020).

A quiet environment (i.e., low indoor noise level) is a basic acoustic requirement for a pleasant indoor environment and high work performance (Annu Haapakangas, Hongisto, Varjo, & Lahtinen, 2018; Pierrette, Parizet, Chevret, & Chatillon, 2015; Yang & Mak, 2020). Some studies have already shown that indoor environmental satisfaction decreases with the increase in perceived noise level through questionnaire surveys (Kim & de Dear, 2012; Perrin Jegen & Chevret, 2017). Kim and de Dear (2013) found that reducing the noise level in OPOs can improve employees' environmental satisfaction. S. Kang et al. (2017) also showed that a low noise level is very important to increase the acoustic satisfaction of occupants in open-plan research offices. Moreover, many studies have performed acoustic measurements to determine how the noise level in OPOs impacts occupants' work performance and feelings about the acoustic environment (Cao et al., 2012; H. Tang, Ding, & Singer, 2020; Wong, Mui, & Hui, 2008). For instance, Liu et al. (2021) revealed that noise could increase annoyance when noise levels exceed 50 dBA. Jahncke et al. (2011) found that participants could perform better and be more satisfied with the environment at a low noise level in comparison to the condition with a high noise level. H. Tang et al. (2020) reported that the increase of noise level in steps of 1dBA could result in a 0.18-point decrease in 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 (ISO 3382-3, 2022). High speech privacy commonly represents less speech disturbance for work productivity (S. Kang & Ou, 2018; Y. Zhang, Ou, & Kang, 2021) and job satisfaction (Annu Haapakangas et al., 2014; Pyoung Jik Lee et al., 2016; Park et al., 2020). Since speech privacy is often regarded as the opposite of speech intelligibility, many studies have used the speech transmission index (STI) to assess speech privacy for OPOs (Haka et al., 2009; Roelofsen, 2008; Virjonen, Keränen, Helenius, Hakala, & Hongisto, 2007). They believe that the larger the STI value, the worse the speech privacy and the lower the work performance. STI is an objective metric for evaluating speech intelligibility. In addition, speech decay-related parameters such as spatial decay rate of speech ($D_{2,S}$), comfort distance (r_C) and distraction distance (r_D) are provided by the international standard (ISO 3382-3) to evaluate OPOs’ speech privacy. The spatial decay rate of speech ($D_{2,S}$) refers to the rate of spatial decay of A-weighted sound pressure level of speech per distance doubling in decibels. Distraction distance (r_D) is the distance from the sound source where the speech transmission index (STI) is below 0.5, and comfort distance (r_C) describes the distance from the speaker where the SPL of speech is below 45 dB(A) (ISO 3382-3, 2022). Many studies have proven the validity of speech decay-related parameters suggested in ISO 3382-3:2022 on predicting speech privacy and perceived noise disturbance (Valtteri Hongisto & Keränen, 2021; P. J. Lee & Jeon, 2014; Virjonen, Keränen, & Hongisto, 2009).

1.2. Research Problem Statement

Based on the number of employees using a room, OPOs can be divided into three categories, namely large (over 24 employees using an office), medium-sized (10-24 employees using an office) and small (4-9 employees using an office) OPOs (Bodin Danielsson, Wulff, & Westerlund, 2013; Danielsson & Bodin, 2008; Danielsson, Bodin, Wulff, & Theorell, 2015). Different OPO types can affect employees' work productivity, environmental satisfaction and health (Bodin Danielsson, Chungkham, Wulff, & Westerlund, 2014; Danielsson & Bodin, 2008). For instance, Seddigh et al. found that smaller OPOs may have more positive effects on workers in comparison to larger ones (Seddigh, Berntson, Bodin Danielson, & Westerlund, 2014). In 2015, they revealed that small OPOs are more suitable for employees to perform cognitive tasks compared with large OPOs (Seddigh, Stenfors, et al., 2015). Danielsson revealed that noise problems occurring in large OPOs (LOPOs) are more than those in medium-sized OPOs (MOPOs) through a questionnaire survey (Bodin Danielsson, 2008). These findings above suggest that the type of OPO may affect occupants' perception and demands of indoor acoustic environments (i.e., indoor noise level and speech privacy), but few studies have explored differences in the acoustic needs of various OPO types.

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 (Bradley, 2003; Valtteri Hongisto, Haapakangas, Varjo, Helenius, & Koskela, 2016; Park et al., 2020). Among these parameters, ceiling absorption and screen height are more significant in increasing speech privacy. In 2012, an experimental study conducted in an OPO showed that the ceiling surface with high sound-absorbing material is essential for improving acoustic performance (Passero & Zannin, 2012). Another laboratory study in 2020 verified again that increasing ceiling absorption is the most effective method to strengthen the attenuation of speech and pointed out the importance of high screens for speech attenuation in OPOs (Kernen, Hakala, & Hongisto, 2020). According to the international standard (ISO 22955:2021), 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 (ISO 22955, 2021). In summary, studies on the acoustic improvement of OPOs concentrate on characteristics of decorating materials (e.g., sound absorption coefficient, screen height, etc.) and masking sound systems (e.g., masking signals, masking sound level, etc.). However, few studies explore the effects of office characteristics (e.g., offices' geometrical dimensions, the density of the workstation, etc.) on acoustic improvement.

The international standard ISO 3382-3 provides several parameters (e.g., $D_{2,S}$, $L_{p,A,S,4m}$, r_D, r_C, $L_{p,A,B}$, etc.) to evaluate acoustic performance of OPOs. Short r_D, high $L_{p,A,B}$, and low $L_{p,A,S,4m}$ are independently beneficial to reduce the disturbance of noise in OPOs (Annu Haapakangas et al., 2017). Virjonen et al. (2009) gave an acoustic classification and the corresponding target values of OPOs based on 16 real OPOs, but the acoustic classification was based on the distribution of measured results without concerning occupants' perception of acoustic environments. In addition, Annex C of ISO 3382-3: 2022 also proposes two examples of typical values of all parameters, which represent good and poor acoustic environments, respectively (ISO 3382-3, 2022). 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. To the best of the author’s knowledge, laboratory studies analyzing the impact of acoustic quality levels on work performance and acoustic environmental perceptions in OPOs are still limited.

Speech intelligibility is also 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 STI. Many studies explored the impact of speech intelligibility on occupants’ work performance and acoustic environmental perceptions in OPOs 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 OPOs’ acoustic environments. In addition, many previous studies have found a big difference in the perceived speech intelligibility of different languages under the same STI value. By definition of speech privacy, it has a significant negative correlation with speech intelligibility. The linguistic environment may be a factor affecting occupants' perceived speech privacy. The interaction between multicultural and multilingual people in OPOs is gaining importance with the development of the modern and globalized world. Thus, it is necessary to explore whether language environments affect the relationship between work performance and speech intelligibility, even under the same STI condition.

Several previous studies have proposed prediction models of work performance by analysing the results of experimental research in which the impact of different STI values on work performance was determined (Annu Haapakangas, Hongisto, & Liebl, 2020; V. Hongisto, 2005; Renz, 2019). These prediction models can predict the decrease in work performance through STI values. For instance, Ranz in 2019 created a prediction model to show how the STI affects and the decrease in work performance (DP) in OPOs based on a number of experimental studies carried out in German environments (Renz, 2019). Hongisto, in 2005, created an STI-DP model to show the impact of irrelevant speech on the decrease in work performance in OPOs (V. Hongisto, 2005). Based on this STI-DP model, the work performance decrease takes place between STI 0.2 and 0.5. In 2020, Haapakangas et al. revised Hongisto's STI-DP model through a systematic literature review (Annu Haapakangas et al., 2020). The work performance decrease takes place between STI 0.12 and 0.51. In the studies of Hongisto (2005) and Haapakangas et al. (2020), the impact of language environments was not taken into account when developing the STI-DP model. In addition, most of the data were collected from experimental studies conducted in Western language environments, and little came from experimental studies conducted in Chinese environments. Since the language environment is an important factor when considering the relationship between perceived speech intelligibility and STI value, it is necessary to develop an STI-DP model for Chinese OPOs.

1.3. Research Objectives and Significance

Due to the limitation of the previous studies on acoustic classification, improvement and evaluation of OPOs in Chinese environments, this thesis aims at investigating the acoustic environment of real open-plan offices, the impacts of acoustic quality levels, work performance prediction, and the impacts of reverberation time and speech intelligibility in Chinese open-plan offices by means of acoustic measurements, objective experiments, subjective questionnaires, and acoustic simulation of open-plan offices. The principal objectives of this research are presented as follows (see Figure 1.1 in detail):

1) To evaluate the acoustic environment of different types of OPOs in China by conducting acoustic measurements and questionnaire surveys. The influential design parameters of OPOs are identified, and their effects on acoustic performance will be investigated. In addition, occupants' acoustic environment demands of different OPO types will be compared.
2) To investigate the influence of room acoustic quality levels on work performance and acoustic perceptions in OPOs through a laboratory experiment. The OPOs' acoustic quality levels are divided into four groups, according to Annex C of ISO 3382-3:2022.
3) To explore the effects of speech intelligibility and reverberation time on the serial recall task in Chinese OPOs through a laboratory experiment. Two questions are explored: i) the changing trends of work performance and acoustic environment perceptions with the increase in STI; ii) the effects of speech environments with the same STI value on participants under different reverberant environments.
4) To propose a prediction model to assess how much work performance is reduced by speech noise with different intelligibility in Chinese OPOs with a short reverberation time. The sigmoidal function was used to simulate the relationship between STI and the decrease in work performance (DP). The impact of linguistic environments is also considered.

This thesis concerning in-site acoustic measurement, acoustic simulation, listening test method, questionnaire survey, and numerical prediction of acoustic environments of

Chinese OPOs should contribute to improving the understanding of OPOs' acoustic environments. The in-site measurements can obtain the relationships between office design parameters (e.g., geometrical dimensions, the density of workstations, room area and volume, etc.) and acoustic parameters in OPOs (i.e., active noise levels and speech decay-related parameters), which could provide a guideline for designers or acoustic engineering to design the acoustic environment of OPOs. The acoustic simulation, listening test and questionnaire survey can confirm the validity of the acoustic classification criteria in ISO 3382-3:2022 and determine the impact of speech intelligibility and reverberation time. The numerical simulation can provide specific information on the numerical and modelling method for the acoustic classification of OPOs, which can help acoustic engineers rapidly assess the impact of speech intelligibility on work performance.

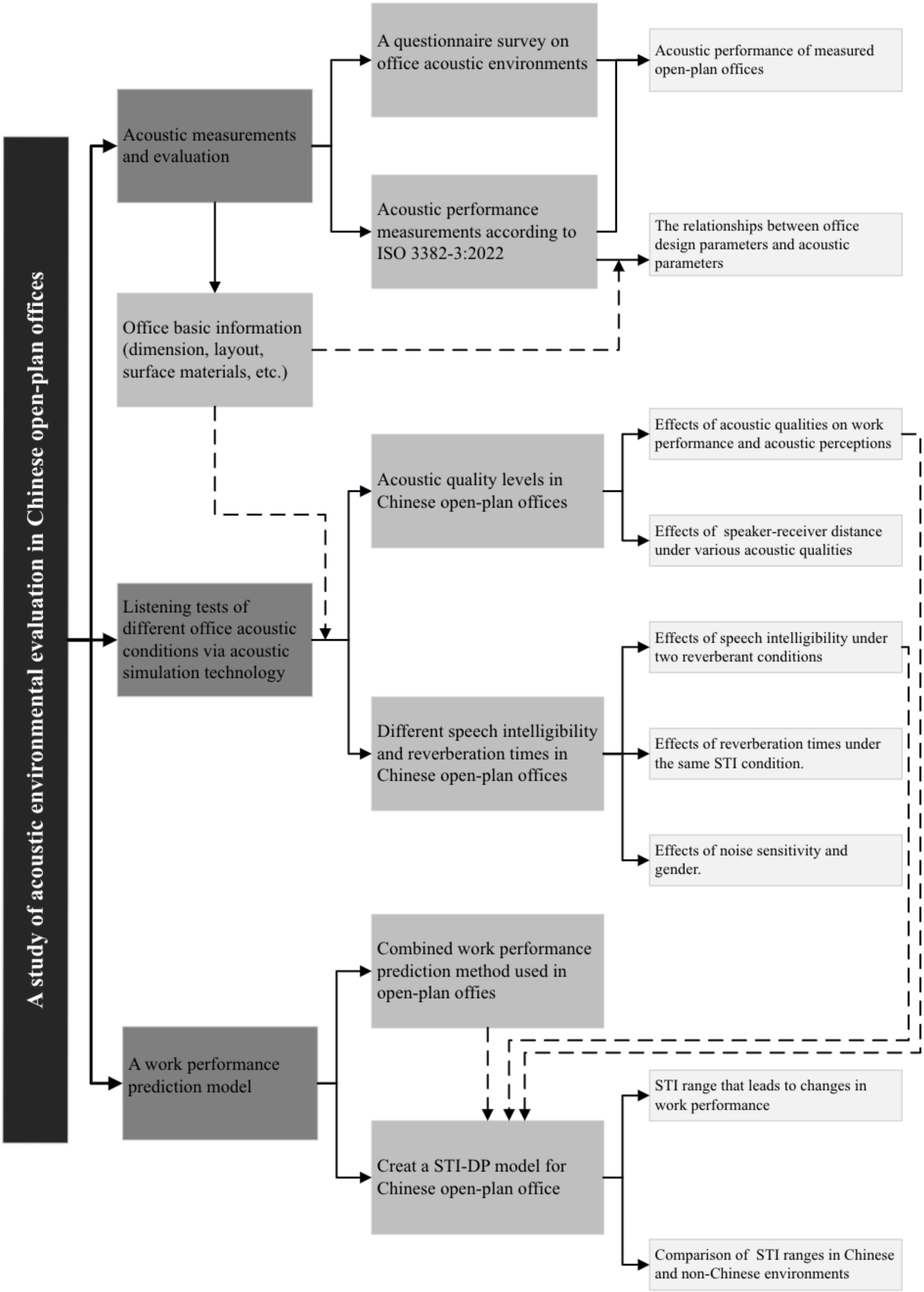


Figure 1.1 The outline of the research contents

1.4. Outline of This Thesis

This chapter introduces the research background, problems, objectives, and significance of the research and emphasizes the necessity of this study. The other chapters of this thesis can be summarised as follows:

Chapter 2 reviews relative literature concerning acoustic environment assessment, the impacts of office design parameters on acoustic performance, and the effects of linguistic environments on speech intelligibility.

Chapter 3 describes a survey of the acoustic environment carried out in 16 OPOs in Shenzhen, China. This Chapter determines the relationship between the design parameters of OPOs and indoor acoustic environments. It also examines whether occupants' requirements for the acoustic environment differ between large and medium-sized OPOs.

Chapter 4 presents a laboratory experiment exploring the impacts of acoustic quality levels on work performance and acoustic environmental perceptions in OPOs. This chapter aims to 1) explore whether good acoustic qualities of OPOs cause high work performance and acoustic satisfaction, and 2) study how speaker-receive distances affect work performance and perceptions of acoustic environments in different acoustic qualities.

Chapter 5 identifies the changing trends of work performance and acoustic environment perceptions with the increase in STI under different RT conditions. In addition, this chapter also presents how room RT affects work performance and perceptions of the acoustic environment under the same STI condition.

Chapter 6 proposes an STI-DP model that predicts serial recall performance based on speech intelligibility in Chinese OPOs with a short reverberation time. This chapter also shows the differences in STI-DP models among different language environments.

Chapter 7 reviews the research objectives and the main contributions of all works performed in this PhD project. It also shows the limitations of these works and gives recommendations for future studies on acoustic qualities in open-plan offices.

Chapter 2

Literature Review

2.1. Office Types

There are five typical offices, i.e., cell offices, open-plan offices, shared-room offices, combi offices and flex offices (Bodin Danielsson et al., 2013; Danielsson, 2016). The definitions of office types are shown in Figure 2.1. Occupants working in different office types have different requirements for the indoor environment. Danielsson and Bodin investigated the influence of office types on occupants' health status and job satisfaction (Danielsson & Bodin, 2008). The results show that occupants working in cell offices and flex offices have better health than employees in OPOs. Low noise levels and high sound privacy are more important to employees in OPOs, whereas adequate lighting and comfortable furnishing receive higher priority by cell offices (Kim & de Dear, 2013). In summary, the quality of the acoustic environment is related to the OPOs occupants' health and environmental satisfaction.

OPOs can be subdivided into three categories, i.e., large (over 24 employees using a room), medium-sized (10-24 employees using a room) and small (4-9 employees using a room) OPOs (see Figure 2.1), based on the number of workers using a room (Bodin Danielsson et al., 2013; Danielsson & Bodin, 2008; Danielsson et al., 2015). The type of OPOs also has impact on occupants’ work productivity, environmental satisfaction and health (Bodin Danielsson et al., 2014; Danielsson & Bodin, 2008). Seddigh et al.

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 (Seddigh et al., 2014). Later, Seddigh et al. revealed that small OPOs are more suitable for employees to perform cognitive tasks compared with large OPOs (Seddigh, Stenfors, et al., 2015). Danielsson (2008) 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).

Figure 2. 1 Definitions and features of office types

2.2. Impact of Speech Noise in Open-plan Offices

Noise disturbance in OPOs has become a serious acoustical problem, since noise can transmit with little hindrance in a large office space with no partition walls. Irrelevant speech noise is a common OPO noise and has a significantly negative effect on occupants' work performance (Annu Haapakangas et al., 2014; S. Kang, Mak, Ou, & Zhang, 2022b; S. Kang & Ou, 2018), job satisfaction (Annu Haapakangas et al., 2014; Pyoung Jik Lee et al., 2016; Park et al., 2020), environmental satisfaction (S. Kang et al., 2017; C. M. Mak & Lui, 2011) and mental health (Kaarlela-Tuomaala et al., 2009; Liu et al., 2021). Several studies have researched why speech noise can lead to work performance decrease and acoustic environmental dissatisfaction. For example, Sörqvist et al. found that the semanticity of irrelevant speech is the main cause of distraction in the workplace (SÖRqvist, NÖStl, & Halin, 2012). Marsh et al. found that speech noise has a higher negative effect on work performance when the semantic meaning of irrelevant speech is relevant to work contents (Marsh, Perham, Sörqvist, & Jones, 2014).

Speech intelligibility is regarded as a critical acoustic index for evaluating room acoustic environment in OPOs. 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 OPOs. This is because lower speech intelligibility in an OPO is associated with higher work performance (Annu Haapakangas et al., 2020; V. Hongisto, 2005; S. Kang, Mak, Ou, & Zhang, 2022c) and acoustic satisfaction (Haka et al., 2009; S. Kang & Ou, 2018; Lou & Ou, 2020). The recent standard, ISO 22955:2021, proposes an important criterion between workstations in OPOs that speech intelligibility should be reduced to increase discretion. In addition, speech privacy, which is frequently considered to be inverse to speech intelligibility, has been proposed as an acoustic metric to evaluate the acoustic quality of OPOs (Pyoung Jik Lee et al., 2016). According to the standard ANSI/ASA S12.70-2016, speech privacy is a measure of how well speech noise is audible and understandable by unintentional listeners.

2.3. Impact of Speech Intelligibility in Open-plan Offices

2.3.1 Speech Transmission Index

As mentioned in Section 2.2, speech intelligibility is a key index affecting work performance, acoustic satisfaction and speech disturbance. Speech Transmission Index (STI) is an important parameter for evaluating room speech intelligibility (IEC 60268-16:2020, 2020) and is frequently utilized in laboratory experiments to explore the impacts of speech intelligibility on work performance (Annu Haapakangas et al., 2020; V. Hongisto, 2005; Lou & Ou, 2020). Its value ranges from 0 (not intelligible) to 1 (perfectly intelligible). 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. An STI above 0.76 implies excellent speech intelligibility, and an STI below 0.36 means nearly unintelligible speech (IEC 60268-16:2020, 2020).

In OPOs, the low STI value represents high speech privacy and acoustic comfort (Haka et al., 2009; Jahncke, Hongisto, & Virjonen, 2013; Poll et al., 2014). Studies on the impacts of irrelevant speech in OPOs commonly concentrate on the impacts of STI values on occupants' work performance (Haka et al., 2009; Venetjoki, Kaarlela-Tuomaala, Keskinen, & Hongisto, 2007; Virjonen et al., 2007). In general, with the increase in STI, work performance and acoustic satisfaction decrease, and speech disturbance increases. Hongisto has developed a mathematical model based on the results of much previous literature in which speech impacts on the performance of different tasks had been measured in laboratory environments (V. Hongisto, 2005). Depending on Hongisto's model, there is no detrimental effect on task performance if the STI value is below 0.20, while performance decrease reaches the top when the STI value exceeds 0.5. Haka et al. (2009) proved the validity of Hongisto's model based on a laboratory experiment. Haapakangas et al. (2020) revised Hongisto's model based on some laboratory experiments in which STI values were manipulated by various steady-state noise levels. The revised model shows a decrease in task performance when the STI value rises from 0.12 to 0.51 (Annu Haapakangas et al., 2020).

2.3.2 Physical Parameters Affecting STI Values

Both speech-to-noise ratio (SNR) and reverberation time (RT) are key acoustic parameters affecting perceived speech intelligibility and the STI value in an environment (Houtgast & Steeneken, 1985; IEC 60268-16:2020, 2020).

A high SNR will result in high speech intelligibility (i.e., a large STI value) (Valtteri Hongisto, Keränen, & Larm, 2004). Changing the SNR value by introducing masking sounds is a common method for exploring the impact of STI values on work performance and acoustic environmental perceptions. For instance, Haka et al. adjusted the sound pressure levels of speech and masking signals to study the effects of STI conditions (STI=0.10, 0.35, and 0.65) on work performance and subjective speech disturbance (Haka et al., 2009). Kang and Ou 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 (S. Kang & Ou, 2018). Lou and Ou studied the impact of STI conditions 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) (Lou & Ou, 2020). Jahncke et al. researched the impacts of STI conditions and office task characteristics by changing the sound pressure levels of speech and masking signals to determine 5 STI conditions (0.08, 0.16, 0.23, 0.34, and 0.71) (Jahncke et al., 2013). The STI value in the studies mentioned above was determined based on Hongisto's method (Valtteri Hongisto et al., 2004) or Houtgast and Steeneken's method (Houtgast & Steeneken, 1985) 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 (S. Kang et al., 2022b; Keränen & Hongisto, 2013; Kernen et al., 2020; Park et al., 2020; Passero & Zannin, 2012; Virjonen et al., 2009; Yadav et al., 2019), the RT value of real open-plan offices is between 0.2s and 1.5s. Thus, it is necessary to determine the impact 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 (Beaman & Holt, 2007). Beaman and Holt showed that environments with longer RTs could decrease the speech disturbance of occupants (Beaman & Holt, 2007). However, Braat-Eggen et al. revealed that a longer RT could increase the perceived disturbance of speech noise (Braat-Eggen, Poll, Hornikx, & Kohlrausch, 2019). As mentioned above, RT could affect perceived speech disturbance, but the relationship between RT and perceived speech disturbance is unclear. Moreover, Meng et al. 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 (Meng, An, & Yang, 2021). 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.

2.3.3 The Effects of Linguistic Environments

With the development of globalization, the interaction between multicultural and multilingual occupants in offices has become more and more common. The effects of linguistic environments on speech intelligibility should be considered. Kang compared the speech intelligibility between Chinese and English under noisy and reverberation environments (J. Kang, 1998). Galbrun and Kitapci examined the effects of acoustic conditions on the speech intelligibility of four languages (i.e., Mandarin, English, Polish, and Arabic) (Galbrun & Kitapci, 2016). These studies showed that, even under the same room acoustic environment (i.e., the same reverberation time, noise environment or STI value), the perceived speech intelligibility of different linguistics is different.

The linguistic environment is also vital when concerning OPOs' acoustic environments. As mentioned in Section 2.2, speech intelligibility, an important acoustic index for OPOs, is closely related to work performance and acoustic satisfaction. This means that work performance and acoustic satisfaction may also be affected by linguistic environments. However, there is no study investigating the effects of linguistic environments in OPOs. Other researchers also found that language environments could affect the relationships between the decrease in work performance (DP) and STI values in OPOs. Kang and Ou revealed that the effects of STI values on work performance are different between Chinese and non-Chinese linguistic environments (S. Kang & Ou, 2018). Hongisto showed that the relationships between STI and occupants' work performance are different among different linguistic environments (V. Hongisto, 2005). For instance, the performance of the serial recall task starts to decrease when the STI value is over 0.35 in the Finnish environment (Haka et al., 2009; Valtteri Hongisto, Varjo, Leppämäki, Oliva, & Hyönä, 2016), while the performance in the Swedish environment begins to decrease after exceeding the STI of 0.23 (Liebl et al., 2016). Besides, for conditions where the decrease in performance of the serial recall task reaches the top, the STI value should exceed 0.62 in the Finnish environment (Haka et al., 2009; Valtteri Hongisto, Varjo, et al., 2016) but only need to be over 0.34 in the Swedish environment (Liebl et al., 2016). This is not surprising because the characters of speech noise (e.g., grammar, pronunciation, etc.) and OPOs occupants' working practices are different under different linguistic environments. Thus, a systematic and quantitative study is needed to explore whether the linguistic environments influence occupants' perception of speech privacy and the relationship between STI (speech intelligibility) and DP.

2.4. Acoustic Evaluation of Open-plan Offices

2.4.1 Physical Parameters for Acoustic Performance in Open-plan Offices

In order to assess room acoustic performance correctly, it is important to select suitable acoustic parameters for room acoustic evaluation. Moreover, successful acoustic measurements are the foundation of acoustic environment evaluation (Ma, Mak, & Wong, 2020a, 2020b; Cheuk Ming Mak & Wang, 2015; T/CECS 1136, 2022).

2.4.1.1 Speech Privacy-related Parameters

The index Speech privacy is affected by various acoustic descriptors. For instance, spatial decay of sound (spatial decay rate of speech, $D_{2,S}$), the level and quality of speech signal (speech-to-noise ratio, SNR), speech intelligibility (speech transmission index, STI), reverberation conditions (early decay time, EDT), etc.

In North America, the evaluation of speech privacy in OPOs deeply depends on the speech intelligibility of each workstation. Articulation Index (AI) is a metric used to rate the amount of speech an occupant can hear (ANSI S3.5-1969, 1969). It is generally regarded as a physical parameter of speech intelligibility. AI has been proposed for speech privacy evaluation in OPOs (ASTM E1130-2016, 2016). As recommended in the ASTM E1130-2016, the information of speech noise cannot be heard clearly when the AI value is below 0.05. This situation is regarded as "confidential" speech privacy. Little speech can be understood when the AI value ranges from 0.05 to 0.15. This situation represents "acceptable" or "normal" speech privacy, which means that non-intrusive speech privacy can be achieved. Besides, speech privacy improved significantly as a result of the decrease of AI value from 0.15 to 0.05 in steps of 0.05. There is essentially no privacy when the AI value is above 0.40 (ACC, 1973; Bradley & Gover, 2003). The aforementioned privacy levels and target values for AI have been determined by listening tests on perceived privacy ratings.

In Europe, STI is used as the objective parameter of speech privacy. According to the findings of Haapakangas et al. (2020) (see Section 2.3.2), in terms of work performance, an STI value below 0.12 can reach "good" speech privacy; an STI value ranging from 0.12 to 0.5 is "moderate" speech privacy; and the STI value over 0.51 is "worse" speech privacy. However, Pop and Rindel performed a series of listening tests utilizing the auralization technology (Pop & Rindel, 2005). The research results showed that STI values below 0.30 can reach the requirements of "moderate" speech privacy. If the STI value is below 0.15, indoor speech privacy may be rated as "confidential". In addition, Roelofsen (2008) gave a table showing the relationship between STI and speech privacy qualities. Speech privacy is good if STI is below 0.30, while speech privacy is bad when STI exceeds 0.45. It seems to be a slight difference between objective measurement and subjective evaluation of speech privacy qualities.

It is worth mentioning that the evaluation of speech privacy by AI or STI concentrates on the impacts of speech noise between two workstations (i.e., the speech privacy of certain workstations). However, the locations of speech noise are unpredictable in a real OPO and noise disturbance is not limited to the adjacent workstations. It is time-consuming to evaluate the speech privacy of all workstations by AI or STI. Virjonen et al. (2009) proposed a new method to measure and assess the acoustic performance of the whole OPO, including both nearby and distant workstations from the speech noise. This new method provides scientific evidence for the published international standard (ISO 3382-3) in 2012.

2.4.1.2 Speech Decay-related Parameters

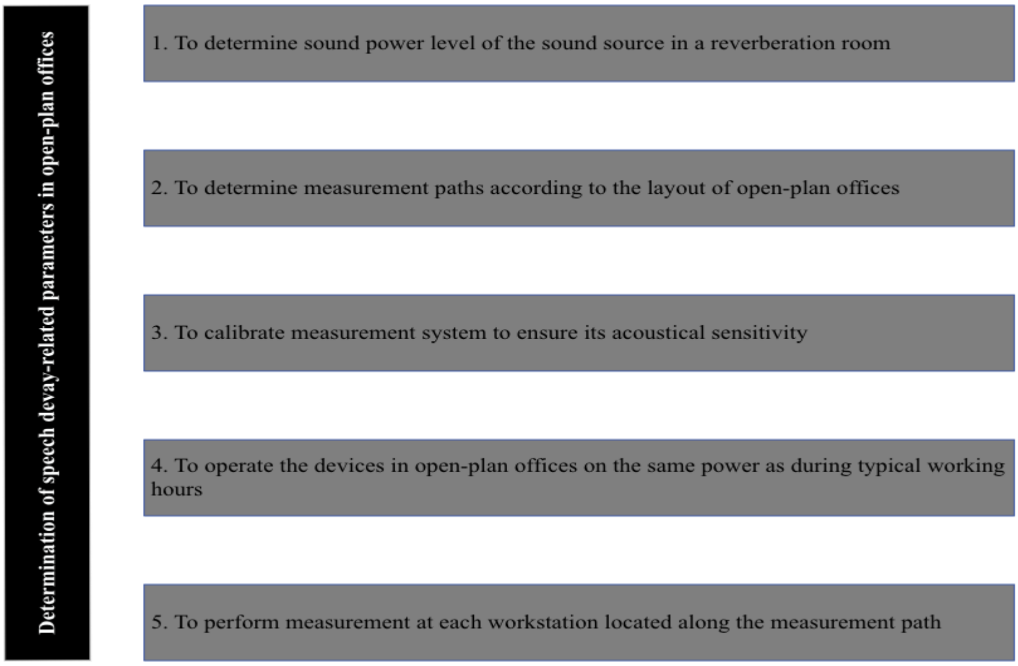
The revised measurement standard for acoustic environments in open-plan offices, ISO 3382-3:2022, was published in 2022. As recommended in ISO 3382-3:2022, spatial decay rate of speech ($D_{2,S}$), speech level at 4m distance ($L_{p,A,S,4m}$), distraction distance (r_D), comfort distance (r_C), and background noise level ($L_{p,A,B}$) should be used to indicate 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. r_C describes the distance from the speaker where the sound pressure level (SPL) of speech is below 45 dB(A), which is used to determine the effect of spatial attenuation in OPOs (ISO 3382-3, 2022). $L_{p,A,S,4m}$ refers to nominal A-weighted SPL in decibels at the distance of 4.0 m from the middle point of the omnidirectional sound source. $L_{p,A,B}$ indicates A-weighted mean SPL of background noise in decibels present at the workstations along the measurement path during working hours when occupants are absent. Some previous studies showed. Haapakangas et al. (2017) explored the validity of the single-number quantities of ISO 3382-3:2022 in predicting perceived noise disturbance utilizing the meta-analysis. The analyzed results demonstrated that those speech decay-related parameters are useful for assessing indoor noise disturbance. The importance of r_D in the prediction of perceived noise disturbance in OPOs was also emphasized by Haapakangas et al. (2017). All these parameters should be considered during evaluating and improving OPOs acoustic performance. The four parameters, namely $D_{2,S}$, $L_{p,A,S,4m}$, r_D, and r_C are related to the decay of speech noise in OPOs (ISO 3382-3, 2022), and are hereinafter referred to as speech decay-related parameters.

2.4.2 Acoustic Measurement in Open-plan Offices

The measurement of room acoustic parameters is the first step for objectively evaluating the acoustic environment, followed by the acoustic environment judgment according to the parameters (Ma, Wong, & Mak, 2018). ISO 3382-3:2022 gives a systematic method to measure speech decay-related parameters.

Two methods for determining speech decay-related parameters are recommended in ISO 3382-3, i.e., conventional method and impulse response measurement. For the conventional method, the omnidirectional sound source should emit noise with a high sound power level. The sound pressure level of the omnidirectional sound source should be larger than that of normal speech in the range of 125 Hz to 8000 Hz (see ISO 3382-3:2022) and exceed the background noise level by at least 6 dB at each measurement location. For the impulse response measurement, both maximum length sequence (MLS) and sine sweep can be utilized as signals to determine the room impulse response.

For the conventional method, five steps are needed (as shown in Figure 2.2). The first step is to determine the sound power levels of the sound source used in the OPOs' acoustic measurements. As recommended in ISO 3741: 2010, a minimum of six microphone positions and one sound source position are used in a reverberation chamber. The second step is to choose the straightest possible path crossing over workstations in measured OPOs. The number of workstations, along with the measurement path, should range from 4 to 10. The omnidirectional sound source is located at the workstation at one end of the measurement paths. Figure 2.3 shows an example of measuring paths in an open-plan office in which furniture is present. Subsequently, a sound calibrator should be used to calibrate the acoustical sensitivity of the measurement system. In stage 4, all devices in OPOs should be opened and operate on the same power as during typical work hours. Since background noise level caused by devices in offices is an important parameter impacting the determination of r_D. Finally, acoustic measurements are performed in real OPOs using the same sound power level and equipment as in Step 1.



Determination of speech devay-related parameters in open-plan offices

1. To determine sound power level of the sound source in a reverberation room

2. To determine measurement paths according to the layout of open-plan offices

3. To calibrate measurement system to ensure its acoustical sensitivity

4. To operate the devices in open-plan offices on the same power as during typical working hours

5. To perform measurement at each workstation located along the measurement path

Figure 2. 2 The flow of acoustic measurement using the conventional method

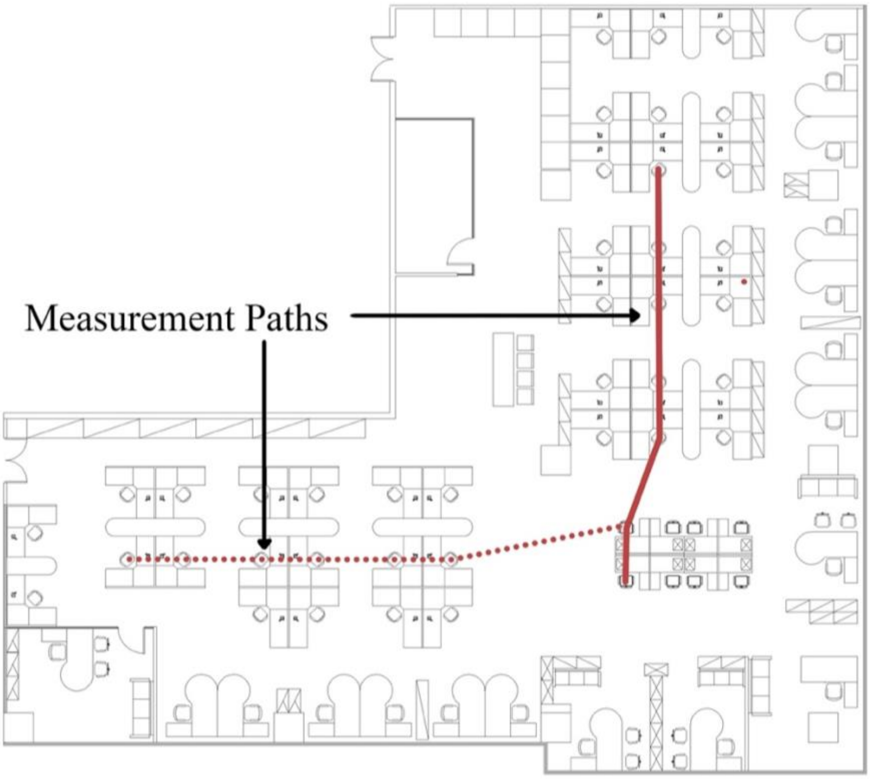


Figure 2. 3 Example of measurement paths in an OPO

It is worth mentioning that at least two measurement lines are necessary to measure speech decay-related parameters in OPOs. If only one measurement line is possible, acoustic measurements should be carried out with two source locations in opposite directions on the measurement path (see ISO 3382-3, 2012). Yadav et al. (2019) have explored variability in the vital single-number quantities according to these quantities' repeatability and reliability. Two types of repeated measurements have been carried out in 27 OPOs. Type one is one measurement line with two source positions, and type two is two measurement lines within the same office. The results show that the repeatability standard deviations of single-number quantities are large no matter what measurement type is conducted. In open-plan offices, repeated acoustic measurements and measuring all measurement lines in both directions are strongly suggested to decline the measurement uncertainty (Yadav et al., 2019).

2.4.3 Acoustic Classification Criteria

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. Table 2.1 summarizes the acoustic performance criteria. For instance, in 2009, Virjonen et al. proposed an acoustic classification method and corresponding target values of speech decay-related parameters based on the data obtained from 16 OPOs (Virjonen et al., 2009). 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 proposed four acoustic quality levels of r_D based on data from

26 open-plan offices (Valtteri Hongisto & Keränen, 2021). However, the acoustic classification criteria of Virjonen et al. (2009) and Hongisto and Keränen (2021) 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. 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 (Jo, Santika, Lee, & Jeon, 2022). However, the impact of room acoustic quality levels on work performance was 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, typical values of speech decay-related parameters in the two examples are insufficient as the criteria to assess to the acoustic performance of OPOs. Furthermore, 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.

Table 2. 1 Different acoustic performance criteria

Criteria	**Level**	$D_{2,S}$**/ dB**	$L_{p,A,S,4m}$ **/ dB**	r_D**/ m**	r_C**/ m**	$L_{p,A,\mathrm{B}}$ **/dB**
Virjonen et al. (2009)	A	> 11	< 48	<5	--	--
	B	9-11	48-51	5-8	--	--
	C	7-9	51-54	8-11	--	--
	D	<7	>54	>11	--	--
Hongisto and Keränen (2021)	A	>11	<47	<6	<5	--
	B	9-11	47-49	6-8	5-7	--
	C	7-9	49-51	8-10	7-9	--
	D	5-7	51-53	10-12	9-11	--
ISO 3382-3 : 2022	Good	> 8	< 48	< 5	< 5	40-45
	Poor	< 5	> 52	> 11	> 11	< 35 or > 48

Table 2.2 Office noise levels for different types of activities in OPOs by NF S 31-199:2016

The primary activity in OPOs	Target values of noise level (dB)
Telephone with people	48~52
Chatting in-person and over the telephone for collaboration between occupants	45~50
Reception	< 55

Active noise level is also a major parameter for OPOs acoustic evaluation. It is defined as the mean SPL of background noise during working time. Both active noise level and background noise level refer to the indoor sound pressure level of noises. The difference between them is that background noise level indicates the noise level of OPOs when not occupied, while active noise level shows the noise level of OPOs in an occupied condition. Previous studies revealed that active noise level is strongly related to occupants' perception of noise disturbance (Park et al., 2020; Seddigh, Berntson, et al., 2015). The ideal sound level of OPOs is different among different primary work activities (Yadav, Cabrera, Kim, Fels, & de Dear, 2021). A French standard (NF S 31-199:2016) suggests the target values according to the primary work activity in OPOs (see Table 2.2). For OPOs in which main activities are performed over telephones, the noise level should range from 48 dB to 52 dB. For OPOs, where the main activities consist of chatting in person and over telephones for collaboration between occupants, the noise level needs to be between 45 dB and 50 dB. For the reception area of OPOs, the requirement of noise level is just below 55 dB. In addition, a recent international standard (ISO 22955:2021) also suggests suitable noise levels for different types of activity (see Table 2.3).

Table 2.3 Office noise level for different types of activities in OPOs by ISO 22955:2021

Workspace type	**Target values of noise level (dB)**
Informal meetings	48
Outsider of the room communication (phone)	48
Collaborative[1]	45
Non-collaborative [2]	42
Focused phone	42
Focused individual work	40

Note:

[1] either focused or creative, in a one-to-one situation, informal meeting area or chat booth;

[2] the activity does not have noise control etiquette.

2.5. Offices Design and Acoustic Comfort

As mentioned in Section 2.2, clear speech noises have detrimental effects on occupants' acoustic comfort, work productivity and mental health. Thus weakening the intelligibility of speech noise is the major principle of OPOs acoustic improvement. In general, the methods of decreasing speech intelligibility compose strengthening speech attenuation and decreasing indoor speech-to-noise ratio (SNR). For strengthening speech attenuation, OPOs surfaces (i.e., walls, ceiling and floor) covered with high absorptive acoustic material and installing high screens between workstations are common acoustic treatments in OPOs. For decreasing the SNR of OPOs, playing a masking sound with a suitable sound level via the OPOs sound masking system is one of the effective methods.

Figure 2.4 briefly shows the transmission paths of speech noises in OPOs. The office ceiling is the most critical surface for acoustic improvement (ISO 22955, 2021). It is the main reflection surface for speech noise to transmit from speakers to other occupants in OPOs (C. Wang & Bradley, 2002a; J. Yu, Wang, Qiu, Shaid, & Wang, 2016) and has a larger area than other surfaces of OPOs. Thus, the ceiling should be as absorptive as possible to increase the attenuation of speech noise (Jean, Schmich-Yamane, Jagla, & Chevret, 2016; Kernen et al., 2020; Nilsson, Hellström, & Berthelsen, 2008). A laboratory study verified that increasing ceiling absorption coefficient is the most effective method to strengthen the attenuation of speech (Kernen et al., 2020). Walls covering high absorption material are also an effective acoustic treatment to reduce the adverse effects of speech noise. Nevertheless, their performance is lower than the ceiling. It is because of the walls' lower area proportion compared with the ceiling (ISO 22955, 2021). Another reason for the low absorbing performance is that the wall absorbers only work on speech reflections of workstations near walls. As shown in Figure 2.4, the diffraction over the screen and the transmission through the screen is also the major speech transmission paths (Kernen et al., 2020; C. Wang & Bradley, 2002b; J. Yu et al., 2016). Screens' height and sound absorption coefficient can affect speech noise transmission ((Utami, Arifianto, & Nadiroh, 2017; Virjonen et al., 2007; Yildirim, Akalin-Baskaya, & Celebi, 2007). As recommended in ISO 22955:2021, speech attenuation strengthens with the increase in screen height, and screens with a height of 1.1 m can cause 1.1 dB(A) speech attenuation (ISO 22955, 2021). Screens between 1.5m and 1.7m can perform better for speech attenuation (Kernen et al., 2020; Yıldırım, Güneş, & Yilmaz, 2019), and further increases in screen height cannot significantly strengthen speech attenuation after reaching 1.7m (Bradley, 2003).

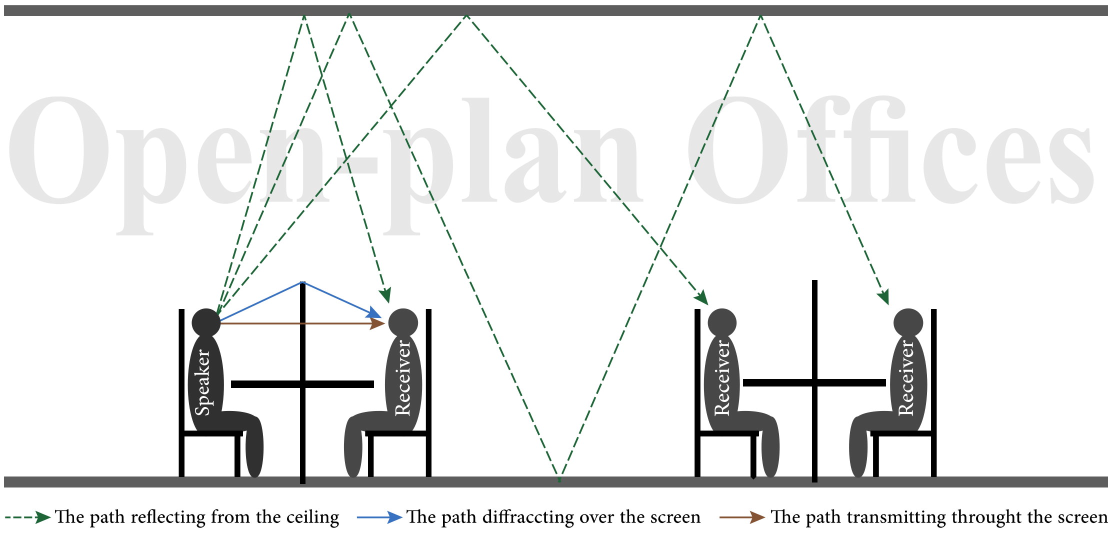


Figure 2. 4 Transmission paths of speech noises in OPOs

Apart from the increase of indoor acoustic absorption, many office design parameters (e.g., office layout, workstation size and geometric dimension) can affect the speech privacy between speakers and listeners. A reasonable office layout is the foundation of an excellent acoustic environment (Al Horr et al., 2016; Y. S. Lee, 2010; Morrison & Smollan, 2020). Grouping cooperating workstations together and separating different teams or services are good layout plans for improving the acoustic environment and facilitating communications between colleagues in one group (Y. S. Lee, 2010; Nilsson et al., 2008). Keränen and Hongisto (2013) found the importance of OPOs' geometric dimension (i.e. office heights and length) to spatial decay of speech. Workstation size is also an indispensable design parameter for acoustic performance. Newsham et al. (2008) revealed that workstation size is positively correlated with employees' acoustic satisfaction. Earlier studies highlight the importance of low-spatial density in OPOs as high-spatial density might increase disturbance by poor speech privacy and noise (Duval, Charles, & Veitch, 2002; Valtteri Hongisto, Haapakangas, et al., 2016).

As mentioned above, many studies have highlighted the importance of high sound-absorbing materials covered by OPO surfaces for high acoustic performance. However, there is still a lack of experimental evidence for the impacts of office parameters on the acoustic environment. Office parameters, such as geometric dimensions, furnishing arrangement (e.g. workstations, stores, etc.), and the density of workstations, are of priority when designing an open-plan office. Findings on relationships between the acoustic environment and office parameters can help architects and indoor designers determine an appropriate office configuration and decoration. Therefore, the impacts of office design parameters on the acoustic environment of OPOs need further systematic and quantitative research.

2.6. Non-acoustic Factors Affecting Work Performance and Acoustic Perceptions in Open-plan Offices

2.6.1 Individual Factors

The individual factor is a critical non-acoustic factor that affects work performance and perceptions of acoustic environments (Reinten, Braat-Eggen, Hornikx, Kort, & Kohlrausch, 2017). The noise sensitivity of occupants is one of the critical individual factors. Lee et al. reported a significant relationship between speech privacy and noise sensitivity (Pyoung Jik Lee et al., 2016). Ellermeier and Zimmer found that participants with high noise sensitivity had lower serial recall performance in a noise environment than participants with low noise sensitivity (Ellermeier & Zimmer, 1997). The study by Zhang et al. indicated that occupants with low noise sensitivity tend to feel more comfortable with certain masking environments in open-plan offices (Y. Zhang et al., 2021). However, some studies (Braat-Eggen et al., 2019; Waye et al., 2002) 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 (Fried, Melamed, & Ben-David, 2002; S. Kang et al., 2017; Y. Zhang et al., 2021). Pellerin and Candas (2003) showed that males prefer less noisy environments than females. Meng et al. (2021) reported that gender could affect participants' visual cognitive performance.

2.6.2 Cognitive Tasks

Several cognitive tasks (such as serial recall tasks, reading comprehension, operation span tasks, mental arithmetic, and etc.) are frequently utilized to determine the adverse effects of bad acoustic environments in laboratory experiments studying the relationship between work performance and STI values (Annu Haapakangas et al., 2014; Annu Haapakangas et al., 2011; Venetjoki et al., 2007). For these studies, the selection of task types is an important aspect in determining the negative impact of acoustic environments because the impact of acoustic environments on task performance varies by task types (Reinten et al., 2017). Kang and Ou found that STI has a significant impact on serial recall performance, but the impact of STI is not statistically significant on the performance of mental arithmetic, proofreading and reading comprehension (S. Kang & Ou, 2018). The study of Haapakangas et al. indicates that there is a significant effect of acoustic conditions on serial recall performance, but the effects of acoustic conditions on the performance of creative thinking and proofreading tasks are not statistically significant (Annu Haapakangas et al., 2011).

Figure 2.5 shows the DP_{max} of various task types in different language environments. The DP_{max} is the decrease in performance between silence and the highest speech intelligibility in each study. As seen in Figure 2.5, DP_{max} varies for different tasks. In terms of the Finnish environment (see Figure 2.5 a), speech noises have significantly detrimental effects on the serial recall task (Annu Haapakangas et al., 2014; Annu Haapakangas et al., 2011) and the operation span task (Annu Haapakangas et al., 2014) (DP_{max} > 5%), while the text memory task has been hardly affected by speech noises.

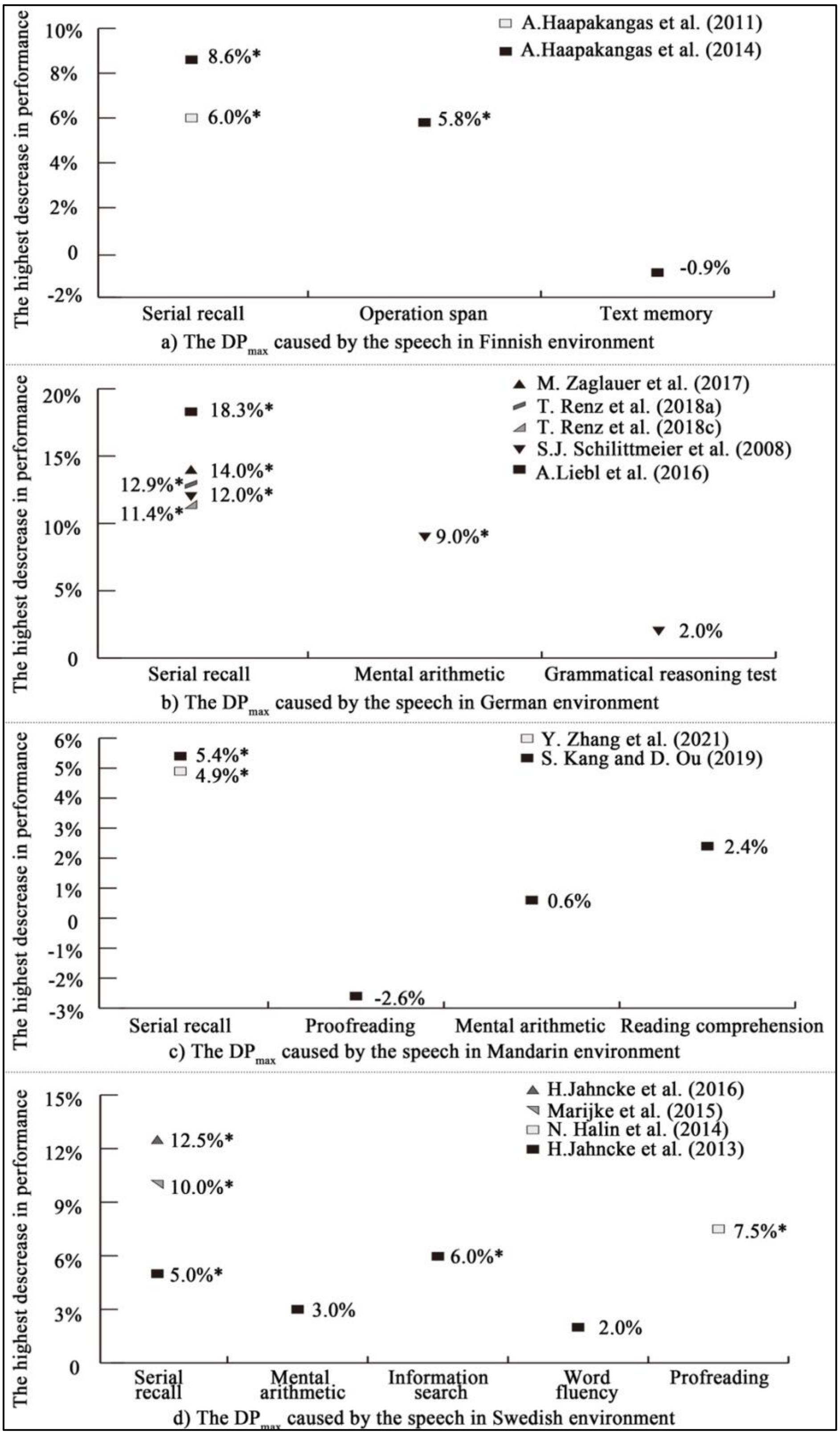


Figure 2.5 The DP$_{max}$ caused by the speech of different language environments (* indicates the DP$_{max}$ was statistically significant)

In terms of the German environment (see Figure 2.5 b), the serial recall task (Liebl et al., 2016; Renz, Leistner, & Liebl, 2018a, 2018c; Schlittmeier, Hellbrück, Thaden, & Vorländer, 2008; Zaglauer, Drotleff, & Liebl, 2017) and the mental arithmetic task (Schlittmeier et al., 2008) have been significantly affected by speech noises (DP_{max} > 9%), but speech has a slight influence on the performance of grammatical reasoning task (Schlittmeier et al., 2008). In terms of the Mandarin environment (see Figure 2.5 c), only the serial recall task has been significantly interfered with by speech noises (DP_{max} > 4.9%) (S. Kang & Ou, 2018; Y. Zhang et al., 2021). In terms of the Swedish environment (see Figure 2.5 d), speech noises have exerted significantly adverse effects on the serial recall task (Jahncke, Björkeholm, Marsh, Odelius, & Sörqvist, 2016; Jahncke et al., 2013; Keus Van De Poll et al., 2015), the information search task (Jahncke et al., 2013), and the proofreading task (Halin, Marsh, Haga, Holmgren, & Sörqvist, 2014).

Some researchers (Halin, Marsh, Hellman, Hellström, & Sörqvist, 2014; Hughes, Hurlstone, Marsh, Vachon, & Jones, 2013; Venetjoki et al., 2007) attribute differences in DP_{max} among various tasks to the task complexity difference. They believe that speech noises are easier to reduce the performance of difficult tasks (Liu et al., 2021). Compared with easy tasks, difficult tasks require occupants to concentrate more on the task itself and devote more effort, so difficult tasks are more sensitive to surrounding conditions. Other researchers have distinguished tasks based on the theory of cognitive psychology (S. Kang & Ou, 2018). Short-term memory tasks, such as the serial recall task, belong to the episodic memory task (Michael & Mark, 2015; Neath, 2010) in cognitive psychology. Episodic memory refers to a system that aids in remembering experienced events and then figuratively travels back in time (Michael & Mark, 2015).

When doing an episodic memory task, the disturbance caused by speech noises could destroy the integrity of memory processes and then decrease episodic memory tasks' performance.

It is worth mentioning that the serial recall task is frequently used to test short-term memory efficiency among the common cognitive tasks (Botvinick & Bylsma, 2005; Michael & Mark, 2015) and to evaluate the effects of environmental changes on work performance (Brocolini, Parizet, & Chevret, 2016; Ebissou, Parizet, & Chevret, 2015; Annu Haapakangas et al., 2014; Schlittmeier et al., 2008). This task requires subjects to recall a list of items in the order in which they appeared (Haberlandt, 2011; Michael & Mark, 2015). Moreover, compared with other cognitive tasks, the serial recall task is more susceptible to speech noise of different intelligibility no matter in what kind of language environment.

2.7 Summary and Scopes of This Thesis

This chapter reviews the previous studies related to the investigation of speech privacy, speech intelligibility, acoustic classification, and acoustic evaluation in open-plan offices. The following research scopes of this thesis are summarized as follows:

1) Evaluate the acoustic environments of different OPO types in China. Acoustic measurements and a questionnaire survey on acoustic environments will be carried out in real OPOs to find the relationships between design parameters and acoustic parameters, and to discuss the effects of OPO types on occupants' perceptions of acoustic environments.

2) Investigate the acoustic quality levels on work performance and acoustic perceptions in Chinese OPOs. Listening tests and cognitive tasks will be tested in different OPOs’ acoustic quality levels to confirm the validity of the acoustic classification criteria in ISO 3382-3:2022. The effects of different speaker-receiver distances on work performance and acoustic perceptions will be discussed.
3) Investigate the impacts of speech intelligibility and reverberation time in Chinese OPOs. Listening tests and cognitive tasks will be tested in different acoustic conditions varied in STI and RT values. The changing trends of work performance and acoustic environment perceptions with increasing STI under different RT conditions will be researched. The effects of RT on work performance and perceptions of the acoustic environment under the same STI condition will be discussed. In addition, the impacts of gender and noise sensitivity will also be explored.
4) Develop a prediction model for evaluating serial recall performance against the STI value in Chinese OPOs. The effects of linguistic environments on serial recall performance will be discussed.

Chapter 3

Acoustic Environment Surveys in Chinese Large and Medium-sized Open-plan Offices

This chapter shows the acoustic environment survey carried out in 16 Chinese OPOs. These 16 OPOs have been divided into medium-sized open-plan offices (MOPOs) and large open-plan offices (LOPOs), according to the number of employees sharing an OPO. Both objective acoustic measurements and subjective assessments related to key aspects of acoustic environments (i.e., noise level and speech privacy) have been collected from seven LOPOs and nine MOPOs in China. Two questions were explored, namely, 1) how OPOs' design parameters impact the indoor acoustic environment, and 2) whether the acoustic environmental demands of occupants differ between LOPOs and MOPOs.

The survey results showed that the spatial density of workstations in OPOs is positively correlated with speech level at 4 m distance ($L_{p,A,S,4m}$) and comfort distance (r_C), and negatively correlated with the spatial decay rate of speech ($D_{2,S}$). The height of OPOs' storey is negatively correlated with $L_{p,A,S,4m}$ and r_C, and positively correlated with $D_{2,S}$. Perceived noise levels have the most significant impact on occupants' acoustic satisfaction, and speech interference on employees' re-concentration is the primary acoustic cause of work productivity decrease. In addition, occupants' acoustic satisfaction in MOPOs is higher than that in LOPOs, and the disturbance level of speech noises is higher in MOPOs than in LOPOs, by comparing the subjective assessment results of MOPOs and LOPOs. In LOPO, perceived speech privacy is an important acoustic factor affecting work productivity, but not in MOPO.

3.1. Description of the Experimental Procedure

3.1.1 Offices in Case Studies

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 3.1, acoustic measurements and questionnaire surveys were carried out in 16 OPOs (offices A-P) from April to May 2021. Among those offices, ten offices (offices B-K) are located within the same building (see Table 3.1). 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. The layout of Offices G-K is different. That is, 7 OPOs with different layouts and interior decorations are provided in this building (see Table 3.1 and Figure 3.1). Offices L-P are located at different buildings and with different layout and decorations (see Table 3.1).

7 LOPOs (offices A-G) and 9 MOPOs (offices H-P) were sampled. Some photos taken in these offices are given in Figure 3.1. 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 3.1). 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 3.1).

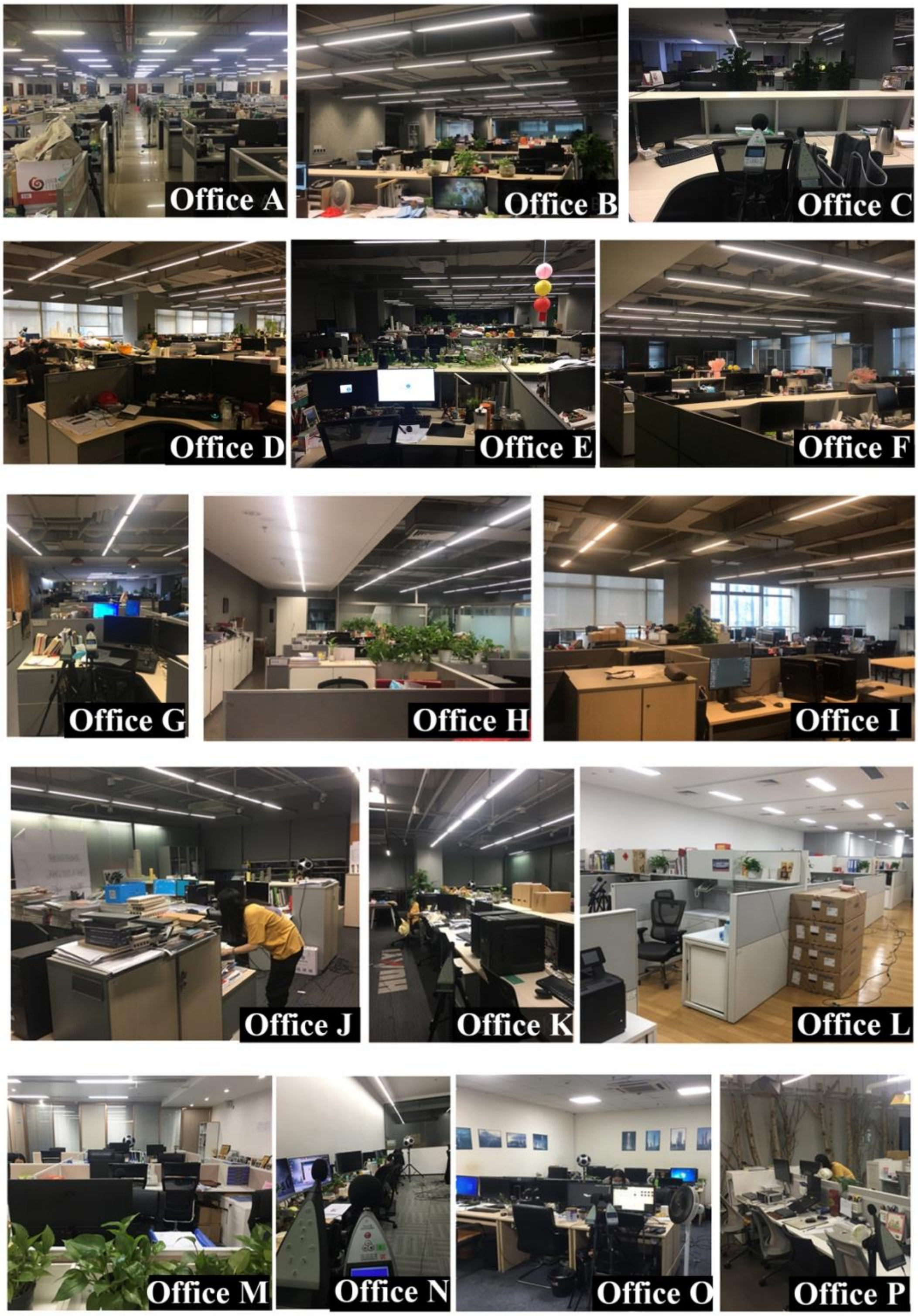


Figure 3.1 Pictures of some offices (Offices A-G are LOPOs, and offices H-P are MOPOs. Offices B and C have the same layout and decorations. Similarly, offices D–E have the same layout and decorations).

Table 3. 1 Basic information of the OPOs

Offices	**Area m^2**	**No.**[1]	**Workstation density**[2]**,%**	**Screen height, m**	**Ceiling type**	**Office length, m**	**Office width, m**	**Storey height,m**	**Office type**
A	714.7	72	10.07	1.10	Concrete	31.5	22.7	2.6	LOPO
B	723.2	94	13.00	1.15	Concrete	15.7~41.4	10.9~13.2	3.6	LOPO
C	723.2	94	13.00	1.15	Concrete	15.7~41.4	10.9~13.2	3.6	LOPO
D	670.2	83	12.38	1.15	Concrete	15.7~37.2	10.9~13.2	3.6	LOPO
E	670.2	83	12.38	1.15	Concrete	15.7~37.2	10.9~13.2	3.6	LOPO
F	670.2	83	12.38	1.15	Concrete	15.7~37.2	10.9~13.2	3.6	LOPO
G	464.8	50	10.76	1.15	Concrete	15.7~25.7	10.9~13.2	3.6	LOPO
H	89.3	10	11.20	1.15	Concrete	11.5	6.9	3.6	MOPO
I	169.1	12	7.10	1.15	Concrete	16.0	10.7	3.6	MOPO
J	82.8	14	16.91	1.15	Concrete	10.8	7.7	3.6	MOPO
K	82.8	14	16.91	1.15	Concrete	10.8	7.7	3.6	MOPO
L	142.7	14	9.81	1.69, 1.23	Suspended plasterboard	16.9	8.4	3.2	MOPO
M	66.4	14	21.07	1.05	Suspended plasterboard	10.1	6.6	2.6	MOPO
N	32.2	13	40.34	No screen	Concrete	8.4	3.8	2.9	MOPO
O	49.5	16	32.36	No screen	Suspended ceiling	8.8	5.6	2.9	MOPO
P	52.3	16	30.58	1.10	Concrete	7.7	6.8	3.4	MOPO

Note:

[1] The number of workstations;

[2] The spatial density of workstations.

3.1.2 Acoustic Measurement of OPOs

Speech decay-related measurements were conducted at night-time or at weekends when employees were absent, as recommended in ISO 3382-3:2022. The conventional method was used to determine speech decay-related parameters. The main reason is the facility of obtaining sound sources. In addition, the conventional method has no requirement on the spectrum shape of the sound source.

Since offices B and C have almost identical acoustic characteristics when not occupied, the speech decay-related measurement was carried out 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 applied as a sound source, and a sound level meter (B&K 2239) was utilized to record the signals. The software Dirac 6.05 was utilized to generate, play, record, and analyze the signals in OPOs (as shown in Figure 3.2). The sound power level of the sound source was determined in a reverberation chamber of Huaqiao University, Xiamen, China. Figure 3.3 shows the locations of the omnidirectional source (B&K 4292) and receivers in the reverberation chamber and a photo of the test site.

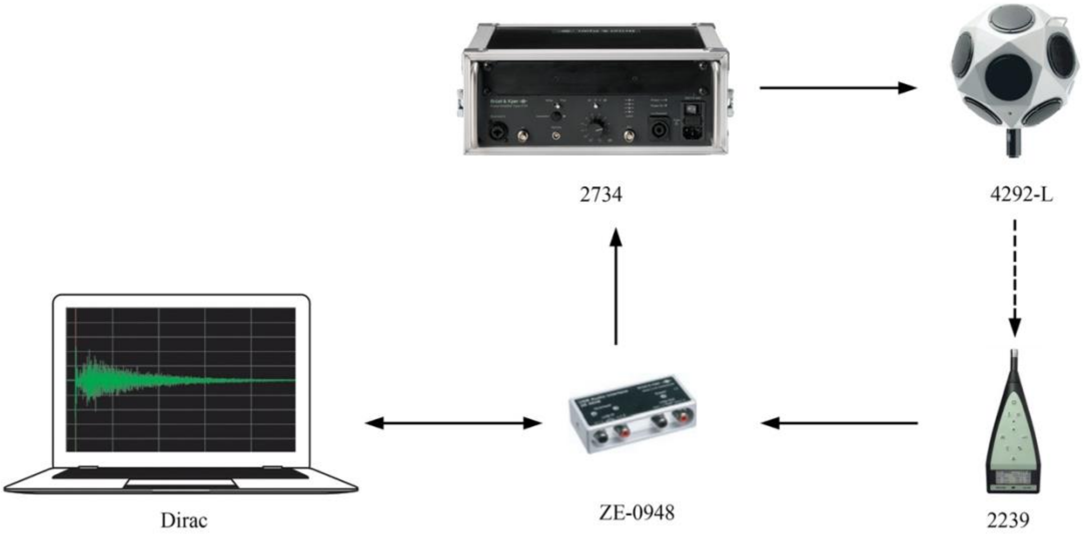


Figure 3. 2 Dirac acoustic measurement system used in OPOs

Measurement lines of measured OPOs, which indicate the path connecting the sound source and several successive measurement positions, were determined according to ISO 3382-3:2022. 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 chapter, 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 the tables. Based on the speech decay-related measurements, speech level at 4m distance ($L_{p,A,S,4m}$), spatial decay rate of speech ($D_{2,S}$), distraction distance (r_D), comfort distance (r_C), and background noise level ($L_{p,A,B}$) were determined.

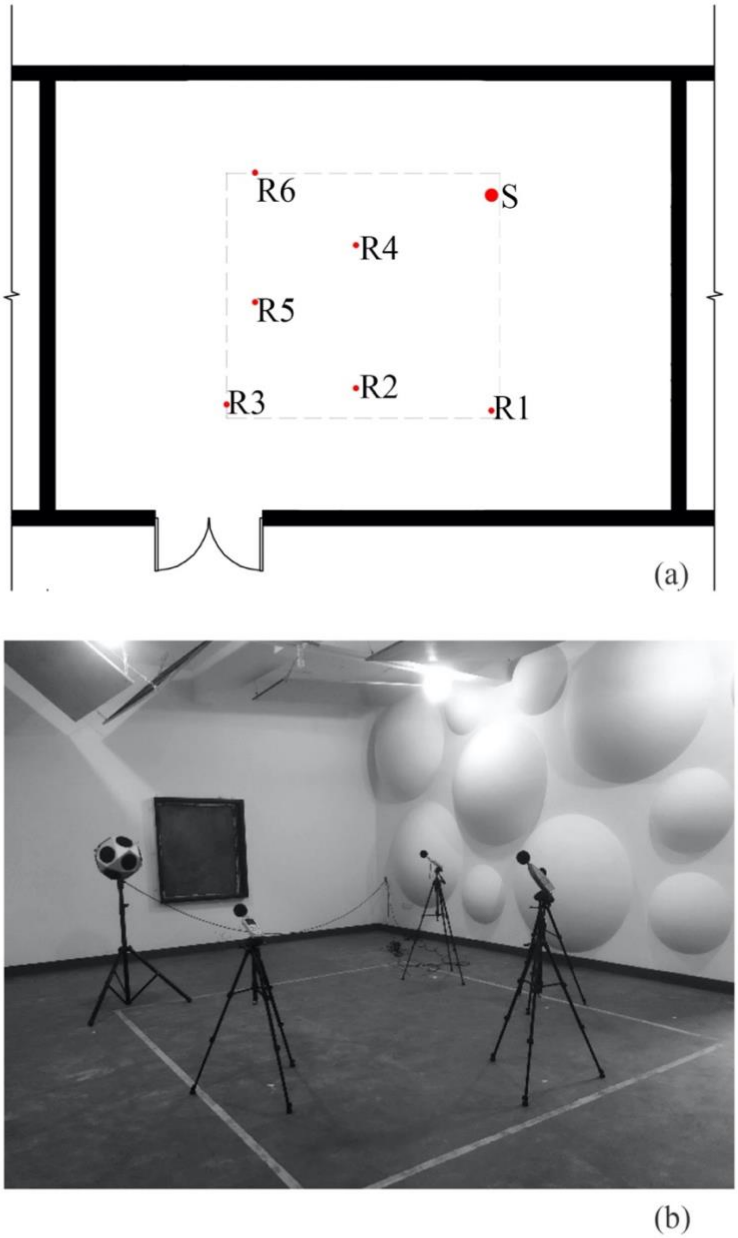


Figure 3. 3 Determination of sound power level in the reverberation room: (a) the schematic diagram of the sound source and receiving positions; (b) a photograph of the reverberation room

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. Each measurement position was more than 1.0 m away from the OPOs' windows and walls, and 1.2 m from the ground. 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 utilized to present the sound pressure levels of the active noises in OPOs. Two statistical sound levels (i.e., L_{10} and L_{90}) were also considered.

3.1.3 Questionnaire Survey and Respondents

The questionnaire consists of three parts. The first part aims to obtain the employees' basic 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 utilized to evaluate perceived speech privacy: "How much do you think others can hear your conversation content?" and "How much do you hear the content of others' 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 evaluated using 7-point scales (1 = "strongly low" ~ 7 = "strongly high"). Thirdly, the perceived noise level is rated using a 7-point scale (1 = "strongly low" ~ 7 = "strongly high"). Finally, acoustic satisfaction and the impact of acoustic interference on work productivity are evaluated. The question of acoustic satisfaction is evaluated from 1 (strongly dissatisfied) to 7 (strongly satisfied). The impact 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. 377 questionnaires were returned, out of which 348 were valid. The valid response rate is 92.3%. Of these valid responses, 286 questionnaires (99 females and 187 males) were from LOPOs, and 62 questionnaires (19 females and 43 males) were from MOPOs.

3.2. Results

3.2.1 Results of Objective Acoustic Measurements

Results of active noise levels are given in Table 3.2. 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 decay-related measurements are also listed in Table 3.2. 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 3382-3:2022, 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 3382-3:2022. 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 (2021) shows that the ranges of r_C values for the medium class C and the worst class D are from 7 to 9 m and from 9 to 11 m, respectively. In other words, offices A-G measured in this chapter have acceptable comfort distances, although they do not satisfy the requirement of good office acoustic conditions in annex C of ISO 3382-3:2022. 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 3382-3:2022.

Table 3. 2 Results of acoustic measurements in OPOs

Office	**Active noise level**			**Speech decay-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	$1.98^{\#}$	$54.95^{\#}$	$130.2^{\#}$	8.60	$44.02^{@}$
O	61.29	64.60	52.88	$1.99^{\#}$	$56.15^{\#}$	$194.4^{\#}$	$4.43^{@}$	$50.36^{\#}$
P	54.61	57.30	46.02	$1.48^{\#}$	$52.55^{\#}$	$137.3^{\#}$	6.30	$42.10^{@}$

Note:

$^{\#}$: "Poor" values based on the criteria in annex C of ISO 3382-3:2022, 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 3382-3:2022, 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 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 3.3 and Table 3.4.

As shown in Table 3.3, 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 decay-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 3.3).

Table 3. 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 3.4, 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 3. 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	$L_{p,A,\mathrm{B}}$
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.

3.2.2 Results of Subjective Ratings

The reliability and validity of the data collected from the questionnaires in this survey were tested using Cronbach's alpha and Kaiser-Meyer-Olkin (KMO) measures, and the calculated results are given in Table 3.5. Cronbach's alpha ranges from 0.793 to 0.856 (see Table 3.5), indicating that the question has good internal consistencies (S. Kang et al., 2017; Tavakol & Dennick, 2011; Xue, Mak, & Cheung, 2014). The KMO value is 0.871. As recommended in the previous study, KMO values above 0.5 are acceptable. (Carminati et al., 2016). Therefore, it can be considered that the scale has good reliability and validity.

The mean scores of participants' perception of the acoustic environments are listed in Table 3.6, and Table 3.7 shows how respondents' feelings about acoustic factors impact on acoustic satisfaction and work productivity by utilizing Spearman rank correlation coefficients. The greater the absolute value of the Spearman correlation coefficients, the stronger the correlation between variables.

Table 3. 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		

Table 3. 6 Mean scores and standard deviation (SD) of participants' 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)

Table 3. 7 Spearman rank correlation coefficients of acoustic factors, acoustic satisfaction and the impact of acoustic interference on work productivity

	Speech privacy		**Speech interferences**		**Perceived noise level**
	Own conversation privacy	**Other's conversation privacy**	**Re-concentration**	**Problem-solving speed**	
Acoustic satisfaction	0.162**	0.260**	-0.384**	-0.304**	-0.517**
Acoustic interference [1]	-0.184**	-0.229**	0.622**	0.591**	0.396**

Note:

[1] The impact of acoustic interference on work productivity;

Coefficients values with – symbols represent negative correlations.

Significant findings are shown in bold.

** Correlation is significant at the 0.01 level (two-tailed).

As shown in Table 3.7, 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 impact 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 negative impact of the acoustic environment on work productivity extremely stems from speech interference on employees' abilities of re-concentration and problem-solving speed.

3.2.3 Comparison of Investigation Results between LOPOs and MOPOs

Mann-Whitney U Tests are performed 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 3382-3:2022 to assess speech privacy in OPOs and should be taken into account at the same time. For better comparing the results of speech privacy between LOPOs and MOPOs, the objective results of speech decay-related parameters are summarised in Table 3.8. As seen in Table 3.8, 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 3.8). The larger the privacy score, the higher the speech privacy of OPOs. As shown in Table 3.8, all LOPOs except Office A have much higher privacy scores than MOPOs.

Table 3. 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

<table>
<tr><td>Typical values with good acoustic condition</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>5</td></tr>
<tr><td>Typical values with poor acoustic condition</td><td>-1</td><td>-1</td><td>-1</td><td>-1</td><td>-1</td><td>-5</td></tr>
<tr><td colspan="7">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 3382-3:2022. 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.</td></tr>
</table>

Mann-Whitney U Tests are used to explore whether there are significant differences in the assessment results of acoustic satisfaction and the impact of acoustic interference on work productivity between respondents in LOPOs and MOPOs. The results are shown in Table 3.9. Significant differences between LOPOs and MOPOs are found in terms of acoustic satisfaction and the impact of acoustic interference on work productivity, as seen in Table 3.9. 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 impact 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 3. 9 Mean scores and standard deviation (SD) of participants' 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***
Acoustic interference [1]	3.77 (1.04)	3.42 (1.37)	**0.038***

Note:

[1] The impact of acoustic interference on work productivity;

[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 3.10). 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 3. 10 Mean scores and standard deviation (SD) of participants' 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 utilized to explore how the acoustic factors affect acoustic satisfaction and work productivity. The results are listed in Table 3.11 and Table 3.12.

As seen in Table 3.11, 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 3. 11 Spearman rank correlation coefficients of acoustic satisfaction and factors of the acoustic environment in LOPOs and MOPOs

	Speech privacy		**Speech interferences**		**Perceived noise level**
	Own conversation privacy	**Other's conversation privacy**	**Re-concentration**	**Problem-solving speed**	
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 3.12, the impact of acoustic interference on work productivity in LOPOs has 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 3. 12 Spearman rank correlation coefficients of acoustic interference on work productivity and factors of the acoustic environment

	Speech privacy		**Speech interferences**		**Perceived noise level**
	Own conversation privacy	**Other's conversation privacy**	**Re-concentration**	**Problem-solving speed**	
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).

3.3. Discussion

3.3.1 Acoustic Environment of Open-plan Offices

The active noise levels (L_{Aeq}) in 16 Chinese OPOs ranges from 46.9 to 61.3 dBA (see Table 3.2), which is consistent with previous studies (Pyoung Jik Lee et al., 2016; Trompette & Chatillon, 2012). The values of L_{90} in this chapter (41.8-52.9 dBA) are consistent with the findings of S. K. Tang (1997), 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. (2021), in which the L_{90} values of 43 Australian OPOs were between 27.1 and 38.7 dBA. As reported by previous studies (De Salvio, D'Orazio, & Garai, 2021; Yadav et al., 2021), 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. also found similar results that noise levels from operating HVAC in China were louder than those in Korea (Pyoung Jik Lee et al., 2016). It is worth noting that the L_{Aeq} is significantly associated with the L_{90} (see Table 3.3). This may be because of the Lombard effect. Speech noise level increase with the increase in L_{90}, and then the active noise level increases. Bottalico et al. found that the Lombard effect can be generated when the background noise level is more than 43.3 dBA (Bottalico, Passione, Graetzer, & Hunter, 2017).

The values of $D_{2,S}$ in nine MOPOs (1.48-4.53 dBA) are much smaller than those in OPOs (4.0-12.4 dBA) measured in previous studies (Annu Haapakangas et al., 2017; Keränen & Hongisto, 2013; Virjonen et al., 2009). This inconsistency may be due to the little sound absorption of the ceiling in OPOs. The high absorption coefficient of ceilings has great effectiveness to increase spatial decay of speech (i.e., $D_{2,S}$) in OPOs (ISO 3741, 2010). The materials of ceilings in measured OPOs, however, are concrete or suspended plasterboard with a very low sound absorption coefficient (see Table 3.1).

The role of $L_{p,A,B}$ on r_D is confirmed again by the negative correlation between background noise levels and distraction disturbance (see Table 3.3). This result is consistent with previous studies (Annu Haapakangas et al., 2017; Passero & Zannin, 2012; Virjonen et al., 2009). In addition, the findings of no significant correlation between $D_{2,S}$ and r_D and between $D_{2,S}$ and $L_{P,A,S,4m}$ are also in agreement with the findings of Haapakangas et al. (2017).

Employees' acoustic satisfaction depends largely on perceived noise level, speech interference, and speech privacy in OPOs (see Table 3.7). Among these factors, the perceived noise level has the highest negative correlation with acoustic satisfaction, which is in line with a previous study (S. Kang et al., 2017). In addition, the speech interference on re-concentration is found to have the highest positive correlation with the impact of acoustic interference on work productivity (see Table 3.7), which demonstrates again previous findings (Annu Haapakangas et al., 2014; C. M. Mak & Lui, 2011; Pierrette et al., 2015; Smith-Jackson & Klein, 2009; Venetjoki et al., 2007) 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 3.6), which are in line with the study of Banbury and Berry (2005). However, these results are not in agreement with the study of S. Kang et al. (2017), 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 work and Banbury and Berry (2005) were conducted in commercial OPOs in which information interchanges with each cooperative company by telephone are the common activity, while the survey of S. Kang et al. (2017) was carried out in university research OPOs in which occupants' main activity is to complete complex mental work independently.

3.3.2 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 3.4), implying that a smaller spatial density could give rise to lower $L_{p,A,S,4m}$. As reported by Haapakangas et al. (2017), smaller $L_{p,A,S,4m}$ values are associated with a lower probability of high noise disturbance in the OPO. In other words, increased spatial density has an adverse effect on the decrease in speech disturbance, which supports the view of Gavhed and Toomingas (2007) that a high density of workstations in OPOs may result in more noise disturbances. Furthermore, the low spatial density of workstations means that personal workspace is larger in OPOs, which is important in the improvement of employees' satisfaction with office layout (S. Kang et al., 2017; Lou & Ou, 2019). 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 (Keränen & Hongisto, 2013; Kernen et al., 2020) and the ISO 22955:2021, in which screen height has significant effects on sound attenuation in OPOs. A possible explanation is the limited samples of screen heights in this chapter. Most of the screens in measured OPOs are 1.15 m in height (see Table 3.1).

As shown in Table 3.4, 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 target values for good acoustic environments. In particular, increasing storey height is beneficial to decrease the noise level of OPOs. Keränen and Hongisto (2013) 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 3.4). 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 (2013), 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 chapter, 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.

3.3.3 Comparison of Acoustic Environments between LOPOs and MOPOs

Good speech privacy can reduce acoustic distractions to work productivity (Annu Haapakangas et al., 2017; Haka et al., 2009; Roelofsen, 2008). With the exception of Office A, all LOPOs have higher privacy scores than MOPOs (see Table 3.8), and the mean scores of perceived speech privacy are greater in LOPOs than in MOPOs (see Table 3.10). 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 3.9). 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 impact 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 decay-related parameters rather than adding the weighted score of each parameter based on its effects on perceived speech privacy. The weightings of speech decay-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 decay-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 utilized to explore the correlations between perceived speech privacy and speech decay-related parameters. As mentioned in Section 3.1.2, 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 decay-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 decay-related parameters on perceived speech privacy for future studies.

3.4. Summary

In this chapter, both physical and subjective measurements were conducted to evaluate 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 ($D_{2,S}$), the comfort distance (r_C) and speech level at 4 m distance ($L_{p,A,S,4m}$). Besides, distraction distance (r_D) is significantly correlated with the background noise level ($L_{p,A,B}$).
2) Both acoustic satisfaction and the impact 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) The acoustic satisfaction of employees in MOPOs is higher than in LOPOs. Employees at MOPOs experience less speech disturbance than at LOPOs. Speech privacy is an important index affecting employees' work productivity in LOPOs, but not in MOPOs.

Chapter 4

The Effect of Room Acoustic Quality Levels on Work Performance and Perceptions in Open-plan Offices

This chapter introduces a laboratory experiment which was conducted to determine the effects of acoustic quality levels on work performance and acoustic environmental perceptions in OPOs. A total of forty-one students (aged from 18 to 31 years) from Huaqiao University were recruited in this experiment. A cognitive task (serial recall task) and perceptions of the acoustic environment reported by all participants were tested in eight acoustic conditions. These acoustic conditions represent the acoustic environments of two receiving locations in four office scenes. As recommended in the revised international standard (ISO 3382-3:2022), the sound quality levels of the four office scenes can be divided into four levels could be divided into four levels, namely, good, high-medium, low-medium, and poor acoustic qualities.

The validity of the acoustic classification criteria in ISO 3382-3:2022 was confirmed. The results show that occupants who worked in OPOs with good acoustic quality have strongly larger work performance and acoustic satisfaction than those who worked in OPOs with poor acoustic quality. In addition, a comparison of objective and subjective results between the two receiving locations implies that greater distance from the person speaking can improve work performance and acoustic satisfaction in OPOs with poor acoustic quality. However, this improvement of greater speaker-receiver distance is negligible in OPOs where acoustic quality is good.

4.1. Description of the Experimental Procedure

4.1.1 Participants

In this chapter, 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.

4.1.2 Laboratory Room

A 6.6 (length) x 6.5 (width) x 3.0 m (height) test laboratory was used (Figure 4.1). 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 4.1, two workstations, R1 and R2, were arranged as test positions and were separated by a 1.5 m high partition. Workstation E was used as the control console.

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.

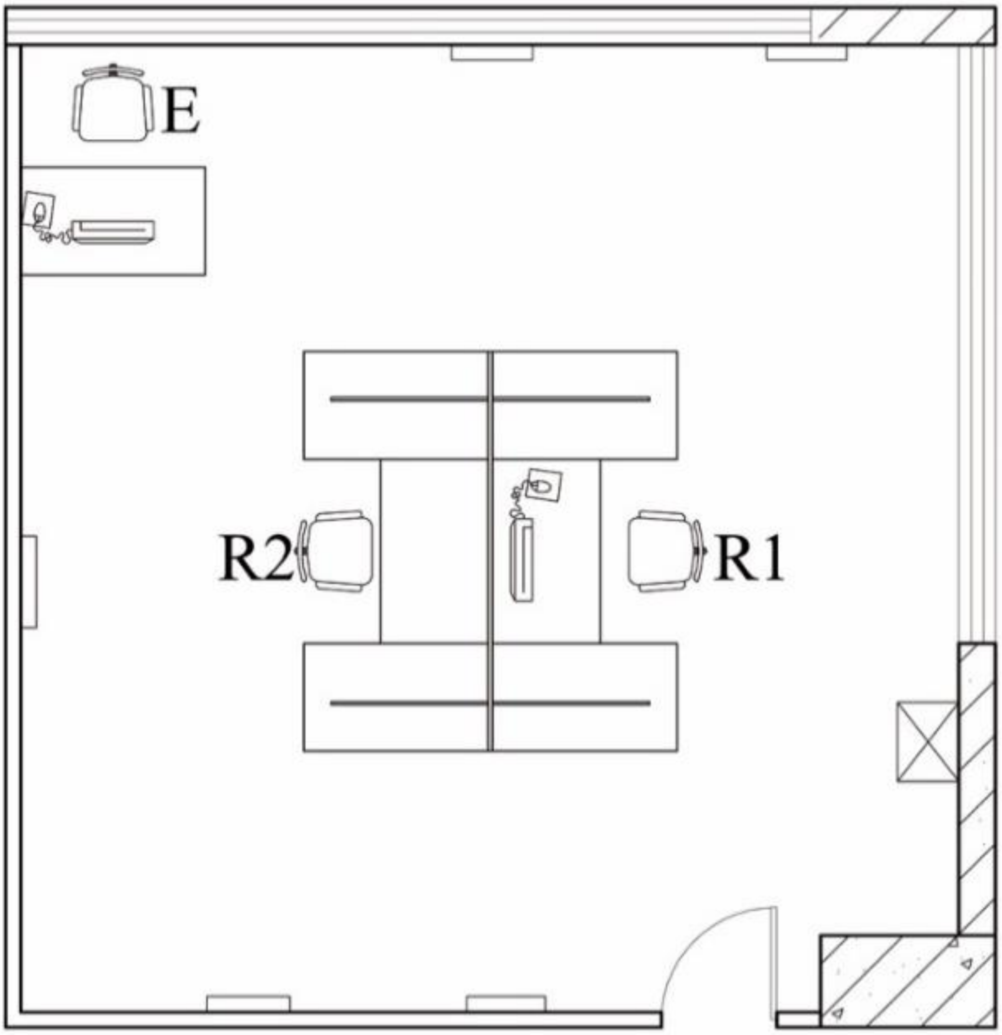


Figure 4. 1 Layout of the test laboratory (E represents the position of the control console, and R1 and R2 represent the test positions).

4.1.3 Open-plan Offices

Based on the in-site measurement results of our recent study (S. Kang et al., 2022b), an open-plan office was modelled using Auto CAD and SketchUp software. The layout of the simulated open-plan office is shown in Figure 4.2. 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.

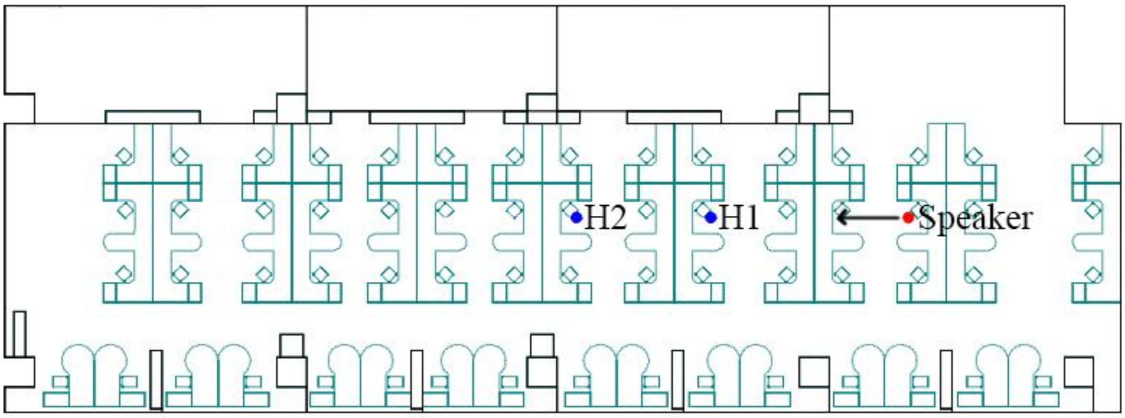


Figure 4. 2 Layout of the simulated open-plan office (H1 and H2 present receiving positions).

Odeon simulation software (version 13) was used for the acoustic simulation. This chapter created four office scenes by modifying the sound absorption at each surface. Detailed information for each office scene is presented in Table 4.1. According to Annex C of ISO 3382-3:2022, Scene 1 had good room acoustic quality (Table 4.1). 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, because the value of speech decay-related parameters (i.e., $D_{2,S}$, $L_{p,A,S,4m}$, r_C, and r_D) was within the poor acoustic quality range (Table 4.1). Although the value of speech decay-related parameters of scenes 2 and 3 was between the range of good and poor acoustic quality (see Table 4.1), the acoustic environment of Scene 2 was better than that of Scene 3. This is because occupants in OPOs with short r_D and small $L_{p,A,S,4m}$ are less likely to be disturbed by speech noise, according to previous studies (Annu Haapakangas et al., 2017; Valtteri Hongisto, Haapakangas, et al., 2016). Thus, the room acoustic quality of the four office scenes could be divided into good, high-medium, low-medium, and poor.

All office scenes had a speaker location and two receiving locations (see Figure 4.2). As shown in Table 4.1, 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 4.2). 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 SPL of speech ($L_{A,S}$) and total SPL of acoustic conditions ($L_{Aeq,total}$) changed in the ranges of 35.8–46.4 dBA and 40.7–46.8 dBA (Table 4.1), respectively.

Table 4. 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.

Scene	**Position** [1]	**Condition**	$D_{2,s}$	$L_{p,A,S,4m}$	r_C	r_D	$L_{A,S}$	$L_{p,A,B}$	$L_{Aeq,total}$	**EDT**	**Level** [2]
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:

[1] Receiving positions;

[2] Room acoustic quality level;

"Poor" values are based on the criteria in Annex C of ISO 3382-3:2022, 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 3382-3:2022, 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.

4.1.4 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 4.1. Figure 4.3 gives 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). All sound stimuli were intended to represent the acoustic environment of four office scenes when a single person was speaking in a natural tone.

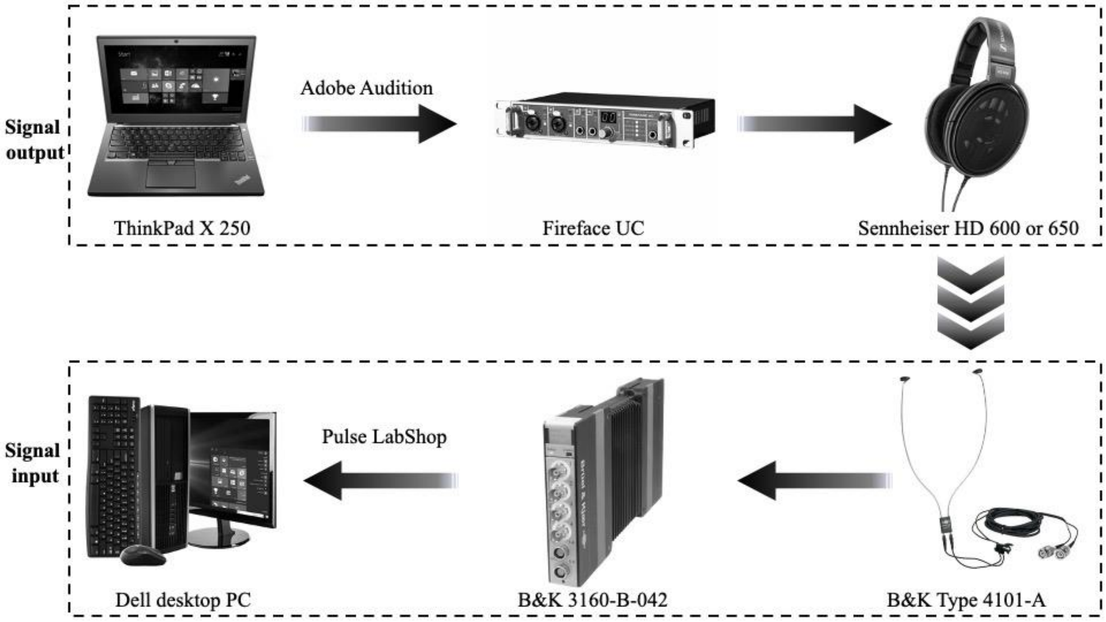


Figure 4.3 Schematic drawing of playing and measuring the test material in an anechoic chamber

The sound materials used in this chapter comprised 14 speech recordings of female and male native Mandarin speakers in an anechoic room before the experiment. Moreover, ventilation sounds were recorded in an OPO and used as the background noise in this experiment. The above speech and ventilation sounds have been used in our previous studies (S. Kang & Ou, 2018; Lou & Ou, 2020; Y. Zhang et al., 2021). Detailed information about ventilation sounds and speech materials can be found in the study of Y. Zhang et al. (2021).

4.1.5 Cognitive Task

In this experiment, the serial recall task was tested. It is frequently utilized to determine work performance in OPOs (Haka et al., 2009; Schwarz et al., 2015; Yadav & Cabrera, 2019). Each serial recall task included 10 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 the study of Y. Zhang et al. (2021). Accuracy rate (%) was considered as the objective performance and was calculated as the number of correctly recalled words divided by the total number of words.

4.1.6 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) gave basic information on participants’ age, gender, and whether they have 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.

4.1.7 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. Figure 4.4 gives the procedure of this experiment.

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 and 650 headphones, an RME Audio Fireface UC sound card, and a ThinkPad X250 laptop (see Figure 4.3).

The experiment lasted for approximately 2 h 20 min. A researcher controlled all the acoustic conditions in the laboratory. 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.

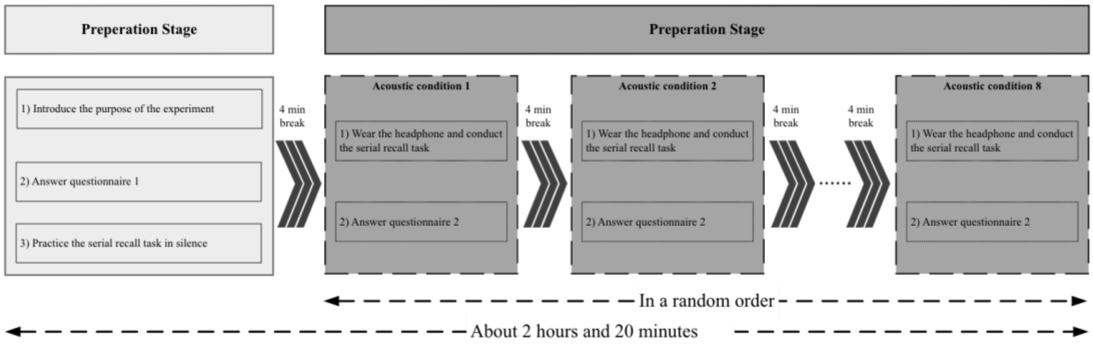


Figure 4. 4 The experimental procedure

4.1.8 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 locations, 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.

4.2. Results

4.2.1 Effects of Acoustic Conditions at a Close Receiver (H1)

The mean scores of 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 4.5. In addition, the mean score of the mental workload, measured with the NASA-TLX, in each office scene is provided in Figure 4.5. A higher score indicates a higher mental workload.

For the objective performance, the average accuracy rates follow the expected pattern; the accuracy rates decrease when the room acoustic quality worsens (Figure 4.5). 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 strongly larger than that in ML_H1 (P<0.05) and PO_H1 (P<0.01).

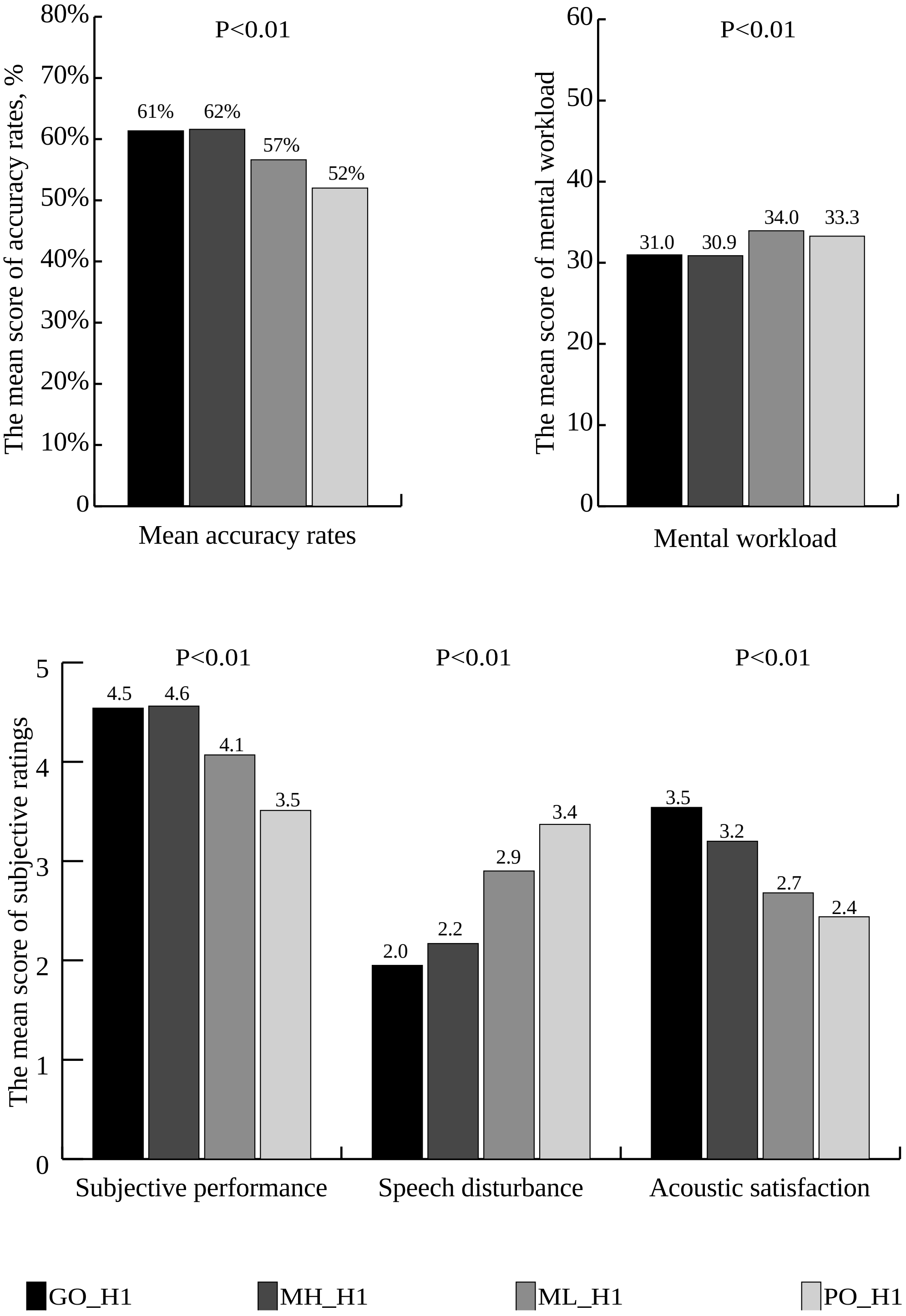
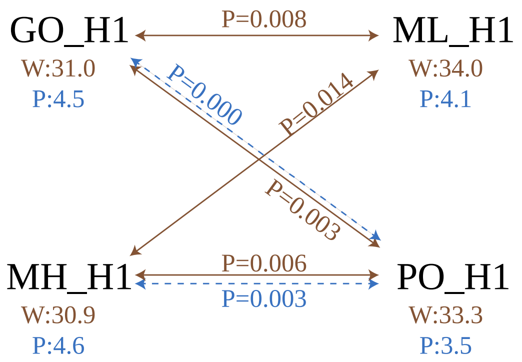


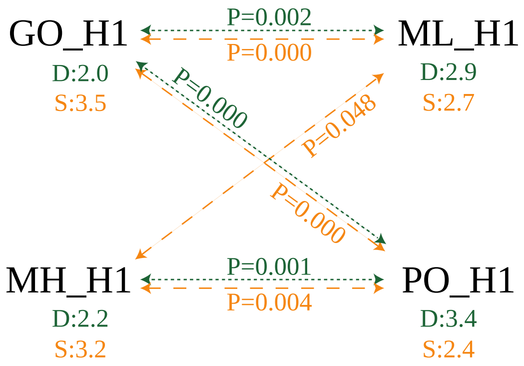
Figure 4.5 Mean results of objective performance and subjective evaluation of participants at the receiving position H1 in different office scenes. Room acoustic quality levels in scenes 1, 2, 3, and 4 are described by GO, MH, ML, and PO, respectively, and H1 refers to the position at 7 m from the speaker. Accuracy rate (%)

was the number of correctly recalled words divided by the total number of words. The mental workload of the participants was the sum of all NASA-TLX item scores.

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 4.5). Subsequently, pairwise comparisons were conducted, and the results are provided in Figure 4.6. The average scores of subjective evaluations, provided in Figure 4.5, and the analysis of post hoc tests, provided in Figure 4.6, 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

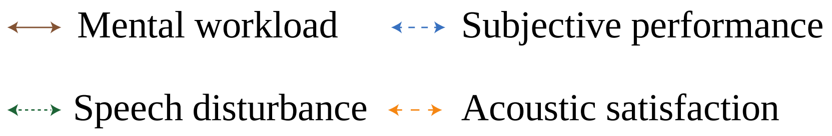


Figure 4. 6 Pairwise comparisons of room acoustic quality levels at receiving position H1 in terms of mental workload, subjective performance, speech disturbance, and acoustic satisfaction. Room acoustic quality levels in scenes 1, 2, 3, and 4 are described by GO, MH, ML, and PO, respectively, H1 refers 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.

4.2.2 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 4.7.

For the objective performance, the average accuracy rates decreased when the room acoustic quality worsened (Figure 4.7). 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 4.7). 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 4.6, and the results of pairwise comparisons, shown in Figure 4.8, 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).

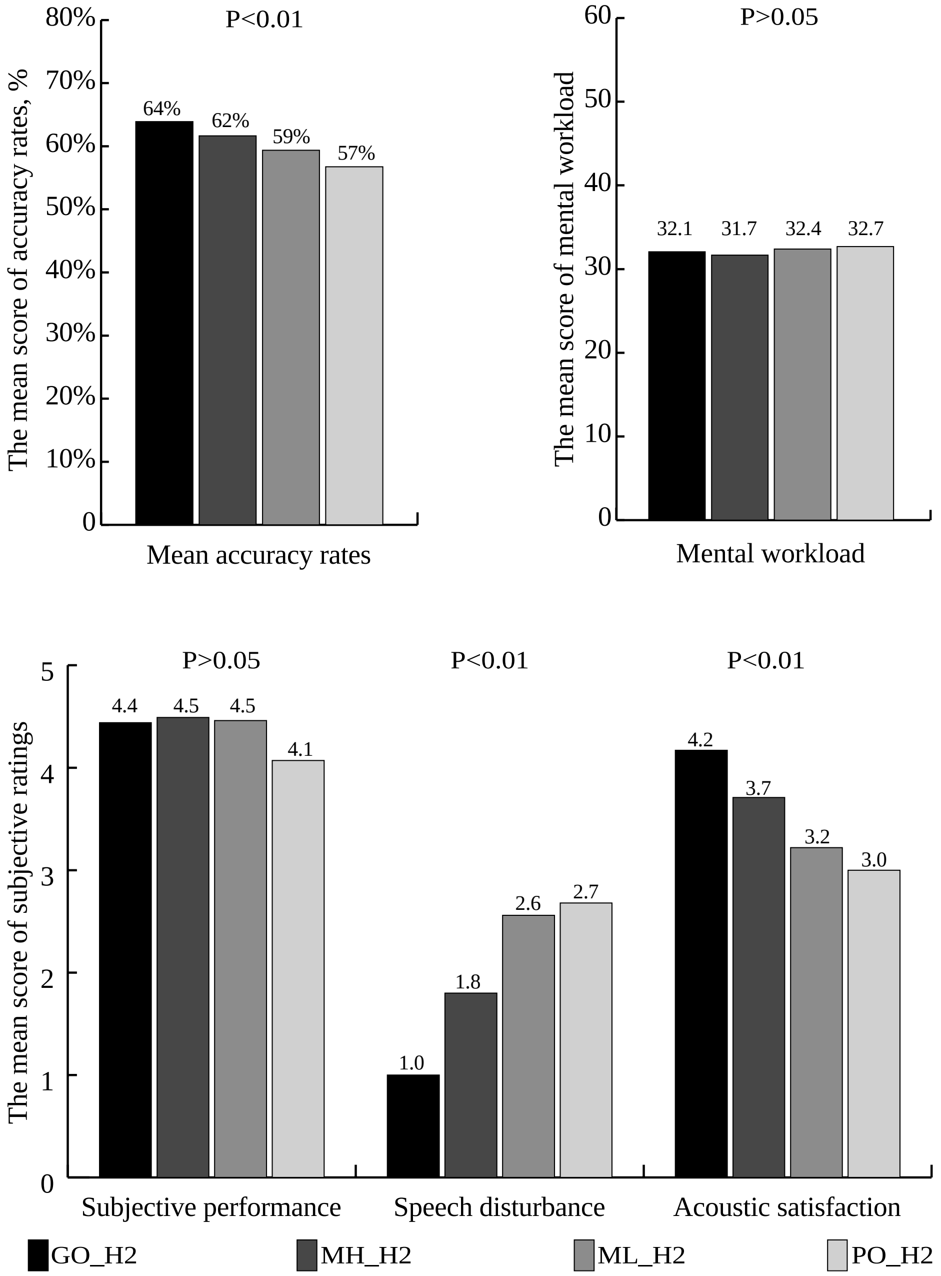


Figure 4.7 Mean results of objective performance and subjective evaluation of participants at the receiving position H2 in different office scenes. Room acoustic

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.

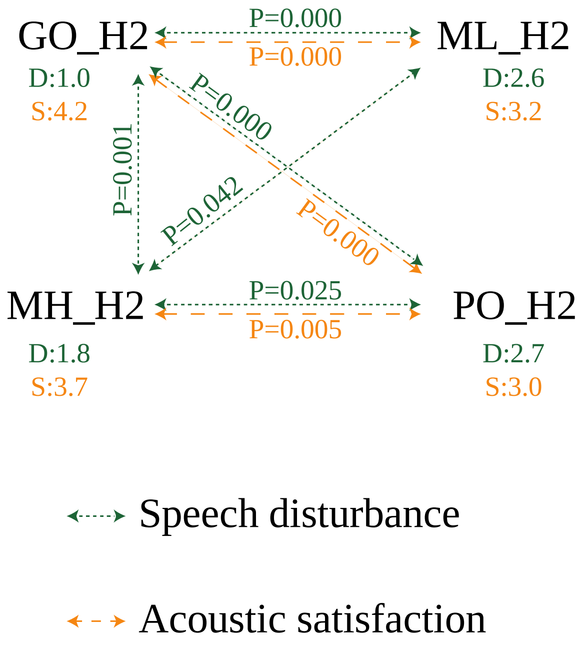


Figure 4. 8 Pairwise comparisons of room acoustic quality levels at the receiving position H2 in terms of speech disturbance and acoustic satisfaction. Room acoustic quality levels in scenes 1, 2, 3, and 4 are described by GO, MH, ML, and PO, respectively, H2 refers to the position at 11 m from the speaker, and D and S refer to the mean scores of speech disturbance and acoustic satisfaction, respectively.

4.2.3 Effects of the Speaker-receiver Distance

As shown in Figures 4.5 and 4.7, 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 4.5 and 4.7).

Paired-samples t-tests and Wilcoxon tests were performed to explore the differences between the two receiving locations, H1 and H2, regarding objective performance and subjective evaluations. The results are presented in Table 4.2. The average results, shown in Figures 4.5 and 4.7, and the pairwise comparison results, shown in Table 4.2, 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 4. 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.

4.3. Discussion

4.3.1 Comparisons among Different Office Scenes

The analysis presented in Section 4.2 demonstrates that the impact of room acoustic quality levels on work performance and reported acoustic environmental perceptions differed for different office scenes and receiving positions. The room acoustic quality levels at the two receiving locations were compared and ranked according to each objective and subjective item (Table 4.3). 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 4.3) 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 4.3, 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 environment.

Table 4. 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.

		Accuracy rate	**Speech disturbance ^{R}**	**Acoustic satisfaction**
Acoustic conditions at the position H1	**GO_H1**	A-	A	A
	MH_H1	A	A-	A-
	ML_H1	B	B	B
	PO_H1	B	B-	B-
Acoustic conditions at the position H2	**GO_H2**	A	A	A
	MH_H2	A-	B	A-
	ML_H2	B	C	B
	PO_H2	B-	C-	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.

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 (see Table 4.3). As recommended in the ISO 3382-3:2022 Annex C, 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. More specifically, 1) open-plan offices with typically 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 typically 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 (see Figures 4.5 and 4.7).

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 locations (H1 and H2) in terms of accuracy rate and subjective performance in scenes 1 and 2 (see Table 4.2), implying that the increase in source-receiver distance does not lead to 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 locations 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 4.2 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. Concerning office scene 1, the privacy distance (r_P), which refers to the distance between the speaker and the workstation when the STI drops to 0.2 (ISO 3382-3, 2012), is 9.96 m. The disturbance of speech on work performance disappears when STI falls below 0.2 (ISO 3382-3, 2012; V. Hongisto, 2005). That is to say, speech noise in office scene 1 has little interference with the work performance if the speaker-receiver distance is more than 9.96 m. In this chapter, the mean speech disturbance score at H2 (1.0) demonstrates that the negative effect of speech is few when the speaker-receiver distance exceeds r_P (i.e., STI < 0.2). Concerning office scene 4, the r_D value is 12.3 m, indicating that the distracting effects of speech noise are significant within the range of 12.3 m from the speaker. In addition, at a range of 12.3 m, speech intelligibility decreases with the speaker-receiver distance, reducing distracting effects of speech on occupants in OPOs (Annu Haapakangas et al., 2020; V. Hongisto, 2005).

4.3.2 Limitations

The experimental findings of this chapter are expected to be utilised as references for designing pleasant acoustic environments in open-plan offices. Despite these findings, this chapter 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 chapter is typical for large-sized open-plan offices based on previous studies (Keränen & Hongisto, 2013; Virjonen et al., 2009). In contrast, the speaker-receiver distance of 11 m could be large or even non-existent for small-sized open-plan offices (S. Kang et al., 2022b). 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 OPO could not be reconstructed, due to 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 (Lavandier & Culling, 2010). The convolved background noise of this chapter 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 the impact of background noise in the laboratory. Despite these limitations, the study in this chapter is meaningful because it provides evidence for academic and design practitioners that occupants in open-plan offices with high-medium or good acoustic quality perform better, and their acoustic satisfaction is higher.

4.4. Summary

This work was the first experimental laboratory study on the effects of room acoustic quality levels in open-plan offices. Both the work performance and perceptions of the acoustic environment were examined at two receiving locations in four office scenes corresponding to different acoustic quality levels. The findings of this chapter 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 environments 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 decreased when the acoustic quality level increased from poor to good. In poor acoustic environments, 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 acoustic environments.

Chapter 5

Effects of Speech Intelligibility and Reverberation Time on the Serial Recall Task in Chinese Open-plan Offices: A Laboratory Study

This chapter introduces a laboratory experiment which was carried out 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 chapter varied in speech intelligibility (STI of 0.21, 0.42, and 0.61) and reverberation time (RT of 0.4s and 1.4s). Thirty-two students (aged 18 to 30 years) from the Hong Kong Polytechnic University, Hong Kong, took part in this experiment.

The main outcome 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.

5.1. Description of the Experimental Procedure

5.1.1 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 5.1.

Table 5. 1 Basic information of the participants

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

Note:

[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.

5.1.2 Laboratory Room

A 4.2 (length) x 3.2 (width) x 2.8 m (height) test laboratory was used (Figure 5.1). As shown in Figure 5.1, 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 5.1). The background noise level in the laboratory was around 33.3 dBA.

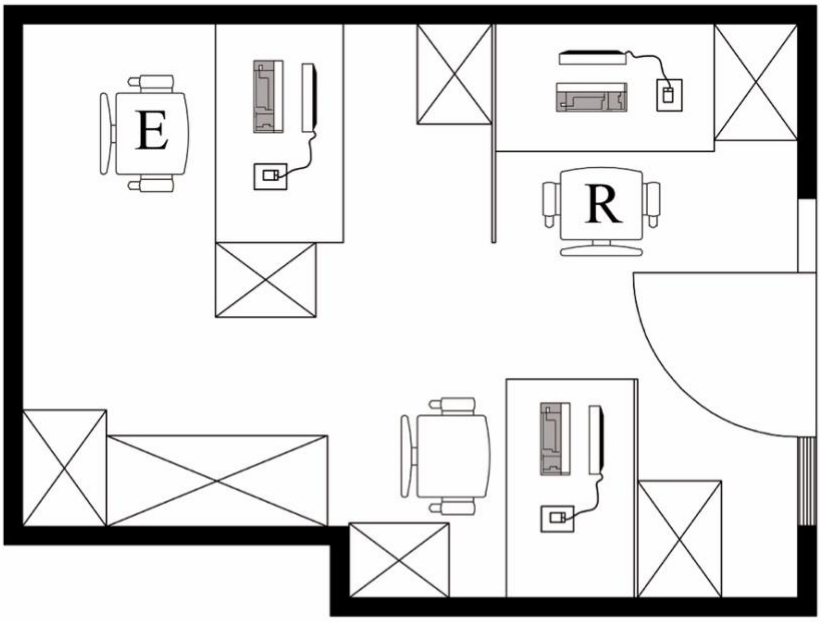


Figure 5. 1 Layout of the test laboratory (E and R represent the position of the control console and the test position, respectively).

5.1.3 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 (S. Kang et al., 2022b). 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 5.2 and Figure 5.2, respectively. According to the in-situ measurement results conducted in accordance with ISO 3382-3:2022, the values of $L_{p,A,S,4m}$ and $D_{2,S}$ were 53.8 dBA and 3.6 dBA (see Table 5.2), respectively. In addition, the reverberation time (T_{30}) of the OPO was 0.77s on average over 250 to 4000 Hz octave bands.

Table 5. 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
Note: T_{30} averaged over 250 to 4000 Hz octave bands			

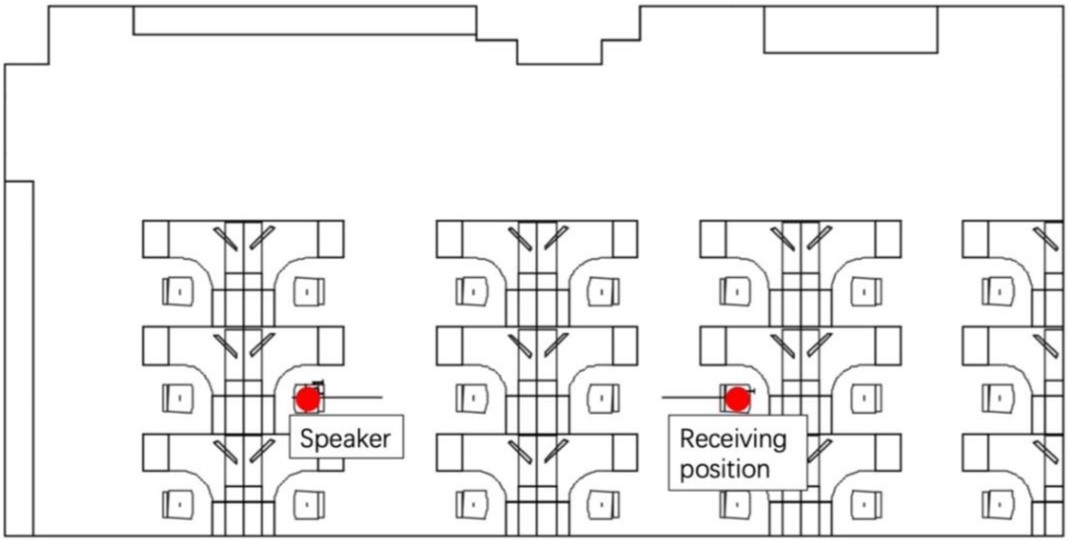


Figure 5. 2 Layout of the simulated open-plan office.

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 5.2 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 (Cabrera, Yadav, & Protheroe, 2018; Valtteri Hongisto, Keränen, Labia, & Alakoivu, 2021; S. Kang et al., 2022b; Kernen et al., 2020; Nilsson et al., 2008; Park et al., 2020; Passero & Zannin, 2012; Virjonen et al., 2009; Yadav et al., 2019; M. Zhang et al., 2012), which measured acoustic performance in real OPOs, the OPOs' RT is between 0.2s and 1.5s (see Figure 5.3). As shown in Figure 5.3, most open-plan offices have RTs between 0.2s and 0.8s, with a few exceeding 1.0s. This chapter 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 office environments have been built by modifying the materials of surfaces (i.e., 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 chapter.

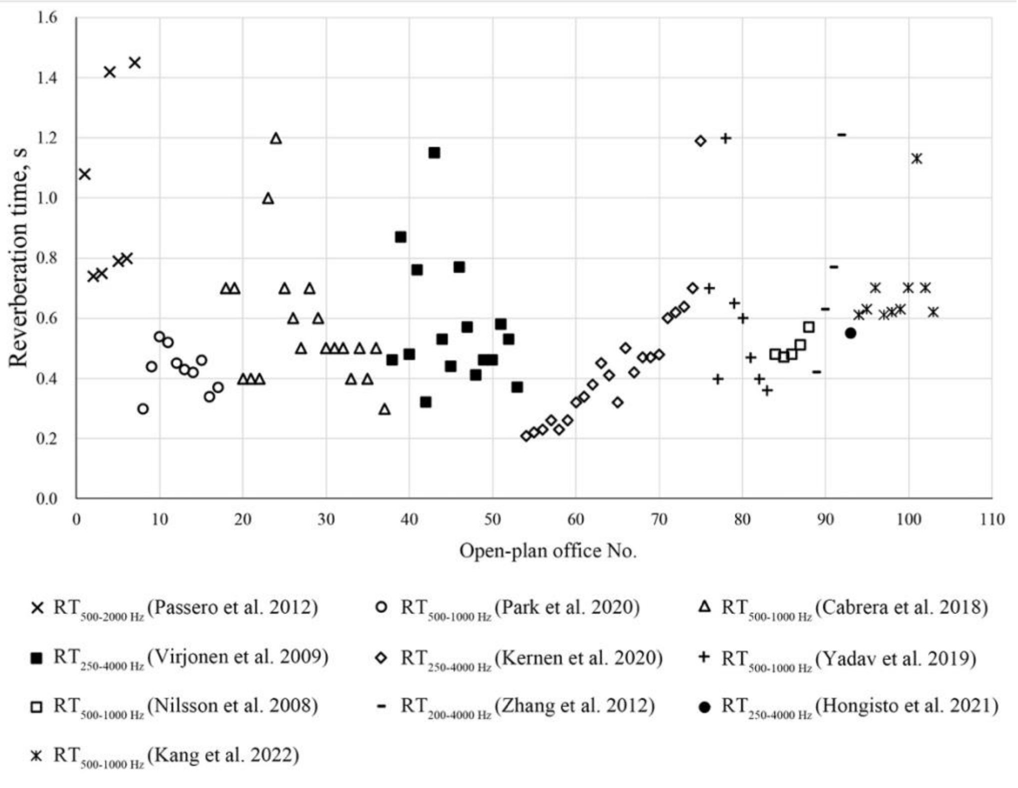


Figure 5. 3 Reverberation time of open-plan offices

5.1.4 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 previous studies (V. Hongisto, 2005; Valtteri Hongisto et al., 2004). In this chapter, the STI was calculated based on the method described by Hongisto et al. (V. Hongisto et al., 2004), which was frequently used in previous studies (Haka et al., 2009; Lou & Ou, 2020; Y. Zhang et al., 2021). Furthermore, a silence condition without playing any sounds was added as a reference. Thus, a total of six acoustic conditions were considered in this chapter.

The speech materials used in this chapter 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 position (see Figure 5.2). 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 (S. Kang & Ou, 2018; Lou & Ou, 2020; Y. Zhang et al., 2021). Details on speech materials and ventilation sounds were shown in the study of Zhang et al.(2021).

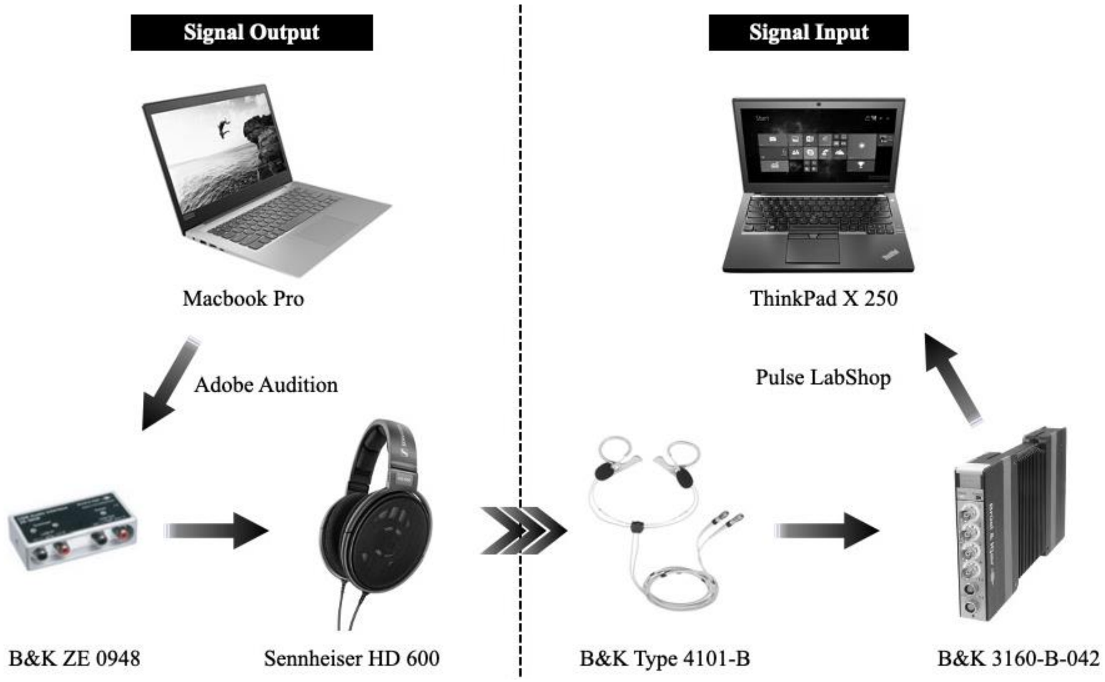


Figure 5. 4 Schematic drawing of measuring the test material

The schematic drawing of playing and measuring the test materials is shown in Figure 5.4. 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 5.3 shows the acoustic parameters of each acoustic condition, and Figure 5.5 shows the SPL of the speech at the receiver position in each acoustic condition and the SPL 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. As shown in Figure 5.5, curves represent the equivalent sound pressure level of each sound source during the test time under each condition. Figure 5.6 shows the T_{30} values by 1/1 octave bands for the absorbing and reverberant models, which were given by the Odeon software.

Table 5. 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	0.4	0.4	0.21
	Abs_0.42	50.8	45.4	52.4	5.4	0.4	0.4	0.42
	Abs_0.61	54.2	35.7	54.5	18.5	0.4	0.4	0.61
Reverberant model	**Rev_0.21**	50.0	49.3	52.8	0.7	1.4	1.4	0.21
	Rev_0.42	49.6	35.4	50.1	14.2	1.4	1.4	0.42
Silence		--	33.3	33.3	--	--	--	--

Note:

[1] The A-weighted SPL of speech;

[2] The A-weighted SPL 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 5.2);

[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. (2004) using EDT values and SNR.

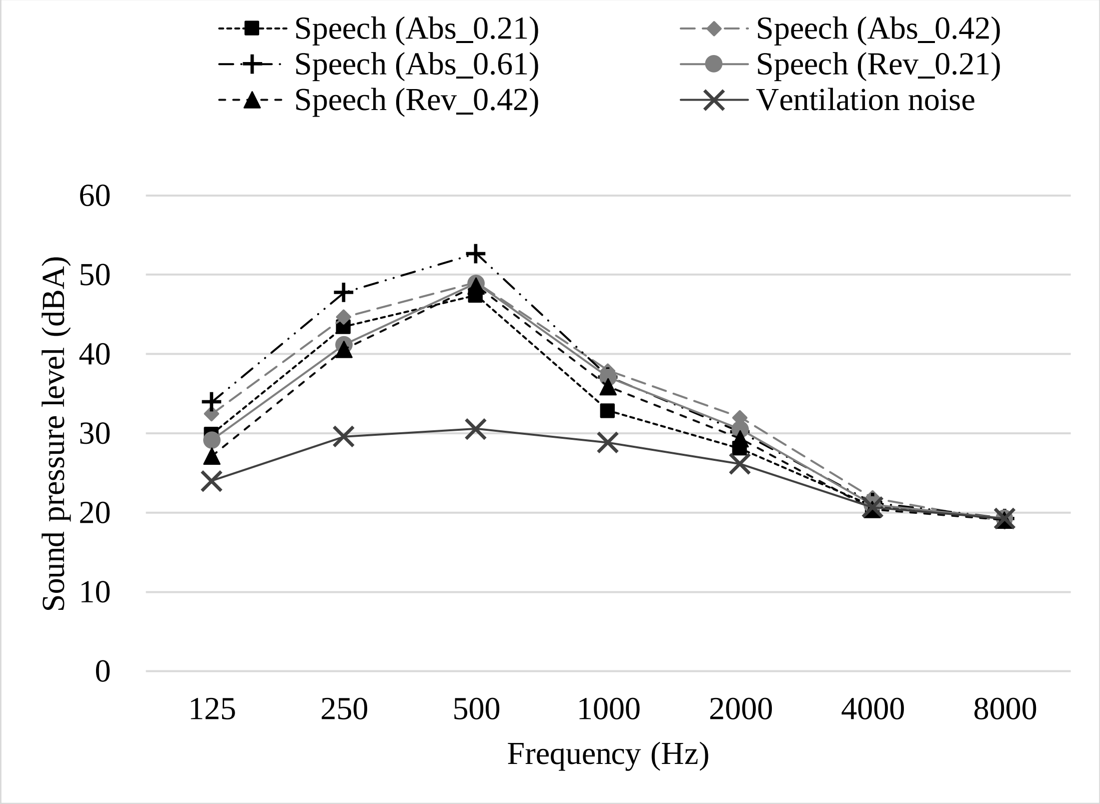


Figure 5. 5 Average sound pressure levels of speech and ventilation noise.

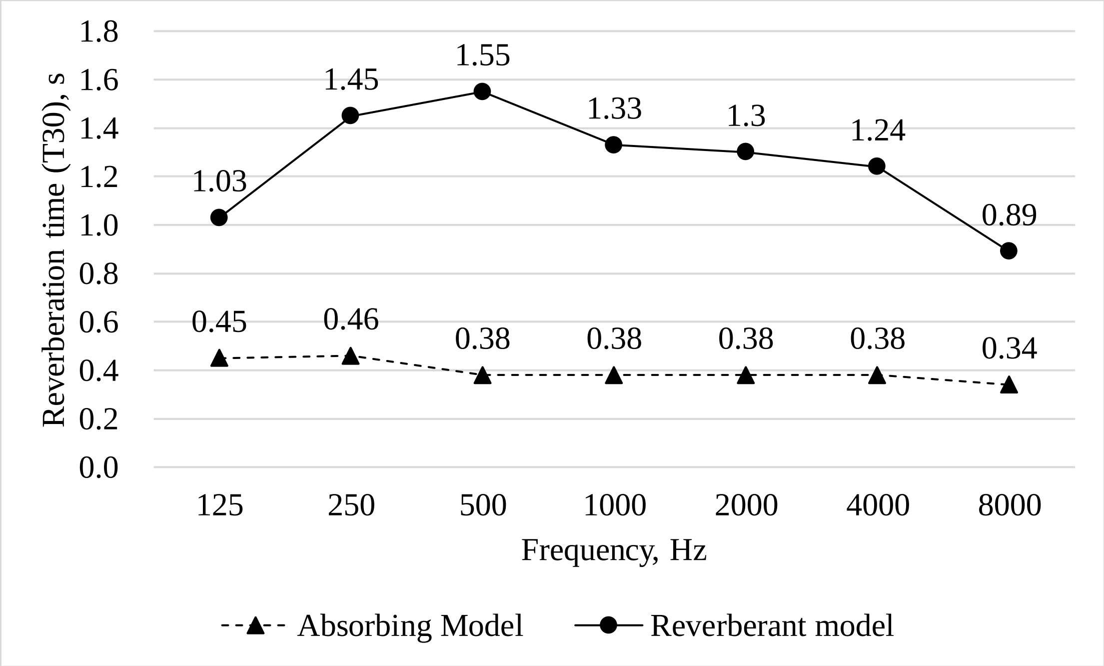


Figure 5. 6 T_{30} values by 1/1 octave bands for the absorbing and reverberant models

5.1.5 Cognitive Task

The serial recall task is a common cognitive task which is frequently utilized to determine work performance in OPOs (Ebissou et al., 2015; Haka et al., 2009; Yadav & Cabrera, 2019). It was utilized in this chapter. 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.

5.1.6 Questionnaire

In this chapter, 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. 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 Table 5.4). 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) (Hart & Staveland, 1988), which is a common scale used for measuring the participants' workload during testing and was frequently utilized in previous studies (Brocolini et al., 2016; Ebissou et al., 2015; Annu Haapakangas et al., 2014; Jahncke et al., 2016). 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.

Table 5. 4 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.”

5.1.7 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 (S. Kang, Mak, Ou, & Zhang, 2022a). Figure 5.7 shows the 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 practiced 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 5.1). One participant was tested at a time. After the experiment was over, participants were given more information about this experiment.

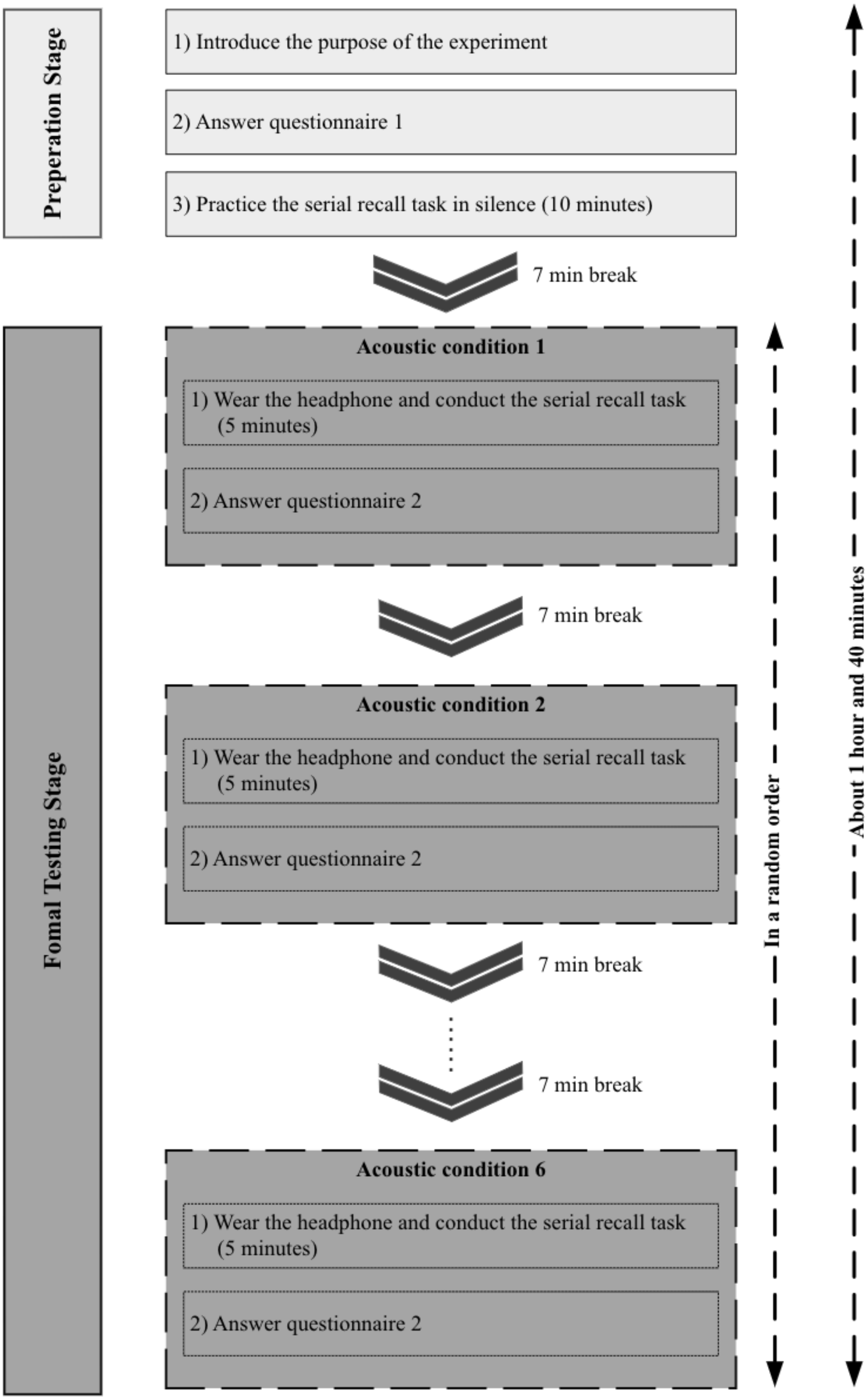


Figure 5. 7 Experimental procedure

5.1.8 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. 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 5.1). 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).

5.2. Results

5.2.1 Effects of STI in the Absorbing Environment (RT = 0.4 s)

5.2.1.1 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 5.8. Figure 5.8 also shows the mean score of the mental workload in each condition. A higher score means a higher mental workload.

For the objective performance, as expected, the average accuracy rates decrease with increasing STI values (Figure 5.8). 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). F (F-ratio (Stamm & Safrit, 1975)) 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 (Maher, Markey, & Ebert-May, 2013). 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).

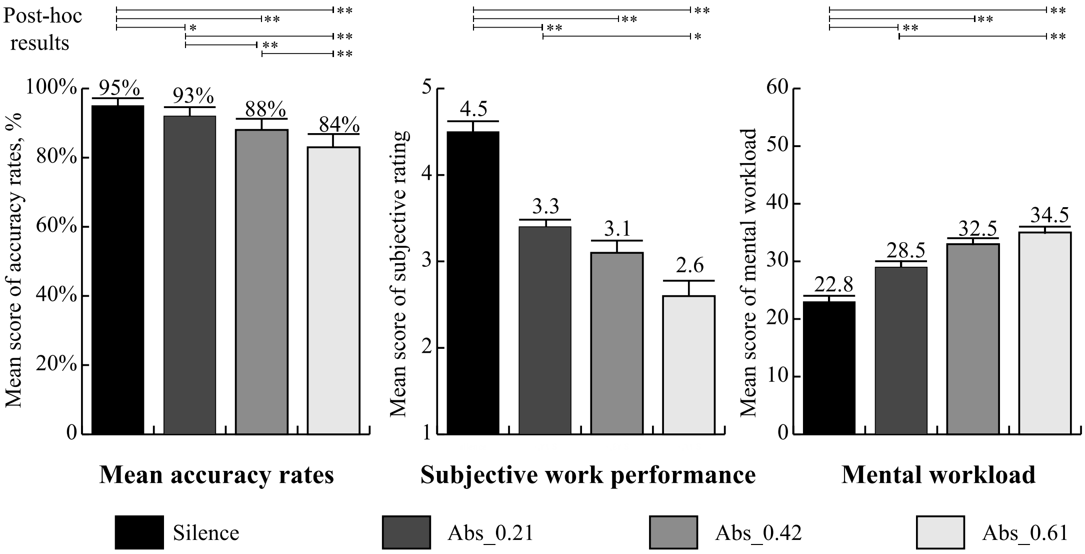


Figure 5. 8 Mean score of objective performance and subjective evaluation results of participants in the silence and 3 STI conditions in the absorbing environment (error bars define standard errors. * refers to Bonferroni P-value<0.05. ** refers to Bonferroni P-value<0.01).

For subjective perceptions, with the increase in the STI, the subjective work performance of participants decreases, and the mental workload increases (Figure 5.8). 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).

5.2.1.2 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 5.9. As shown in Figure 5.9, 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).

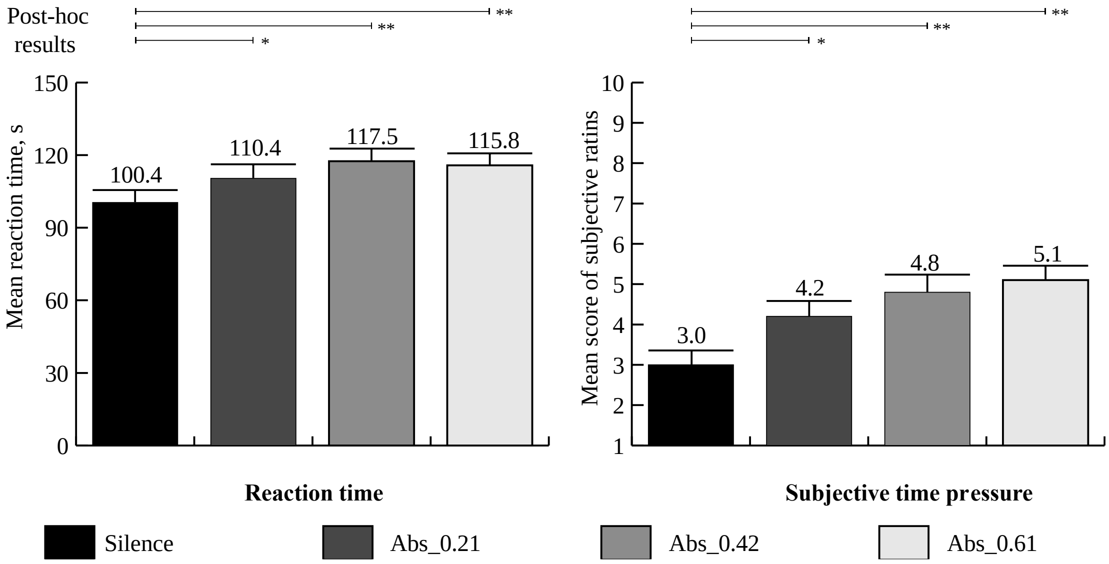


Figure 5. 9 Mean reaction time and the mean score of the subjective time pressure in the silence and 3 STI conditions in the absorbing environment (error bars define standard errors. * refers to Bonferroni P-value<0.05. ** refers to Bonferroni P-value<0.01).

6.2.1.3 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 5.10. With the STI increasing, the mean scores of acoustic adaptability and satisfaction decrease, and the mean scores of speech disturbance increase (see Figure 5.10). 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 5.10, 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-value<0.01 for all comparisons). 2) The mean score of acoustic satisfaction was statistically higher in silence than in the three STI conditions (P-value<0.01 for all comparisons). 3) The mean speech disturbance score was significantly 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_0.42 (P-value<0.05) and Abs_ 0.61 (P-value<0.01).

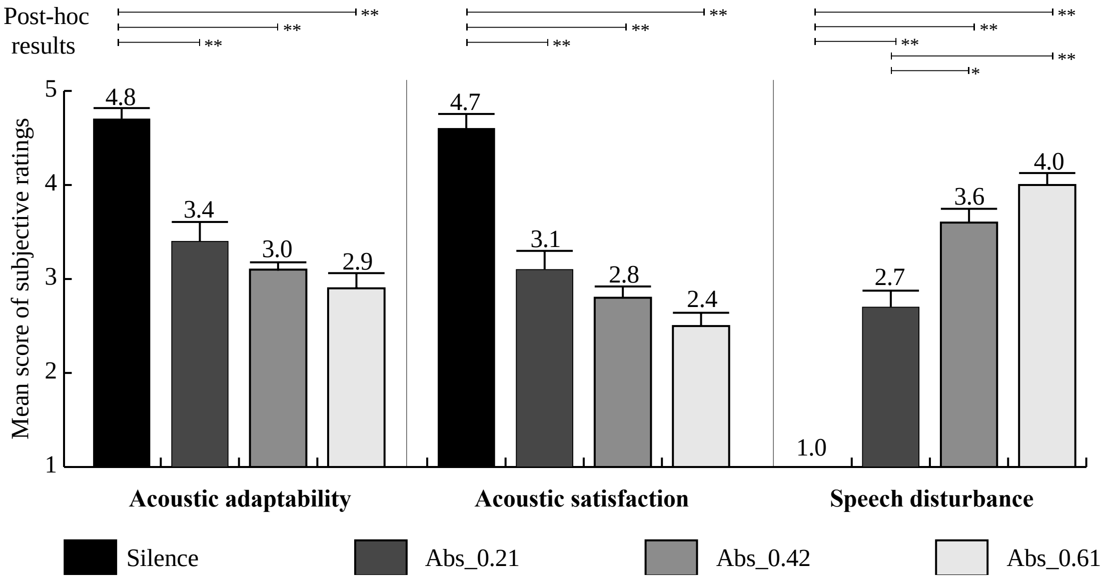


Figure 5. 10 Subjective condition evaluations of participants in the silence and 3 STI conditions in the absorbing environment (error bars define standard errors. * refers to Bonferroni P-value<0.05. ** refers to Bonferroni P-value<0.01).

5.2.2 Effects of STI in the Reverberant Environment (RT = 1.4 s)

5.2.2.1 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 5.11. Furthermore, the mean score of the mental workload, measured with the NASA-TLX, in each condition is also displayed in Figure 5.11.

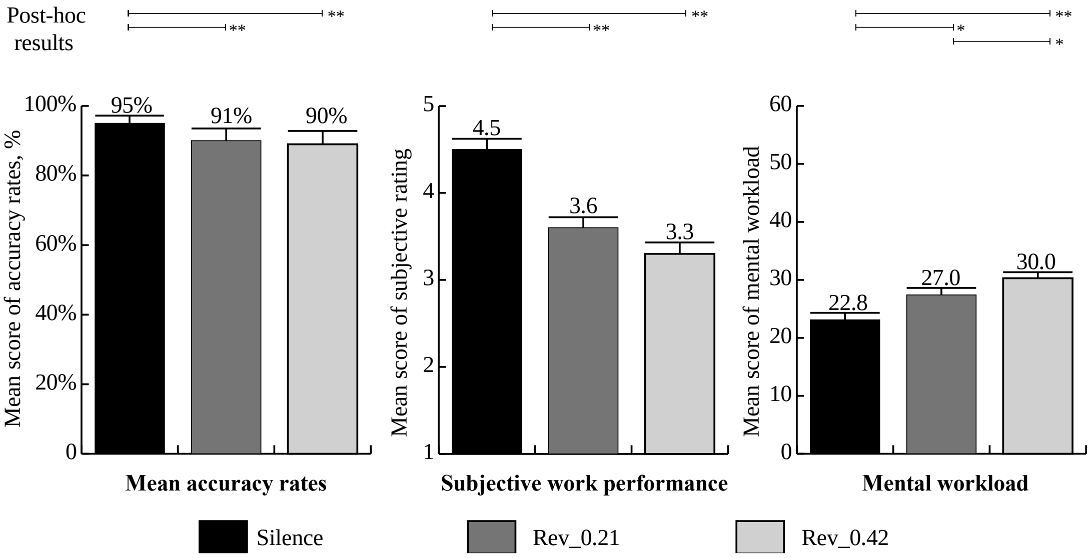


Figure 5. 11 Mean score of objective performance and subjective evaluation results of participants in the silence and two STI conditions in the reverberant environment (error bars define standard errors. * refers to Bonferroni P-value<0.05. ** refers to Bonferroni P-value<0.01).

For the objective performance, the accuracy rates decrease when the STI increases (Figure 5.11). 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 5.11). 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).

5.2.2.2 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 5.12. The mean score of subjective time pressure increases with the increase in STI values (see Figure 5.12). 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).

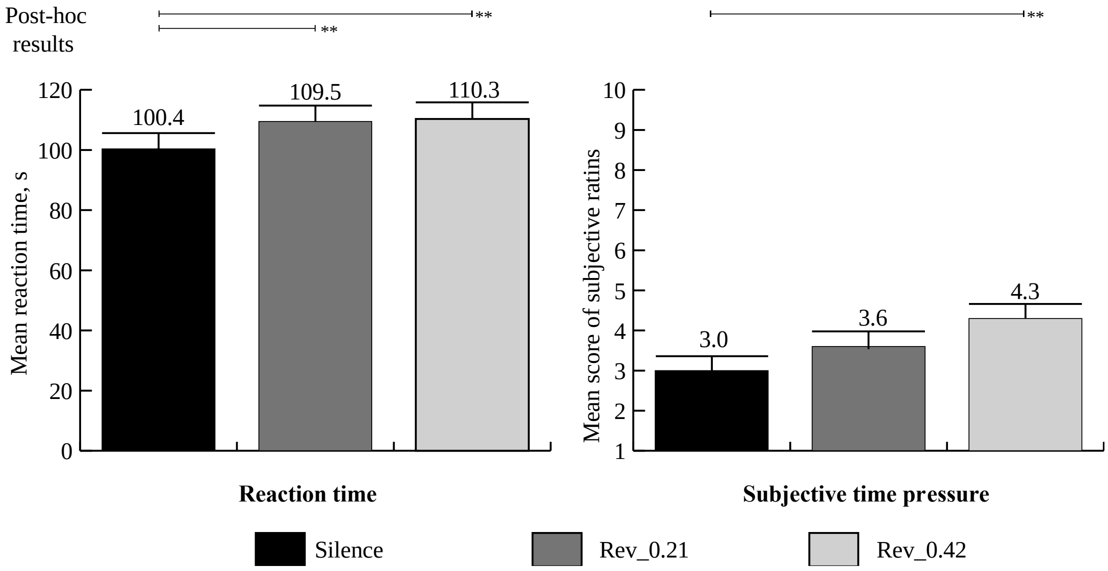


Figure 5. 12 Mean reaction time and the score of the subjective time pressure of participants in the silence and two STI conditions in the reverberant environment (error bars define standard errors. ** refers to Bonferroni P-value<0.01).

5.2.2.3 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 5.13. With the STI increasing, the mean score of acoustic satisfaction decreases, and the mean score of speech disturbance increases (see Figure 5.13). 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 5.13, 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).

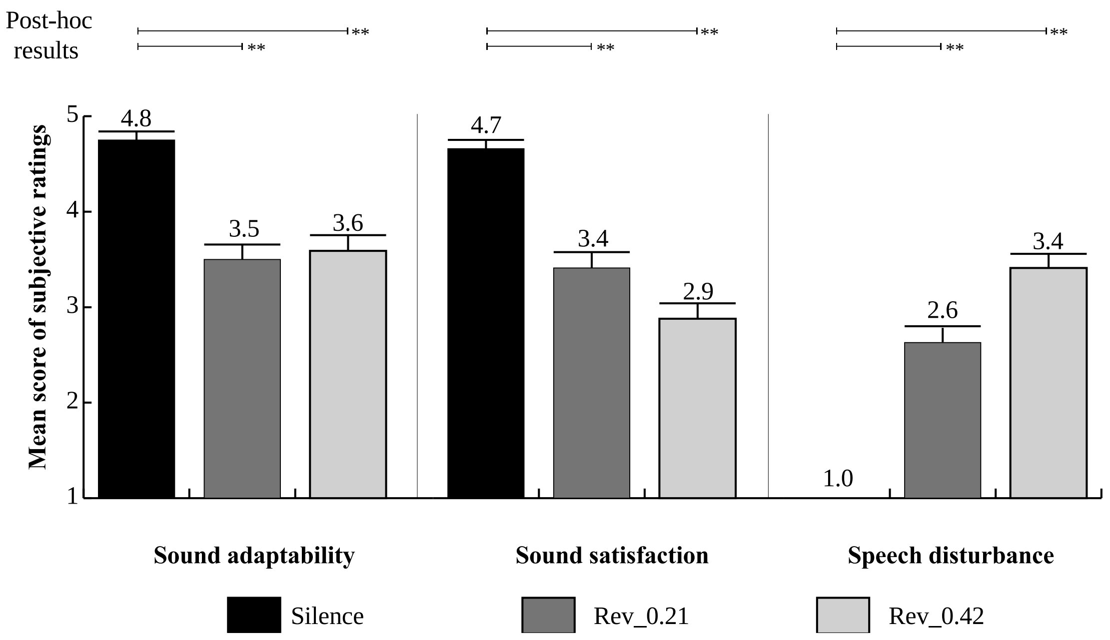


Figure 5. 13 Subjective condition evaluations of participants in the silence and two STI conditions in the reverberant environment (error bars define standard errors. ** refers to Bonferroni P-value<0.01).

5.2.3 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 5.5

.

Table 5. 5 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 5.5). According to the results of paired-samples t-tests and Wilcoxon tests in Table 5.5, 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.

5.2.4 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 5.6, 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 5.6). 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 5.6). 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 5.6). 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. 6 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**
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**
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

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.

5.3. Discussion

One objective of this chapter was to study 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.

5.3.1 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 (Haka et al., 2009; Jahncke et al., 2013; Lou & Ou, 2020) 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 5.3). According to the study of Ranz et al. (Renz, Leistner, & Liebl, 2018b), 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 (Sato, Morimoto, Sato, & Wada, 2008; Sato, Morimoto, & Wada, 2012) 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., even under the same STI condition, the listening effort does not decrease with increasing SNR due to the impacts of RT (Rennies, Schepker, Holube, & Kollmeier, 2014). 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%).

5.3.2 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 RT in a room or a smaller SNR value can reduce speech intelligibility (Valtteri Hongisto et al., 2004). As shown in Table 5.5, 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 chapter, 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 5.5). 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, 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.

5.3.3 Effects of the Individual Factors

Pierrette et al. (2015) found that noise sensitivity significantly affects occupants' noise annoyance in open-plan offices. Zimmer and Ellermeier (1999) showed a weak relationship between noise sensitivity and work performance in noisy environments. Haapakangas et al. (2014) 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 chapter 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, noise sensitivity had no effect on work performance in this chapter, which is in line with previous studies (Haka et al., 2009; Venetjoki et al., 2007). Concerning different gender groups, the result shows that male participants in STI conditions show lower acoustic satisfaction and adaptability than females (Table 5.6), which is in agreement with Pellerin and Candas (2003).

5.3.4 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 chapter, 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 5.3, 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 explore the impacts of speech intelligibility on OPOs' 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 chapter. 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 (Titze & Maxfield, 2017; L. M. Wang & Vigeant, 2004; D. Zhang, Feng, Zhang, & Kang, 2023) 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, the study of this chapter 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 chapter 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.

5.4. Summary

This chapter examined the impact 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.

Chapter 6

A Prediction Model of Serial Recall Performance in Chinese Open-plan Offices

Speech noise can decrease occupants' work performance in OPOs. Several prediction models have been built to predict the decrease in work performance based on speech intelligibility. However, few of them consider the impact of speech intelligibility in a Chinese environment. This chapter aims to create a model that evaluates how much work performance is reduced with the increase in speech intelligibility in Chinese OPOs. This chapter collected all experiment studies which researched the impacts of varying speech intelligibility on occupants' performance of cognitive tasks in Chinese OPOs. Then, a prediction model of serial recall performance was created by analyzing the experimental data from Chapters 4 and 5 and two previous studies. These two studies determined the impacts of STI conditions on serial recall performance in Chinese OPOs.

From the STI-DP model of the serial recall task in Chinese OPOs with a short reverberation time, the decrease in serial recall performance takes place between STI 0.31 and 0.45. Comparing the curves between the work performance decrease and STI obtained in this chapter with previous studies finds that the STI range of serial recall performance change is narrower in Chinese environments than in non-Chinese language environments. In addition, the average rate of change DP for the serial recall task in the Chinese environment is not lower than that in the non-Chinese environment, although speech noise has less impact on serial recall performance in Chinese environments.

6.1. Relationships Between STI and Work Performance in Chinese Open-plan Offices

6.1.1 Prediction Model

The relationship between STI and work performance was one of the focuses of studies on open-plan offices' acoustic environments. The sigmoidal function is usually used to simulate the relationship between STI and the decrease in work performance (DP) in OPOs by previous studies (Annu Haapakangas et al., 2020; V. Hongisto, 2005; Renz, 2019). The normal equation is:

$$F(x) = A - \frac{B}{1+\exp\left[(x-x_0)/k\right]} \tag{1}$$

in which A (%), B (%), x_0, and k are constants to be optimized.

This chapter also selected the sigmoidal function to simplify the relationship between STI and DP in Chinese environments because there is no evidence for any more efficient curve shape. The model is built depending on equation (1) using Solver (Microsoft Office Package, Excel). The optimization task was to minimize the sum of squares of residuals. The constraints of the constants were 2-30 for A and B, 0.1-0.9 for x_0, and 0.02-0.1 for k. The value of R^2 describes the model's goodness of fit, and the Pearson correlation coefficients r_{xy} is calculated to compare with the other STI-DP models proposed by previous studies in this field.

6.1.2 Studies Researching the Impacts of STI in Chinese Open-plan Offices

There are four other experimental studies about the STI-performance relationship in Chinese environments. Table 6.1 shows detailed information on these studies. As seen in Table 6.1, the impact of STI conditions depends on the task type. Of the 11 tests of the STI-performance relationship, six tests (i.e., tests 1-5 and 7) found strongly significant effects of STI conditions on the accuracy rate of the serial recall task. Only one test (i.e., test 6) showed that STI conditions have a strong effect on accuracy on the reading comprehension task. The rest of the other tests (i.e., tests 8-11) did not find a statistically significant effect of STI condition on task accuracy.

As mentioned in Chapter 5, RT is an important factor affecting speech intelligibility, which in turn affects occupants' work performance and acoustic perceptions. As shown in Table 6.1, the range of EDT of all 11 tests used to determine the STI values is extensive (from 0.13 s to 1.4 s). Most of the data were collected in absorbing environments (i.e., RT<0.6 s). In order to minimise the effects of reverberant environments, the data collected from a long reverberant environment (i.e., RT > 0.6 s) are excluded from the development of the STI-DP model in this chapter. Thus, the STI-DP model was developed for the serial recall task according to tests 1, 3, 5, and 7.

Table 6. 1 Descriptive information on eight tests of the STI-performance relationship in Chinese open-plan offices

Test No.	**Study**	**No.** [1]	**Task type**	**Range in STI**	**Range in $L_{Aeq,total}$, dBA**	**EDT**[2]**, s**
1	Experiment from Chapter 4	41	Serial recall task	0.27-0.52	40.7-45.3	0.13-0.34
2	Experiment from Chapter 4	41	Serial recall task	0.45-0.50	43.1-46.8	0.69
3	Experiment from Chapter 5	32	Serial recall task	0.00-0.61	51.8-54.5	0.40
4	Experiment from Chapter 5	32	Serial recall task	0.00-0.42	52.8-50.1	1.40
5	Y. Zhang et al. (2021)	30	Serial recall task	0.00-0.66	54.6-55.2	0.55

6	Lou and Ou, (2020)	20	English literature reading comprehension	0.08-0.78	49.5-50.5	0.30
7	S. Kang and Ou (2018)	38	Serial recall task	0.00-0.67	40.4-47.1	0.33
8	S. Kang and Ou (2018)	38	Mental arithmetic	0.00-0.67	40.4-47.1	0.33
9	S. Kang and Ou (2018)	38	Reading comprehension	0.00-0.67	40.4-47.1	0.33
10	S. Kang and Ou (2018)	38	Proofreading	0.00-0.67	40.4-47.1	0.33
11	R. Yu, Yang, and Liu (2015)	32	Simulated X-ray screening task	0.00-0.69	65.0	--

Note:

[1] The number of participants;

[2] EDT averaged over 250 to 4000 Hz octave bands of the room or receiving position.

The DP in this chapter was obtained by the difference in the average accuracy rate between the reference and speech intelligibility conditions. For the experiment from Chapter 4, the SPL of speech in STI 0.27 (i.e., the condition “GO_H2” in Chapter 4) is very low (31.6 dBA, see Table 4.1). Moreover, as mentioned in Section 4.2.2, the mean score of perceived speech disturbance of STI 0.27 is 1, which means there is little speech disturbance affecting subjects when performing the serial recall task under the condition of STI 0.27. Thus, the STI of 0.27 was regarded as the reference condition to calculate the DP. In the studies of Chapter 5, S. Kang and Ou (2018) and Y. Zhang et al. (2021), the quiet condition (i.e. the condition without masking sound and speech noise) was viewed as the reference condition to calculate the DP of the serial recall task in different STI conditions. Y. Zhang et al., (2021) studied word serial recall performance under different STI conditions with four masking sounds. The DP in different STI conditions masked by pink noise and ventilation sound was calculated because these two sounds were also used in tests 1 and 4, respectively, to vary the STI value.

6.2. Results

6.2.1 STI-DP Model in Chinese Environments

The data from the experimental studies mentioned above are shown as individual points in Figure 6.1, and the S-shaped curve in Figure 6.1 is the result of the sigmoidal function based on the non-linear least-square fitting method. The task-specific model in Chinese environments was created based on the tests listed in Table 6.2. Haapakangas et al. (2020) introduced STI_{10} and STI_{90} to describe the STI range where work performance changes drastically. In their study, STI_n refers to the STI value in which n% of the maximum decrease in performance is reached. Thus, STI_{10} and STI_{90} were computed in this chapter to show the STI range for changing work performance. Table 6.2 shows the variables and correlation coefficients of the STI-DP model. As shown in Table 6.2, the performance decrease takes place between STI 0.31 and 0.45 in the STI-DP model. Pearson's correlation coefficient was calculated to show the relationship between observed and predicted DP. The larger coefficient, the higher model fit. As seen in Table 6.2, Pearson's correlation coefficient of the STI-DP model is 0.88.

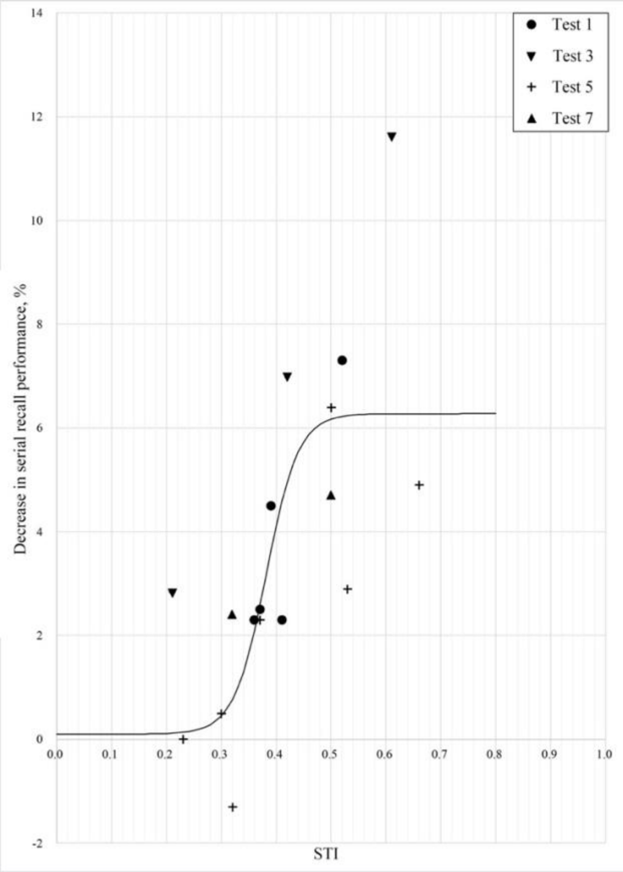


Figure 6. 1 STI-DP model of the serial recall task in Chinese environments.

Table 6. 2 Results of variables in the DP-STI model.

Variables	**Model**
A,%	6.2
B, %	6.3
$\boldsymbol{x_0}$	0.4
$\boldsymbol{k}$	0.03
R^2	0.76
$\boldsymbol{r_{xy}}$	0.88
DP$_{10}$, %	0.6
DP$_{90}$, %	5.6
STI$_{10}$	0.31
STI$_{90}$	0.45

Note:
r_{xy}: Pearson's correlation coefficient for the relationship between observed and predicted DP;

DP$_{10}$: The decrease in performance at STI$_{10}$;

DP$_{90}$: the decrease in performance at STI$_{90}$.

6.2.2 Comparison of Relationships between STI and Serial Recall Performance with Other Studies

A comparison of the curves between STI values and the decrease in serial recall performance was carried out to obtain the difference between this study and the studies of Haapakangas et al. (2020) and Renz (2019). Figure 6.2 shows the three curves and corresponding DP_{10}, DP_{90} and r_{xy} values. In 2020, Haapakangas et al. proposed 4 STI-DP models based on 34 laboratory tests investigating the change in cognitive performance with the increase of STI (Annu Haapakangas et al., 2020). Of these 34 tests, 19 were carried out in Finnish, 6 in German and 7 in Swedish environments. The remaining two tests were conducted in French and Chinese environments, respectively. All speech sounds used for these 34 tests were recorded in the participants' native language to ensure participants could understand. In the study of Haapakangas et al. (2020), model 3 presents the relationship between STI and DP of serial recall task, which was obtained through a summary analysis of 11 experimental studies conducted in 4 language environments (i.e. Finnish, German, Swedish, and French environments). Renz (2019) proposed an STI-DP model based on six laboratory studies that analyzed the change in the serial recall performance with the STI increase in the German environment.

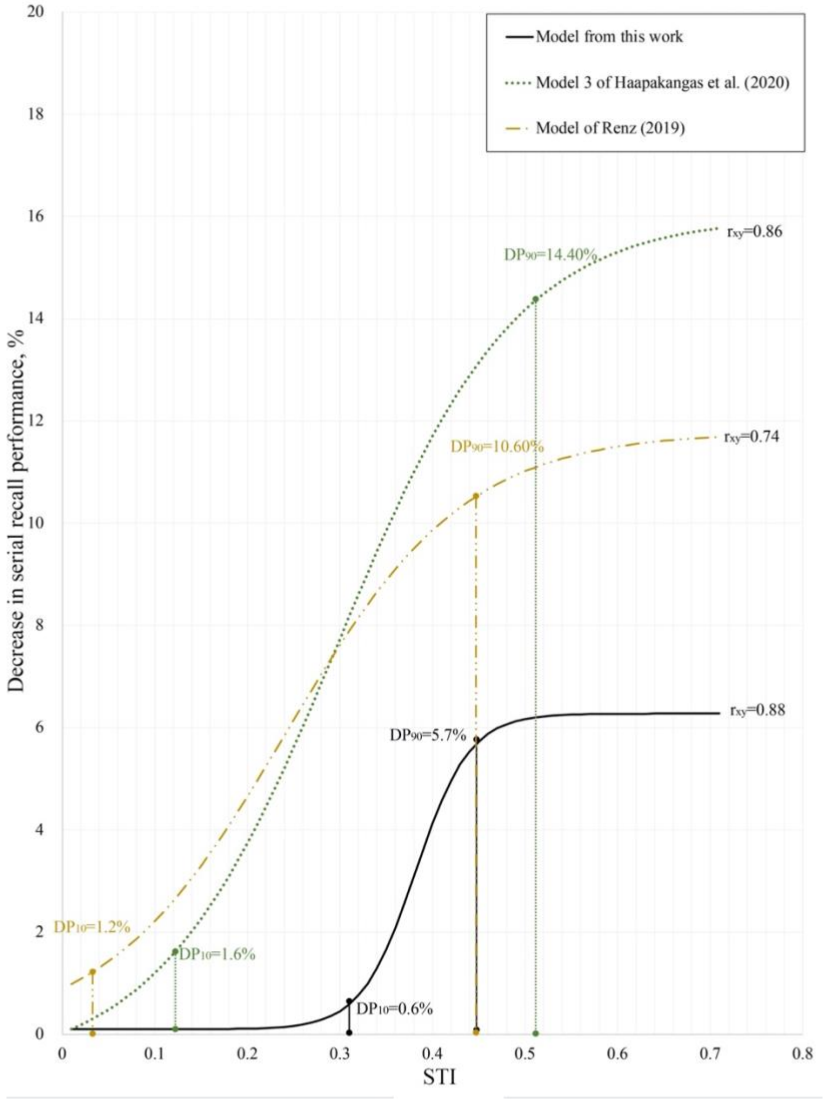


Figure 6. 2 A comparison of models expressing the relationship between STI and DP of the serial recall task. The models of Haapakangas et al. (2020), Renz (2019) and this work are included.

Based on STI_{10} and STI_{90} values in Figure 6.2, the decrease in serial recall performance is located within the STI range of 0.31 and 0.47 in Chinese environments, while it occurs within a larger range (0.03-0.45) in German environments (the model of Ranz).

According to model 3 of Haapakangas et al. (2020), serial recall performance decreases within the STI range of 0.12 to 0.51, which is much larger than the STI range in Chinese environments. Additionally, the DP gradient of the STI-DP model in this chapter from STI_{10} to STI_{90} is close to that of model 3 of Haapakangas et al. (2020) and steeper than that of Ranz (2019) (see Figure 6.2). The DP of the serial recall task in this chapter is always lower than those in the other two models under the same STI condition. These results mentioned above imply that: 1) the decrease in performance on the serial recall task in Chinese environments occurs within a narrower STI range than in Western language environments. 2) The effect of speech noise in the Chinese environment on serial recall performance is less than that in Western languages, while the average change rate of the DP in Chinese environments is not less than in Western language environments within the STI range of 0.31-0.45.

It is worth noting that the maximum differences in the STI_{10} and STI_{90} among the three curves are up to 0.27 and 0.06, respectively (see Figure 6.2). Bradley et al. (1999) found that a just noticeable difference (JND) of STI is 0.03, which means that the differences in the STI_{10} and STI_{90} are large. One possible explanation could be the difference in language environments. Chinese is a monosyllabic language that belongs to the Sino-Tibetan language family. Its syllable information consists of consonants, finals and tones. Unlike many Western languages such as Finnish, German and Swedish, the tone in Chinese is used to distinguish the meanings of words. Furthermore, a difference in the average spectrum is found between Chinese and Western languages (Zhu, Mo, & Kang, 2014). The differences in pronunciation and vocal characteristics mentioned above may cause the difference in perceived speech intelligibility in varying language environments and thus impact the relationship between speech intelligibility and work performance. In addition, previous studies (Galbrun & Kitapci, 2016; J. Kang, 1998) have demonstrated that the perceived speech intelligibility differs among language environments even under the same STI value. That is to say, the STI value representing the same speech intelligibility may differ between Chinese and Western language environments such as Finnish, Swedish and German. Overall, differences in STI_{10} and STI_{90} show that the STI range for work performance changing varies across language environments. Another possible explanation for the difference in STI_{90} could be the differences in the measurement of STI. The STI values reported by Haapakangas et al. (2020), Renz (2019), and Chapters 4 and 5 of this thesis have not been calculated in the same method. In studies of Haapakangas et al. (2020) and Renz (2019), some STI values have been obtained based on the method recommended in IEC 60268-16, which has been revised three times in the past 20 years (IEC 60268-16, 1998, 2003, 2011, 2020); while some STI values have been determined based on the method described by previous studies (Valtteri Hongisto et al., 2004; Houtgast & Steeneken, 1985) by considering the result of reverberation time (or EDT) and the energy-equivalent sound pressure levels of speech and background sounds. In this chapter, the determination of all STI values was based on the method of Hongisto et al. (2004).

6.2.3 Limitations

The STI-DP model of serial recall task involves inevitable uncertainty because of the determination of STI conditions. In Chapters 4 and 5, as well as in two other previous studies, the reported STI values have been determined based on the method described by Hongisto et al. (2004) by using EDT and SNR values. Although similar methods of determining STI conditions are usually applied in previous studies (Haka et al., 2009;

Jahncke et al., 2013; Renz et al., 2018a), it is different from the international standard ISO 60268-16.

Another source of uncertainty is the calculation of the DP. The performance in a quiet environment is usually viewed as an ideal reference to calculate the DP. However, the minimum STI value (0.27, condition GO_H2) in Chapter 4 was used as a reference condition to calculate DP. Although there was no speech disturbance at STI=0.27 based on subjects' rating results (see Figure 4.7), the background noise (i.e. ventilation sound) may also exert adverse effects on subjects than in a quiet environment.

This chapter was limited to the effects of various STI conditions on serial recall performance in absorbing environments. The relationship between STI and work performance may vary by task type. For instance, Kang and Ou found that STI conditions have no main effects on the objective performance of mental arithmetic, proofreading, and reading comprehension (in Chinese) tasks, with the exception of the serial recall performance (S. Kang & Ou, 2018). Lou and Ou revealed that STI conditions have a significant effect on the objective performance of English literature reading comprehension (Lou & Ou, 2020), which was inconsistent with findings on the relationship between STI and reading comprehension performance (in Chinese) (S. Kang & Ou, 2018). More studies are needed to explore the STI-DP model for specific work activities.

6.3. Summary

Based on the results of the laboratory experiment in Chapters 4 and 5 and analysis of experimental data from two experimental studies, an STI-DP model of the serial recall task for Chinese open-plan offices was first proposed by the non-linear least square fitting method. This model can be used to evaluate the effects of speech on serial recall performance in different STI conditions in Chinese open-plan offices with a short reverberation time.

The main findings can be drawn from the analysis results:

1) According to the STI-DP model, in the Chinese environment, serial recall performance starts to decrease when STI is above 0.31, while the decrease in performance reaches the maximum when STI exceeds 0.45. This STI range for changes in serial recall performance is much narrower than in non-Chinese environments.

3) The effect of speech noise in the Chinese environment on serial recall performance is lower in comparison with non-Chinese environments, but the average change rate of the DP in Chinese is not lower than in non-Chinese environments in the range of STI = 0.31 to 0.45.

Chapter 7

Conclusions and Suggestions for Future Work

7.1. Conclusion

This thesis investigates the acoustic environments in Chinese large and medium-sized OPOs, and the effects of room acoustic quality levels, speech intelligibility, and reverberation time on work performance and acoustic perceptions. The survey results of the acoustic environment of large and medium-sized OPOs in China reveal the role of the spatial density of workstations for OPOs' acoustic improvement, and highlight that the acoustical demands of the occupants of large and medium-sized OPOs are different. A series of laboratory experiments using acoustic simulation and auralization confirm the validity of acoustic classification criteria in ISO 3382-3:2022 and reveal the role of long reverberation time on work performance and acoustic perceptions in OPOs. A work performance prediction model shows the relationship between Chinese speech intelligibility and serial recall performance in OPOs and has potential applications in assisting the acoustic design of OPOs.

First of all, the acoustic environments of 16 OPOs in Shenzhen, China, have been investigated. The 16 OPOs are divided into 7 large and 9 medium-sized OPOs according to the number of occupants. Active noise levels during working hours and acoustic performance (i.e., speech decay-related parameters) of all OPOs have been measured. It has been shown that the spatial density of workstations is strongly related to certain speech decay-related parameters (i.e., $D_{2,S}$, $L_{p,A,S,4m}$, and r_C). In addition, a questionnaire survey concerning occupants' feelings on acoustic environments is also carried out in 16 OPOs. This subjective measurement has shown that acoustic satisfaction and the impact of acoustic interference on work productivity are significantly correlated with the perceived noise level, speech privacy and the effects of speech interference on re-concentration and problem-solving speed. The perceived noise level is the most important criterion for acoustic satisfaction. Speech interference on re-concentration is the main acoustic cause of work productivity decrease. Moreover, it is found that 1) speech privacy is an important index affecting employees' work productivity in LOPOs, but not in MOPOs; 2) MOPO employees are less disturbed by the phone ringing and speech noises and have higher acoustic satisfaction compared to employees in LOPOs.

Secondly, the impact of room acoustic quality levels on work performance and acoustic environmental perceptions in OPOs has been investigated. The Odeon software is used to simulate 4 office scenarios. According to the guidance of ISO 3382-3:2022 Annex C, the room acoustic qualities of the four office scenes have been divided into four levels: good, high-medium, low-medium, and poor. A total of 41 participants were asked to complete the serial recall task and some questionnaires at two receiving locations in four office scenes. The experimental results have shown that work performance and acoustic satisfaction are higher in OPOs with good or high-medium acoustic environments based on the acoustic classification in Annex C of ISO 3382-3:2022. In addition, a comparison of objective and subjective results between the two receiving locations in each office scene implies that greater distance from the person speaking can increase work performance and acoustic satisfaction in OPOs with poor acoustic quality. However, this improvement of greater speaker-receiver distance is negligible in OPOs where acoustic quality is good.

Thirdly, the effects of speech intelligibility and reverberation time on the serial recall task in Chinese open-plan offices have been investigated. Five acoustic conditions have been created using acoustic simulation and auralization. The tested acoustic conditions varied in speech intelligibility (STI of 0.21, 0.42, and 0.61) and reverberation time (RT of 0.4s and 1.4s). A total of 32 participants were asked to complete the serial recall task and questionnaires in each acoustic environment. 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.

Last but not least, a model has been proposed to predict the serial recall performance in Chinese OPOs. The sigmoidal function was used to simulate the relationship between STI and DP. The data is collected from laboratory experiments in Chapters 4 and 5 and two previous studies. These two studies explored the effects of STIs on serial recall performance in Chinese environments. In this STI-DP model, serial recall performance starts to decrease when STI is above 0.31, while the decrease in performance reaches the maximum when STI exceeds 0.45 in the Chinese environment.

This STI range for changes in serial recall performance is much narrower than in non-Chinese environments. Speech noise in the Chinese environment has less negative impacts on serial recall performance in comparison with non-Chinese environments, but the average change rate of the DP in Chinese is not lower than in non-Chinese environments in the range of STI = 0.31 to 0.45.

7.2. Suggestions for Future Work

Based on the present works researched in this thesis, future work is recommended as follows:

This thesis only investigated the effects of the acoustic environment on serial recall performance. Task type is a critical 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.

The acoustic environment of small-sized OPOs does not be considered in this thesis because the international standard for acoustic measurement of OPOs (ISO 3382-3:2022) is not applicable to this type of OPOs. Concerning the importance of acoustic quality to OPO occupants, acoustic measurement and assessment methods for small OPOs deserve to be investigated.

In Chapter 4, only one open-plan office size was considered. The speaker-receiver distance of 11 m could be large or even non-existent for small-sized OPOs, although the speech-receiver of 11 m is typical for large-sized open-plan offices. Thus, further work will be conducted to explore the effects of the different acoustic quality of open-plan offices at closer speaker-receiver distances

In Chapter 5, two extreme sound-absorbing models (RT=0.4 s and 1.4 s) were considered, while measurement points between RT 0.4 s and 1.4 s were not included. Since changing the room RT could alter the influence of speech intelligibility on occupants, there is a need to add measurement points ranging from RT 0.4 s to 1.4 s under different levels of speech intelligibility.

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