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JAPAN ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY
Japan Advanced Institute of Science and Technology

Doctoral Dissertation

Research on the mathematical model about the influence mechanism of indoor environment on researchers’ comfort and productivity

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Abstract

With the development of society, the core of modern work has gradually shifted from the manufacturing industry to the knowledge-based departments in indoor office environments. In line with the foregoing, indoor environment quality is an important indicator of the status of the indoor environment. It not only reflects the comfort level of the researchers in the building but also affects their performance, particularly in research institutions. However, due to the inherent correlation among various environmental comfort indexes, it is difficult to evaluate the influence of specific environment physical parameters on researchers' comfort and their research performances. Therefore, the main objective of this paper is to develop a mathematical model that would determine the relationship between environment physical parameters and research performance.

This study was based on an experiment carried out at a controlled research office in a pharmaceutical research company located in the northeast of China. The controlled research office was equipped with a radiant floor heating system that supplied heat in winter. A total of 32 researchers were recruited and divided into four experiment groups. Each experiment group was required to conduct daily research activities under 12 different environment conditions. Data were collected from physical environment measurements, subjective questionnaire surveys, and performance tests.

The results showed that changes in the thermal, visual, and acoustic environments had significant influences on the researchers' environmental perceptions and satisfactions. Moreover, the environment physical parameters exerted significant impacts on the researchers' response times in the performance tests and, consequently, had significant effects on their research performance. For the influence weight of the items under environmental comforts, thermal comfort had the highest weight, followed by visual comfort. Meanwhile, acoustic comfort had the least impact. In addition, there was a positive correlation among the thermal, visual, and acoustic environments.

This paper also developed a mathematical model for evaluating the researchers' performances based on the indoor environment physical parameters. In order to establish the mathematical model, the improved environmental comfort index was obtained by enhancing the three existing mathematical models. Based on a factor analysis of environment comfort, the weight of each comfort index was obtained. Finally, through a nonlinear regression analysis between the performance index and the indoor environment quality index, the relationship between research performance and environment physical parameters was obtained.

Keywords: *Indoor environment quality, environmental comfort, environmental perception, environmental satisfaction research performance*

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Chapter I

Introduction

1.1 Research Background

Nowadays, with the increasing pressure of work and life, overtime work has become the normal phenomenon in Japan and China. According to the "2018 Beijing residents' time usage survey report", an office worker needs to work around 60 hours per week on average [1]. Many companies and institutions regard overtime as one of the core indicators to evaluate the employees' KPI and give the employees who work overtime the priority to promotion and salary increase.

But can overtime really bring higher output? The answer depends on the nature of the work. For the traditional manufacturing industry, because work is a mechanical repetition of simple operation processes, overtime can indeed bring higher output [2]. For example, on the factory assembly line, a worker works 8 hours to produce 800 pieces and 10 hours to produce 950 pieces. Although the efficiency has reduced during overtime, the extended working hours can lead to the production of an additional 150 products. However, for mental workers, their job is not to mechanically repeat the same operation process, but to think and create. Long working hours will make employees physically and mentally exhausted, which hence reduce work quality, and even increase the probability of making mistakes [3].

At the same time, overtime will create a vicious circle. If an employee actively extends his working hours in order to get a promotion or salary increase, other employees have no choice but to work overtime in order not to be eliminated. However, as all employees generally work overtime, the extra hours spent on overtime will become ordinary working hours. If that employee still wants to obtain the promotion chance, he needs to extend working hours again. However, because too long working hours will reduce work efficiency and quality, employees actually create little additional benefits for the company. This also makes the enterprise fall into an embarrassing situation, where employees either refuse to work hard or seem to work hard overtime. But in the end, it does not bring real benefits to the enterprise, but only brings gradually higher employee overtime compensation and utility bills [4].

Overtime will also have a negative impact on employees' subjective enthusiasm. Some employees will conduct performative overtime in order to meet the KPI requirements, but do not want to conduct more tasks [5]. For work tasks that can be completed during core working hours, employees will actively reduce their work efficiency to ensure that there is still work needed to be completed during the overtime.

Based on this situation, how to improve employees' work efficiency within the standard working hours has become an urgent problem to be solved. The research of Wargocki et al. showed that the impacts on employees' work efficiency can be summarized into the following four categories: social environment (relationship between people), personal characteristic (career, commitment to work and home/work relationship), organizations (leadership and organizational structure) and indoor environment [6]. Among them, the first three factors vary greatly due to different individuals and the nature of the company, which belongs to subjective factors. The indoor environmental factor is the only objective factor among the four factors, and it is also the factor that has the greatest impact on work efficiency [7].

At the same time, with the development of society, the core of modern work has gradually shifted from the manufacturing industry to the knowledge-based department in the indoor office environment. Its main feature is mental work, which requires high cognitive, judgment, reaction, and creative abilities [8, 9]. ASHRAE's survey also shows that 80% to 90% of the work time is spent in the indoor environment [10]. Therefore, it is increasingly important to understand the indoor office environment and its impact on occupants' comfort and productivity.

1.2 Current Research Tendency

For a long time, the design methodology of buildings tends to pursue energy conservation and emission reduction to reduce the global energy burden. For example, the activity called the "COOL BIZ campaign" was launched by the Japanese government in the summer of 2005. Through increasing the pre-set cooling temperature of the air conditioner from 26°C to 28°C and modifying the summer work dress code, this activity reduced energy consumption of the commercial building by 1.2% per square meter per year [11]. The Chinese government also issued a similar policy in 2007, requiring that the indoor air conditioning temperature should not be lower than 26°C in summer and not higher than 20°C in winter, and windows should not be opened for ventilation during air conditioning operation. This reduced the peak power load of air conditioning by 10–15% [12]. However, the relevant policies do not take into account the impact of the influence of indoor environment change on indoor personnel's' comfort and work efficiency.

Fig. 1-1. Cool Biz Poster by Ministry of Environment [13]

Similar to the policy concerns on building energy conservation and emission reduction, in existing research, energy conservation and environmental protection are still the main research directions for indoor environment optimization design. For example, Awadh conducted objective research on four different energy-based green building rating systems (LEED, BREEAM, Estidama and GSAS) in order to compare the different emphases of the four rating systems [14]. Through the energy performance evaluation of 321 non-certified multi-family housing complexes, 126 multi-family housing which obtained certificate of Green Standards for Energy and Environmental Design (G-SEED) and 8 multi-family housing which were certificated by Leadership in Energy & Environmental Design, Jeong et al. developed an evaluation process for evaluating the energy performance of both green and non-green residence buildings [15]. Rashid and Yusoff compared and summarized the existing life cycle assessment methods based on energy consumption standards according to different evaluation objects [16]. A six-week empirical study was conducted by Jain et al. with 43 participants to compare the impact of five established design components in different eco feedback interface design on saving building energy consumption [17]. Li et al. compared the disadvantages and advantages of the two indoor thermal environment optimization control methods (thermal sensation-based control and set point-based control method). The resulted showed that the thermal sensation-based control can create a more comfortable thermal environment than the set point-based control method, but the daily energy consumption was increased by 13.8% [18]. Merabet et al. compared the influence of 20 AI tools developed for energy consumption and comfort control on energy saving and comfort. The results showed that with the application of artificial intelligence technology and personalized comfort model, it can make an average energy saving of 21.81% to 44.36% and an average comfort improvement of 21.67% to 85.77% [19].

However, for scientific research facilities, it is not enough to focus only on energy conservation and environmental protection. Since the research institution is the structure with a specific purpose, how to increase researchers' research performance is another goal that must be considered. In order to study the relationship between research performance and indoor environment, it is necessary to introduce a variable for evaluating indoor environment, which is indoor environment quality (IEQ), and an intermediate concept which is indoor environment comfort.

IEQ is an important indicator of the sustainable development of buildings, and it can reflect the comfort levels of residents in buildings. Comfort is the comprehensive psychological response of residents to the indoor physical environment based on their physiological and psychological state [20]. Comfort can be divided into several parts, four of which are thermal, indoor air quality, acoustic, and visual comfort. Mui et al. pointed out that the comfort of occupants in buildings depends on many environmental parameters, such as indoor air temperature and relative humidity [21]. When high IEQ condition is achieved, occupants will have high level of comfort [22]. Relevant literature has shown that the indoor environment has a direct impact on the health and work efficiency of occupants. For example, a bad indoor environment will lead to long-term health problems and reduce the happiness index and work efficiency [23-28].

Many previous studies focused on the impact of single environmental factors (such as thermal parameters) on occupants' environment comfort or academic performance. In terms of thermal environment, Mishra et al. conducted a mixed methods thermal comfort study in a classroom at Eindhoven University of Technology to better understand students' thermal perceptions when entering and adapting to the classroom environment [29]. Pereira et al. took the classroom of Portuguese middle school as an example and conducted a field study using the methods of physical parameter monitoring and a questionnaire survey, in order to compare the judgment of the thermal environment with the field measurement results [30]. A 24-day questionnaire survey was conducted on children aged 9-11 in non-air-conditioned classrooms in three different schools in the Netherlands to test the thermal comfort of children in primary school classrooms. The results showed that the thermal perception predicted by Fanger's predicted mean votes model was 1.5 levels lower than that of actual thermal perception of children [31]. Akimoto et al. measured the immediate thermal environment and workers' behavior, investigated the thermal comfort and fatigue of occupants to determine the influence of workers' behavior and working conditions on workers' thermal comfort and work efficiency [32].

In terms of visual environment, the effect of three lighting arrangements (general lighting, wall washing and cove lighting) and two illuminance levels (320lux and 500lux) on the visual perception about indoor space was studied [33]. Four different visual environments were tested on 15 participants by Zhang et al. to explore the effects of dynamic lighting with daily changes in illuminance and correlated color temperature level on participants' visual perception, comfort and work efficiency [34]. Chraibi et al. studied the effects of different lighting control conditions on individuals' visual perception and visual satisfaction in an open-plan office environment [35]. Konis studied the change of indoor personnel's perception of indoor visual environment after introducing sunlight and reducing electrical lighting for open-plan office conditions [36]. Juslén et al. studied in detail how lighting conditions affect employees' work efficiency by affecting visual perception and visual comfort. At the same time, Juslén et al. also proposed a new evaluation method to study the impact of lighting changes on work performance at workplace [37].

In terms of acoustic environment, Haapakangas et al. studied employees' acoustic perception of office and its relationship with work performance [38]. The study also showed that background noise was the main problem for indoor environment of open-plan office. Through interfering the conversations and tasks which depend on working memory and language processes, background noise level could influence the personal productivity. There are similar findings in the research of Lenne et al., in which background noise was the main source of employees' troubles and would cause the perception and satisfaction decrease about acoustic perception [39]. In order to solve the impact of noise on acoustic perception and satisfaction, Hongisto et al. used principle of masking sound to control the interference caused by speech, and compared the effects of background noise on acoustic perception before and after sound masking [40].

However, according to the work of Zomorodian et al., acceptable indoor conditions cannot be achieved unless overall acceptance of IAQ, thermal, acoustic, and visual comfort is obtained at the same time [9]. But in the actual environment, it is difficult to evaluate the impact of each physical environment parameter on the comfort of occupants separately. This is mainly due to the coexistence of these parameters and their interactions with each other [41].

The number of research studies about the relationship between IEQ and occupants' productivity which focus on educational and research institution are also limited. Moreover, in the limited number of literature reviews, most of the research was based on experiments conducted in university classrooms.

For example, Ishii conducted a one-year experiment with 40 college students to explore the influence of the indoor thermal environment on the thermal comfort of college students in Japan [42]. Catalina and Iordache conducted a questionnaire survey on the indoor environment of 174 students and 20 professors in university classrooms in Romania, and established a multiple nonlinear regression model of the IEQ index of university classrooms based on the questionnaire data [43]. Almeida and Freitas evaluated the indoor environment quality of 24 classrooms in Portugal and formulated optimized solutions according to the evaluation results [44]. Bajc et al. analyzed the relationship between local thermal comfort and productivity loss under four different indoor comfort conditions [45]. Jowkar et al. conducted environmental measurement and questionnaire survey in eight university buildings of Edinburgh and Coventry universities in order to study acclimatization, age and gender related differences on thermal perception [46].

Since the research institution is the structure with a specific purpose, besides environmental protection and energy-saving requirements, improving researchers' performance is another goal that must be considered. The population density, the metabolism levels, and study pressure of researchers are quite different from those of ordinary office workers, it is impossible to directly apply theories from other building uses to the research institution [47].

1.3 Open-plan Office

In the 1950s, F.W. Taylor and H. Ford put forward the concept of "open-plan office". The open-plan office is a large office or similar space that can accommodate a large number of employees to work together at the same time. In the open-plan office, the employees are centrally arranged in various unitary workstations without partitions. Therefore, different from the traditional office, colleagues can talk and interact with others [48]. Now, the open-plan office can be divided into the following types according to the function and structure [49,50]:

(1) Hive type: Hive type is common in open-plan office. As the name suggests, it is like a honeycomb. Three or four tables are assembled together with a certain distance between each other. Because of this, the communication space between employees is reduced, which increases the communication between employees, but also reduces employees' autonomy.

Fig. 1-2. Hive type open-plan office [103]

(2) Nest type: In nest type open-plan office, all the tables are assembled together, and all the employees are working together. Because the communication space is even shorter than the hive type, the interaction between colleagues is much more frequent. This can not only increase the cooperative relationship between employees, but also improve the negotiation efficiency of work, which is suitable for cooperation tasks.

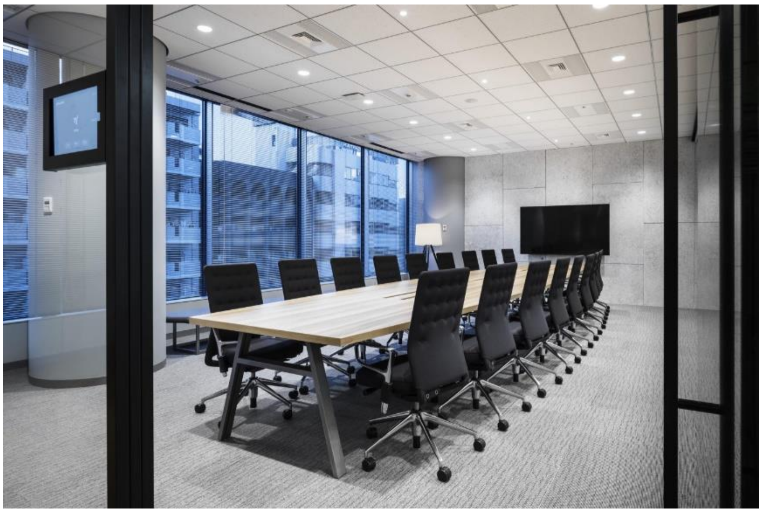


Fig. 1-3. Nest type open-plan office [104]

(3) Club type: Club type is not common in open-plan office. It is designed following the pattern of club, which provide relative independent space for the occupants.

Fig. 1-4. Club type open-plan office [104]

Nowadays, open-plan office is more and more widely used because of its low construction cost, high employee density and relatively low rent, which can better realize natural ventilation and lighting. It can also promote communication, cooperation and knowledge sharing among employees [51]. However, the research of Kang et al. showed that open-plan office design revealed contradictory characteristics. In addition to promoting communication, it also reduced employees' work efficiency. The results showed that the work efficiency of open-plan office was 15% lower than that of closed office, and people's attention was difficult to concentrate [52].

Relevant research showed that the indoor environment has a significant impact on the comfort of open office environment [53]. The research of Lai et al. showed that the acoustic environment quality was most closely related to the overall comfort of office workers, followed by indoor air quality, visual environment and thermal environment [54]. Therefore, for the open-plan research office, it is necessary to study how to improve the research performance of the researchers through adjusting the physical parameters of the acoustic, visual and thermal environment.

1.4 Visual Environment

Vision relies on the response of visual organs to the stimulation of external light sources, which excite sensory cells and produce visual perception through the later processing of visual nerve. Through vision, human beings can perceive the shape, brightness, dynamic status, distance and other information which has great significance to survival [55]. Also, vision is the main source of human perception of external things. For an adult, at least 80% of the external information is obtained through vision [56].

Visual environment is very important for the transmission of visual information. On the one hand, the brain can more efficiently and accurately receive the information carried by external visual signals in a good visual environment. On the other hand, in addition to transmitting information, light will also transmit external brightness and other perceptual information to the brain, which will have a positive impact on the mental state and psychological feeling of the human body [57]. For example, for work and study places, a good visual environment can inspire spirit and improve work efficiency. While for places of rest and entertainment, soft and dim visual environment can create a comfortable, elegant, lively or solemn atmosphere.

For modern architectural design, indoor visual environment design is an indispensable part. Illuminance is an important indicator of indoor visual environment. It refers to the luminous flux of visible light received per unit area (Eq.1-1), where $d\emptyset$ is the luminous flux incident on the point panel and dA represents the area of the point panel. [58]. Illuminance is used to indicate the quantity of light at the object surface. It is generally believed that illuminance is one of the important factors affecting visual perceptions and work efficiency [59,60]. The research of Candas and Dufour showed that at low illuminance environment (50lux), the probability of indoor personnel having the sick building symptoms such as eye irritation, irritability and difficulty in focusing was increased. The learning efficiency and work efficiency of the occupants also declined [61].

$$Illuminance = \frac{d\emptyset}{dA} \quad (Eq. 1-1)$$

Glare is another important indicator, which is used to reflect the uncomfortable feeling caused by uneven illumination distribution, which can reduce the visual perception about details. Therefore, in this experiment, illuminance and glare are the environment physical parameters used to detect indoor visual environment.

1.5 Acoustic Environment

When the sound wave acts on the auditory organ, the vibration of sound wave excites the sensory cells of auditory organ and causes the impulse of auditory nerve. And then through analyzing by the auditory centers at all levels, the feeling is generated, which is called hearing [62]. If the sound wave carries information, the information is transferred through this process and reached the auditory cortex [63]. Because the waveform and frequency of different information is distinct, when the brain processing the related sound waves, different waveforms and frequencies are recognized and converted into corresponding information according to the rule of decoding. This rule of decoding is the knowledge which brain already own [64-66].

For human beings, hearing is not only an important sensory channel, but also the second important long-distance information acquisition channel of human body. The threshold of human hearing is generally between 0dB(A) and 130dB(A). When the sound intensity exceeds 140dB(A), the sound wave no longer causes hearing, but tenderness [67]. However, the auditory threshold is also affected by individual differences, environment, and other factors with a little fluctuation.

In modern office buildings, employees generally work in a semi enclosed area without partition, which is so-called open-plan office. Such office conditions have the characteristics of low cost and convenient communication, so they are favored by more and more companies [68]. However, the relevant studies showed that employees' environmental perception in an open-plan office was significantly lower than that in a traditional office, and the acoustic perception was the most affected [60,70]. This is because that, compared with traditional offices, open-plan offices often have some background noise, like telephone ringing, conversation, walking, typing and machine noise. These noises are often useless, irrelevant and unpredictable, which causes subjective interference and has a negative impact on employees' acoustic environment perception [71].

Previous studies only focused on the impact of high-intensity noise above 80dB(A) on the acoustic perception and occupants' productivity. However, for open-plan office, except for some special cases, the indoor background noise intensity is generally between 40dB(A) (quiet open-plan office conditions) and 75dB(A) (normal busy open-plan office conditions). Moreover, the change of sound intensity not only affects acoustic perception, but also exerts influence on thermal perception and visual perception. However, the number of research about the influence of sound intensity on indoor perception within this sound intensity region is quite limited. In addition, because research task needs more calculation and logistic activity than the ordinary office task, there exists an obvious difference about the work difficulties between the research task and the ordinary office task. Therefore, it is necessary to conduct research about the impact of acoustic environment changes on research performance separately.

Some studies also showed that background noise and background music had different effects on employees' work productivity under the same sound intensity. Sengupta and Jiang's research showed that under the background music, subjects' hand movement during typing task was more stable [72]. Lesiuk's research showed that the learning curve was positively changed when studying with background music, which improved the studying performance of subjects [73]. However, some studies believed that the background music would reduce the work efficiency [74].

1.6 Thermal Environment

Thermal perception is the skin feeling which stimulated by different temperatures. It includes two different sensory systems: warmth perception and cold perception. Warmth perception and cold perception are determined by relationship between stimulation temperature and the skin surface temperature. If the stimulation temperature is above the skin surface temperature, it will cause warmth perception. On the contrary, if the stimulation temperature is below the skin surface temperature, it will cause cold perception [75]. For the indoor environment, the stimulation temperature can be regarded as the average indoor air temperature.

Although thermal perception cannot carry information like vision and hearing, thermal perception is still an important perception used to maintain the functional balance of the body. For the building environment, thermal environment is an important indicator for indoor environment. Bad thermal environment, like overheating or overcooling, will have a negative impact on indoor personnel.

Living and working in such an environment for a long time will not only greatly reduce the work performance, but also affect health, and even produce sick building syndrome [76,77]. Sick building syndrome is closely related to the indoor environment. It refers to the adverse reactions to the occupants' health or comfort after a long residence time in the building. It is not caused by disease or definite pathology and limited to a specific space of the building. Most of the discomfort is eliminated after leaving the building [78].

1.7 Research Objectives

Main objective:

To develop a mathematical model which predicts the researcher's performance based on the environment physical parameters for research institution.

Sub objectives:

In order to solve this main objective, three sub objectives were put forward:

1. To identify the influence mechanism of indoor environments on researchers' environmental perception and satisfaction in an open-plan office of research institution by considering the combinational effect of different aspects of indoor environments.
2. To identify the influence mechanism of indoor environments on researchers' research performance for research institution by considering the combinational effect of different aspects of indoor environments.
3. To identify the correlation effect between different environmental comforts.
4. To identify the weight of each environment indexes for predicting indoor environment quality

1.8 Research Significance and Originality

1.8.1 Mathematical model between environment parameters and research performance

Most of the existing literature used qualitative analysis when studying the impact of indoor environment on occupants' productivity. Since the coexistence of indoor environment parameters and their interaction with each other [79], it is quite difficult to develop a mathematical model between occupants' performance and combinations of different environment conditions. In this research, a mathematical model about the influence of indoor environment on researchers' research performance were established, which filled the gap in this field.

1.8.2 Influence of combinational effect on occupants' perception and satisfaction

For indoor environment, most of the research mainly focused on the influence of single environment parameter on the researchers' comfort [80-85]. According to work by Zomorodian et al., acceptable indoor condition would not be achieved unless a holistic acceptance in air quality, thermal, acoustic and visual comfort at the same time [9]. For this research, besides the research of influence of individual parameter on corresponding comfort, the combinational effect of thermal, visual and acoustic parameters on researchers' comfort were also analyzed, which filled the blank of the existing research.

1.8.3 Fatigue Effect

The researchers need to conduct similar work day by day, where fatigue is a quite important factor when evaluating the researchers' performance. However, most of the research only used the task accuracy as the only indicator to evaluate the occupants' performance [11]. As fatigue will lead to the decline of efficiency, it often takes extra time to complete the same work. For this research, in order to balance the effect of fatigue on researchers' research performance, the accuracy and response time shared the equal weight when calculating the performance index. Meanwhile, in order to prevent the fatigue influence caused by the sequence of experiments on the experimental results, Latin square design was used in this research.

1.8.4 Controlled research office with radian floor heating system

In the existing research, the number of the research studied the relationship between IEQ and occupants' comfort and productivity in research institution are limited. In addition, most of the experiments were conducted in a controlled office using air conditioner to adjust the thermal environment in summer [43, 47]. But this is not in line with the winter heating condition in northern part of China, where radiant floor heating system are widely used instead of air conditioner. Therefore, under the radiant floor heating system in winter, the relationship between IEQ and occupants' comfort and productivity need to be studied separately. Therefore, this research was based on the data from an experiment carried in a controlled research office in a pharmaceutical research institution in

Northeast of China in winter. And the controlled research office was equipped with radian floor heating system which supply heating in winter.

1.9 Thesis Structure

The thesis structure of this paper is shown in Fig. 1-5. Firstly, this paper qualitatively analyzed the impact of indoor environment on researchers' environmental perception (Chapter 3, 4 and 5), which solved the sub objective 1. Secondly, this paper qualitatively analyzed the impact of indoor environment on researchers' research performance (Chapter 3, 4 and 5), which solved the sub objective 2. Thirdly, Chapter 6 of this paper analyzed the correlation among the three environmental comforts, and identified the interaction among the three environmental comforts, which solved the sub objective 3. Fourth, this paper compared the existing three mathematical models of comfort prediction, and improved the existing model equations through linear regression, so as to obtain the environmental comfort index. Through factor analysis of environmental comfort index, the weight of each environmental comfort index in indoor environment quality equation was obtained (Chapter 7), which solved the sub objective 4. Finally, through the nonlinear regression analysis of IEQ index and research performance index, the relationship between IEQ index and Performance Index was obtained. Through the series connection between performance prediction equation, indoor environment quality equation and improved prediction equation of environmental comfort, the relationship between research performance and environment physical parameters in research facilities was established. And this mathematical model was the main objective of this research.

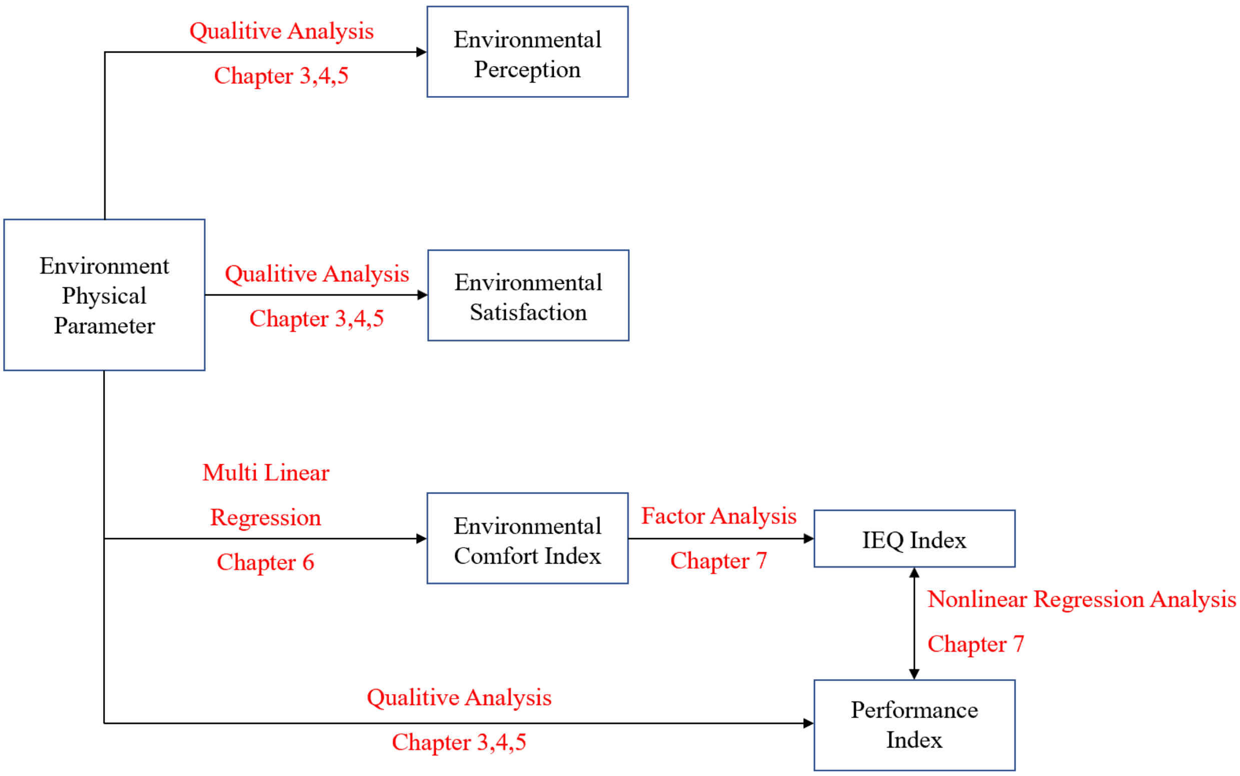


Fig. 1-5. Thesis structure of this paper

Chapter II

Experimental design and research methodology

2.1 Data Collection

The participants of this experiment were researchers from a pharmaceutical research company in northeast of China. In total, 32 participants were recruited, including 16 males and 16 females. The equal number of male and female recruited was to eliminate the interference of gender to the experiment. The age of the participants was between 25 and 40 years old, such age was classified as young people [86]. By just recruiting the young people, the interference of age to the experiment can be eliminated. In this experiment, all the participants were voluntary to participate, and they were healthy, without any history of serious diseases such as hypertension, asthma, diabetes and heart disease. All participants lived in Northeast China for more than two years and adapted to the winter climate conditions of the experimental site, so as to avoid the impact of climate adaptability on the experimental results.

Before participating in the experiment, the subjects were told to keep enough sleep and had a good diet to reduce the impact of fatigue and physical sub-health on the experimental results. At the same time, alcohol and smoking were strictly prohibited within 12 hours before the beginning of the experiment. Drink tea, coffee, other functional drinks that would stimulate human function was also forbidden within four hours before the experiment. In addition, strenuous exercise, like running or jumping were not allowed within four hours before the experiment. Through requiring participants to comply with these regulations, it can avoid the interference of short-term stimuli to the experiment. It can also ensure that the simulated research scene was highly consistent with the real scene when the subjects participated in the experiment.

2.2 Controlled Research Office

This research was conducted in a controlled research office in a pharmaceutical research company in Northeast of China. The controlled office was transformed from an ordinary office, with a total floor area of $64.8m^2$ and the clear ceiling height of 3m. The exterior wall of the controlled office was covered by heat-insulating materials, and the six window shadings were installed to prevent the interference of the nature light. The entire controlled office was heated using a radiant floor heating system, with a total of six water inlet pipes. The amount of hot water flowing into the office was controlled through six valves, which was used to change the indoor air temperature. In winter, the indoor environment was relatively dry; therefore, the room was equipped with a humidifier to keep the average indoor humidity at around 40%. The ceiling of the office was equipped with four groups of eight 40W ceiling fluorescent lamps, which provided about 200lux of illumination on the desk of the participants. Each desk was equipped with an LED desk lamp, providing an additional 300lux illumination. An 80-minute interview program was prepared on a computer for the noisy session to simulate the situation of discussion in the research office. By adjusting the volume of the video, the noise intensity near the desk was maintained around 70dB(A). The plan view of the controlled office and the location of each environmental sensor are shown in Fig. 2-1.

Fig. 2-1. Plan view of controlled research office

Normally, experiments about indoor environment were usually carried out in a in a climate chamber [11]. However, for this experiment, it was conducted in an existing office. The reason is that the traditional climate chamber is generally surrounded by concrete walls with heat insulation panels and no window is installed in the room. This will give people in the climate chamber a cold and depressing feeling [87]. In addition, the traditional climate chamber has a small indoor area, which can only accommodate one participant at one time. Such structure cannot simulate the interaction of indoor personnel in the open-plan office environment. But the experiment conducted in the existing office can well simulate the actual research environment and avoid the impact of difference of structures on the experimental data.

2.3 Experiment Sequence

In this experiment, three environment physical parameters were selected as the independent variables: indoor air temperature (21℃, 24℃, 27℃), the illuminance level of the participants' desktop (200lux, 500lux), and the average background noise level of the research office (45dB(A), 70dB(A)). In total, there were 12 different thermal, visual and acoustic combinations, which were recorded as environment conditions A-L. The description of each environment condition is shown in Table 2-1.

Table 2-1

Illustration of 12 different environmental conditions.

Condition	Illustration	Condition	Illustration	Condition	Illustration
A	21°C, Dark, Quiet	E	24°C, Dark, Quiet	I	27°C, Dark, Quiet
B	21°C, Dark, Noisy	F	24°C, Dark, Noisy	J	27°C, Dark, Noisy
C	21°C, Bright, Quiet	G	24°C, Bright, Quiet	K	27°C, Bright, Quiet
D	21°C, Bright, Noisy	H	24°C, Bright, Noisy	L	27°C, Bright, Noisy

The environmental comfort and research performance of participants are not only affected by indoor environment parameters but are also closely related to personal factors. Because of individual differences, everyone has a different tolerance to fatigue. Therefore, to prevent the fatigue influence caused by the sequence of experiments on the experimental results, a Latin square design was used in this research. The principle of Latin square design is that every independent variable has the same chance to appear at every position of the experimental sequence. The specific experiment sequences of the four experiment groups are shown in Table 2-2.

Table 2-2

Experiment sequence of each experiment group.

	Day 1				Day 2				Day 3			
	08:30-10:00	10:20-11:50	13:30-15:00	15:20-16:50	08:30-10:00	10:20-11:50	13:30-15:00	15:20-16:50	08:30-10:00	10:20-11:50	13:30-15:00	15:20-16:50
Group1	A	B	C	D	E	F	G	H	I	J	K	L
Group2	B	D	A	C	F	H	E	G	J	L	I	K
Group3	C	A	D	B	G	E	H	F	K	I	L	J
Group4	D	C	B	A	H	G	F	E	L	K	J	I

2.4 Experiment Procedure

In this experiment, the participants were divided into four experiment groups. Each experiment group included eight participants, where the number of male and female were equal. Each experiment group needed to participate in the experiment for three days. In each day's experiment, the visual and acoustic conditions were changed four times, while the temperature remained unchanged. Each environmental condition lasted for 90 minutes. The participants needed to carry out daily scientific research activities in the first 80 minutes and complete the subjective questionnaire as well as the productivity performance test in the last 10 minutes. In each condition, the participants needed to remain seated to minimize the influence of activity level on perception. After each condition, the participants had a 20-minute break to eliminate the fatigue impact. In noisy conditions, participants were allowed to discuss their research with others, while this behavior was strictly forbidden in quiet conditions. The corresponding flow chart is shown in Fig. 2-2.

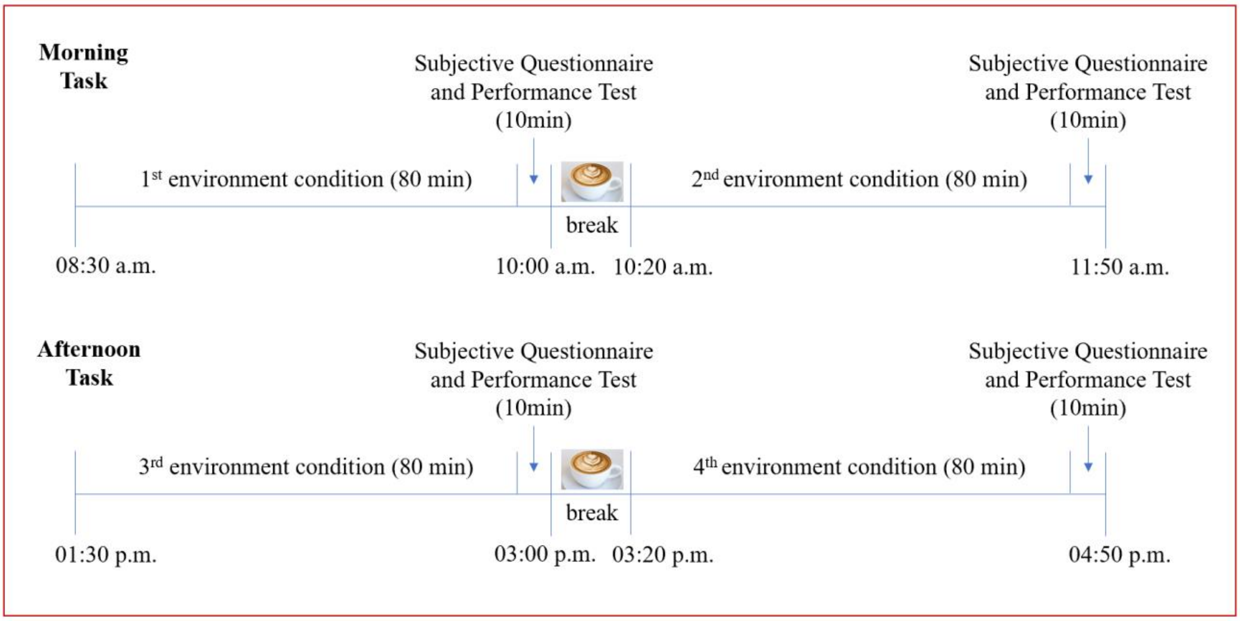


Fig. 2-2. Daily experiment process for each experiment group

In order to avoid the influence of weekly cycle on participants, each experiment group participated in the experiment at the same time every week. For example, the first experiment group participated in the experiment every Monday, the second experiment group participated in the experiment every Tuesday, and so on. In the weekly experiment, the indoor thermal environment of each experiment group remained unchanged. Because the change of indoor thermal environment took a certain time to take effect and maintain stability, the valve of radiant floor heating system was adjusted every Friday, and the controlled research office is left vacant for two days to make the indoor temperature reach the temperature required for the next week's experiment.

One week before the experiment, each participant was asked to be familiar with the entire experiment procedure and understand how to fill in the subjective questionnaire and complete the productivity performance test. The experiment photos are shown in Fig. 2-3.

Fig. 2-3. Photos of participants during the experiment

2.5 Environment Physical Parameters

Four environment physical parameters were recorded during the experiment process: indoor air temperature, relative humidity, the illuminance level of the participants' desktop, and the average background noise level of the research office. The temperature/RH sensor and sound meter were located 1.2 m above the floor at the center of the office, while the luxmeter was set on each desktop. Office temperature and relative humidity were recorded three times in each environmental condition. The illuminance level was measured twice, one was at the beginning and the other was at the end of the experiment session. The noise intensity was measured every 20 minutes during the experiment. The measured environment physical parameters of each experiment group under various environment conditions are shown in Table 2-3.

Table 2-3

Summary of measured environment physical parameters (mean value ± standard deviation) for different environmental conditions

Environment Condition	Air Temperature (°C)	Relative Humidity (%)	Illuminance (lux)	Background Noise Intensity (dB(A))
A (21°C+Dark+Quiet)	21.0 ± 0.50	40.5 ± 3.30	201 ± 28.6	43.7 ± 2.65
B (21°C+Dark+Noisy)	21.0 ± 0.56	43.2 ± 3.08	219 ± 13.8	73.6 ± 3.73
C (21°C+Bright+Quiet)	21.2 ± 0.47	37.7 ± 2.63	509 ± 26.0	41.1 ± 3.51
D (21°C+Bright+Noisy)	20.9 ± 0.40	40.8 ± 3.70	510 ± 30.2	69.5 ± 2.19
E (24°C+Dark+Quiet)	24.3 ± 0.37	41.1 ± 4.19	191 ± 17.8	42.6 ± 3.54
F (24°C+Dark+Noisy)	24.3 ± 0.54	40.5 ± 2.32	187 ± 28.1	71.3 ± 2.61
G (24°C+Bright+Quiet)	23.8 ± 0.48	40.6 ± 4.24	503 ± 27.1	42.9 ± 5.05
H (24°C+Bright+Noisy)	23.8 ± 0.63	38.6 ± 2.92	489 ± 41.0	72.2 ± 3.58
I (27°C+Dark+Quiet)	27.2 ± 0.44	38.4 ± 2.95	186 ± 24.3	42.3 ± 4.39
J (27°C+Dark+Noisy)	27.1 ± 0.35	41.2 ± 4.17	197 ± 15.5	73.8 ± 2.52
K (27°C+Bright+Quiet)	27.1 ± 0.50	38.5 ± 3.70	491 ± 21.5	41.5 ± 4.37
L (27°C+Bright+Noisy)	26.8 ± 0.54	38.0 ± 3.56	506 ± 23.1	74.1 ± 2.84

The temperature/RH sensor used HT618 digital thermo-hygrometer humidity temperature meter (Dongguan Habotest Instrument Technology Co., Ltd, China). The temperature range is from -20°C to 60°C with an accuracy of ±0.1°C. And the humidity range is 0% to 100%, with the accuracy of 0.1%.

Luxmeter adopted HT620l digital LED light meter (Dongguan Habotest Instrument Technology

Co., Ltd, China), with a range of 0 to 200000lux and an accuracy of ±3%.

The sound meter adopted HT622A digital sound level meter/digital noise meter (Dongguan Habotest Instrument Technology Co., Ltd, China), with a range of 30dB to 130dB and an accuracy of ±1.5dB. At the same time, the sound meter can calculate the A-weighted sound level so that the output value is the weighted average background noise intensity.

2.6 Subjective Questionnaire

At present, subjective questionnaire is the main evaluation method to study the perception and comfort of indoor environment to indoor personnel. A specially designed questionnaire was distributed to the participants to assess their environmental perceptions and satisfactions about the environment of the research office. It included three sections: general information, environment preference, and environment perception and satisfaction. General information collected the information of participants' name, gender, age and clothing insulation level when tested. Environment preference collected the information about the participants' preference for thermal environment, visual environment and acoustic environment. Environmental perceptions and satisfactions recorded the participants' perception and satisfaction about indoor thermal environment, visual environment and acoustic environment under different environment conditions.

7-point ASHRAE scale was used for rating the participants' perceptions in this experiment [9, 10]. For each environmental perception, the meaning of the seven scores is listed as following:

(1) For thermal perception, the seven scores corresponded to Very Cold: -3，Cold: -2, Cool: -1, Neutral: 0, Warm: 1, Hot: 2, Very Hot: 3.

(2) For visual perception, the seven scores corresponded to Very Dark: -3，Dark: -2, Slightly Dark: -1, Neutral: 0, Slightly Bright: 1, Bright: 2, Very Bright: 3.

(3) For acoustic perception, the seven scores corresponded to Very Noisy: -3，Noisy: -2, Slightly Noisy: -1, Neutral: 0, Slightly Quiet: 1, Quiet: 2, Very Quiet: 3.

Participants' satisfaction was also scored by 7-point ASHRAE scale. The meaning of the seven scores corresponded to Very Dissatisfied: -3，Dissatisfied: -2, Slightly Dissatisfied: -1, Neutral: 0, Slightly Satisfied: 1, Satisfied: 2, Very Satisfied: 3.

Indoor Environment Assessment

The questionnaire is used to collect the perception and satisfaction of the participants

Part 1: General Information

Name		Gender		Age
Clothing	Sweater	Thick	Medium	Thin
	Trousers	Thick	Medium	Thin
		Long	Medium	Short
	Socks	Thick	Medium	Thin
	Shoes	Thick	Medium	Thin
	Thermal Underwear	Yes	No	

Part 2: Preference Information

1. Do you prefer cool or warm thermal condition?	Cool	Warm
2. Do you prefer listening to music when you study?	Yes	No
3. Do you prefer slightly dark or slightly bright condition when you study?	Slightly Dark	Slightly Bright

Environment Condition A: 21 centigrade, 200lux, 45dBA

Part 3: Indoor Environment Assessment

Q1: What is your feeling about the current thermal condition?

-3	-2	-1	0	1	2	3
Very Cold	Cold	Cool	Neutral	Warm	Hot	Very Hot

Q2: Do you satisfy with the current thermal condition?

-3	-2	-1	0	1	2	3
Strongly Dissatisfied	Dissatisfied	Slightly Dissatisfied	Neutral	Slightly Satisfied	Satisfied	Strongly Satisfied

Q3: What is your feeling about the current visual condition?

-3	-2	-1	0	1	2	3
Very Dark	Dark	Slightly Dark	Neutral	Slightly Bright	Bright	Very Bright

Q4: Do you satisfy with the current visual condition?

-3	-2	-1	0	1	2	3
Strongly Dissatisfied	Dissatisfied	Slightly Dissatisfied	Neutral	Slightly Satisfied	Satisfied	Strongly Satisfied

Q5: What is your feeling about the current acoustic condition?

-3	-2	-1	0	1	2	3
Very Noisy	Noisy	Slightly Noisy	Neutral	Slightly Quiet	Quiet	Very Quiet

Q6: Do you satisfy with the current acoustic condition?

-3	-2	-1	0	1	2	3
Strongly Dissatisfied	Dissatisfied	Slightly Dissatisfied	Neutral	Slightly Satisfied	Satisfied	Strongly Satisfied

Fig. 2-4. Sample of subjective questionnaire.

3-point McIntyre scale was adopted for choosing the participants' clothing level when participating in the experiment. 2-point scale was used to collect the participants' preference about the environment.

2.7 Research Performance

In daily work, we will encounter a common phenomenon: when completing tasks with the same workload, if we pursue the speed of completing tasks, there will be more errors and the quality of task completion will decline; On the contrary, if we pursue the quality of completing tasks, we are bound to spend more working time to improve the quality of the work. The inverse relationship between speed and completion quality is speed – accuracy trade-off [88]. For research work, this situation is more obvious. Therefore, both speed and accuracy need to be considered when evaluating researchers' research performance.

Performance Test

Environment Condition A: 21 centigrade, 200lux, 45dBA

Please calculate the difference between the left and right numbers of each line

1. If the number on the left is less than the number on the right, please fill in "-" value "in the space
2. If the number on the left is equal to the number on the right, please fill in "0" in the space
3. If the number on the left is greater than that on the right, please fill in "+ value" in the space

3		7		10		3		6		3		8		10		7		9		2
7		5		4		3		10		10		9		10		7		10		1
3		5		4		4		6		1		5		10		8		2		0
9		1		1		2		10		6		5		7		4		2		7
0		7		2		5		4		8		3		7		10		2		10
7		5		4		10		0		6		8		4		6		10		6
1		1		9		6		2		1		8		7		0		10		1
4		0		5		1		0		8		10		2		8		3		6
6		4		0		1		8		7		1		1		4		2		0
0		3		0		2		6		10		3		6		6		0		3

Duration

Fig. 2-5. Sample of performance test

In this experiment, a specially designed numerical calculations program was used to evaluate the research performance of participants under various environmental conditions. The program included a 10 × 11 matrix, each component was an integer from 0 to 10. During the experiment, the subjects were asked to calculate the difference between two adjacent numbers in the same row (former minus latter). If the difference was greater than 0, a positive value needed to be typed; if the difference was less than 0, a negative value needed to typed; if the two numbers are equal, the difference was represented by 0. The participants needed to answer the questions from the first line in order to the last line, and each line needed to be completed from left to right. Correcting the previous mistakes was strictly prohibited. At the same time, the participants were required to complete the test within 300s. The sample of performance test is in Fig. 2-5.

2.8 Evaluation of research performance

After the participants completed the performance test, the completed answers were manually brought into the accuracy evaluation program, and the program automatically calculated the participants' answer accuracy under this environment condition. The statistical method is shown in Eq. 2-1, where N_C represents the number of answers correctly completed by the participants, N_T stands for the total number of test questions. The range of accuracy is from 0 to 100.

$$Accuracy = \frac{N_C}{N_T} \times 100 \quad (Eq. 2-1)$$

After the participants completed the performance test, the numerical calculations program automatically counted the participants' response time, and the unit was in seconds. According to the pilot tests, the average response time for the participants to complete the performance test under all environment conditions was 213s, and the standard deviation is 23s. According to the principle of triple standard deviation, the probability of participants completing the performance test within $mean - 3\sigma = 213 - 3 \times 23 = 144\text{s}$ to $mean + 3\sigma = 213 + 3 \times 23 = 282s$ was 99.73%. Therefore, the effect range of response time was between 144s and 282s. Considering the individual differences, the response time range was expanded to 100 to 300s.

Because speed and accuracy needed to be considered at the same time when evaluating researchers' research performance. Therefore, in this experiment, geometric weighted average was adopted to obtain performance indexes, in which the accuracy and speed shared the equal weight, both were 0.5. The performance index was expressed as Eq. 2-2. Because the range of accuracy of the participants' answers was from 0 to 100, and the range of the response time was from 100 to 300s. Through calculating using Eq. 2-2, the range of actual performance index was from 0 to 100.

To express the productivity performance of the participants more intuitively, the performance indexes in each environment condition needed to be standardized. The formula is shown in Eq. 2-3, where PI_{ij} represents the performance index of participant i under environmental condition j, n represents the total environment conditions and equals to 12, and RPI_{ij} represents the percentage of participant i's performance under environmental condition j compared with the average performance under all 12 conditions.

$$Performance\ (PI) = Accuracy^{0.5} \times Speed^{0.5} \times 100 = \frac{Accuracy^{0.5}}{Response\ Time^{0.5}} \times 100 \quad (Eq. 2-2)$$

$$RPI_{ij} = \frac{n \times PI_{ij}}{\sum_{j=1}^{n} PI_{ij}} \times 100\% \quad (Eq. 2-3)$$

2.9 Sample Size Calculation

According to the principle of statistics, there exists a relationship between the level of significance α, statistical power (1-β), the effect size ES and the sample size N. Once three of the above variables are determined, the fourth variable is also determined. Therefore, the sample size N can be estimated using the significance level α, statistical power (1-β) and the effect size ES.

Among them, the significance level α refers to the probability or risk that H_0 is rejected incorrectly in the analysis when the original assumption H_0 is correct, that is also called type I error. In this experiment, the confidence interval was 95%, so the level of significance α was set as 0.05.

Statistical power is related to beta error probability. Beta error probability refers to the probability or risk that H_0 is wrongly accepted in the analysis when the original assumption is wrong, that is also called type II error. Statistical power refers to the probability that H_0 is correctly rejected in the analysis when the original hypothesis H_0 itself is wrong. Therefore, the $statistical\ power = 1 - \beta$. In the experimental analysis, the statistical power is generally greater than 80%, so when estimating the number of samples, the statistical power was set as 0.8.

Effect size ES refers to the difference caused by factors, and it is an index to measure the size of treatment effect. Different from the significance test, effect size is not affected by the sample size. When estimating the number of samples, the effect size is calculated using Cohen's d, generally the value of d was set as 0.5.

Because the relationship among significance level α, statistical power (1-β), effect size ES and sample size N is complex, so the sample size was estimated with the help of online analysis software "understanding statistical power and significance testing" [89]. Fig. 2-6 shows the results of sample size calculation. It can be seen from the results that the total number of samples needed to be at least 31.4. Therefore, in this experiment, the total number of samples was set to 32.

Fig. 2-6. Sample size calculation using online analysis software.

2.10 Data Analysis Method

The data of this experiment were statistically analyzed by SPSS 21.0. Related analysis methods included paired sample t-test, one-way ANOVA, correlation analysis, factor analysis and regression analysis

2.10.1 Paired Sample T-test

Paired sample t-test refers to calculating the difference between the results of two different processing methods for the same sample, and testing the significance of the difference and zero. If there is no difference between two treatments, the overall mean value of the difference should be zero, and the difference should fluctuate around zero. On the contrary, if there is difference between two treatments, the overall mean value of the difference should be far away from zero.

One of the requirements for the paired sample t-test is that the difference between two groups should be normally distributed. In this experiment, paired sample t-test was used to examine the effects of different visual and acoustic environments on environmental perception, satisfaction and research performance.

2.10.2 One-way ANOVA

Analysis of variance, abbreviated as ANOVA, refers to the determination of whether the overall mean value is equal by analyzing the variance of multiple samples. Before analyzing the variance of data samples, the samples need to meet three conditions:

1. The samples need to meet the normal distribution,
2. The samples are independent of each other, and
3. The samples are homogeneous in variance.

In this experiment, analysis of variance was used to examine the qualitative relationship between different thermal environments and environmental perception, satisfaction and research performance. It was also used to examine the significance of the regression equation.

2.10.3 Correlation Analysis

Correlation analysis refers to the analysis of two or more variable elements with correlation, so as to measure the correlation degree of two or more factors. Correlation analysis can be carried out only when there is a certain connection or probability between the relevant elements.

In this experiment, correlation analysis was used to analyze the correlation among participants' actual thermal satisfaction, visual satisfaction and acoustic satisfaction. The correlation coefficient between any two variables was calculated by Pearson’s correlation coefficient.

2.10.4 Factor Analysis

In this experiment, factor analysis was used to calculate the weight of each environmental comfort index in IEQ index equation. The principle is to use the information concentration principle, through studying the internal dependence between many variables, explore the basic structure of observation data and calculate the weight by using the variance interpretation rate.

2.10.5 Regression Analysis

Regression analysis is a predictive modeling technique. The method is to determine the quantitative relationship between dependent variables and independent variables from a set of data. This is also regarded as establishing a mathematical model and estimating the unknown parameters. The common method of estimating parameters is the least square method. The samples of regression analysis should meet the following requirements:

1. There is no collinearity between independent variables, which is detected in the collinearity analysis of independent variables;

2. Residuals should be independent of each other. And there is no correlation among residuals. In addition, the residuals must obey normal distribution. Analysis of residuals was conducted to examine the above three requirement for residuals.

In this experiment, multiple linear regression was needed to improve the three environmental index equations. Nonlinear regression was needed to study the relationship between performance index and IEQ index.

Chapter III

Influence mechanism of thermal environment on environmental perception, satisfaction and research performance

Sick building syndrome is caused by bad indoor environment. It refers to the adverse reactions to the occupants' health or comfort after a long residence time in the building. How to improve the indoor thermal environment and reduce sick building syndrome is an important research direction. In order to answer this question, it is necessary to clearly study the impact mechanism of indoor thermal environment on indoor environmental perception and satisfaction of occupants, which is one of the points to be discussed in this chapter. At the same time, the thermal environment also affects the research efficiency. Therefore, another point to be discussed in this chapter is the influence mechanism of indoor thermal environment on research performance.

3.1 Influence mechanism of thermal environment on thermal perception

In order to compare the effects of different thermal environments on environmental perception and satisfaction, 12 environment conditions were divided into four thermal groups according to different visual and acoustic environment combinations. For each thermal group, the visual environment and acoustic environment remained the same, but the thermal environment was different. Therefore, the average indoor air temperature was the only variable for the analysis within thermal group in this chapter.

The results of subjective evaluation of the participants' thermal perception are shown in Table 3-1 under different combinations of visual and acoustic condition. According to the results, the participants felt cool at 21°C thermal environment, since the average thermal perception at 21°C for all four thermal groups were in the range between -0.75 and -0.50. When the temperature increased to 24°C, the average thermal perception value changed to the range between 0.25 and 0.59. This indicated that at this temperature, no matter how the visual and acoustic environment changed, the participants' perceptions of the thermal environment were warm. For the temperature of 27°C, the results showed that the participants' feelings about thermal environment were concentrated around 1.5, which was regarded as hot.

Table 3-1

Results of thermal perception and thermal satisfaction for different thermal groups

		Environment Condition	Thermal Perception	Thermal Satisfaction
Thermal Group 1	A	(21°C+Dark+Quiet)	-0.75 ± 0.80	-0.38 ± 1.28
	E	(24°C+Dark+Quiet)	0.25 ± 0.72	0.38 ± 0.91
	I	(27°C+Dark+Quiet)	1.53 ± 0.88	-0.56 ± 1.39
Thermal Group 2	B	(21°C+Dark+Noisy)	-0.59 ± 0.76	-0.59 ± 1.04
	F	(24°C+Dark+Noisy)	0.44 ± 0.67	0.16 ± 1.05
	J	(27°C+Dark+Noisy)	1.56 ± 0.95	-0.56 ± 1.34
Thermal Group 3	C	(21°C+Bright+Quiet)	-0.56 ± 0.67	-0.31 ± 1.00
	G	(24°C+Bright+Quiet)	0.59 ± 0.76	0.69 ± 0.86
	K	(27°C+Bright+Quiet)	1.56 ± 0.92	-0.25 ± 1.39
Thermal Group 4	D	(21°C+Bright+Noisy)	-0.50 ± 0.72	-0.41 ± 0.91
	H	(24°C+Bright+Noisy)	0.56 ± 0.76	0.53 ± 0.84
	L	(27°C+Bright+Noisy)	1.63 ± 0.91	-0.47 ± 1.34

In each thermal group, the tendency of thermal perception with temperature for each thermal group is visually displayed in the bubble plot Fig. 3-1. The size of the bubble in the figure reflects the number of votes by the participants at that score. And the straight line represents the linear regression line based on the average thermal perceptions of three different thermal environments. It can be seen from the regression line that the goodness of fit of mean values for four thermal groups were larger than 0.99, which were close to 1. This showed that there existed a linear relationship between the indoor air temperature and the mean values of thermal perception for each thermal group. And in the temperature range of 21°C to 27°C, the thermal perception increased linearly with the increase of indoor air temperature.

In order to analyze whether there existed a significant difference between thermal perception in different temperature environments, one-way ANOVA was used in this experiment. The results of ANOVA for each thermal group are shown in Table 3-2.

According to the results of the test of homogeneity of variables, the significance of Levene variance homogeneity test was greater than the significance level of 0.05. Therefore, it could be considered that the variance between the sample data of each thermal group was homogeneous. In the post hoc analysis, because of the Homogeneity of variance, Tukey honestly significant difference (Tukey HSD) test was used for multiple comparison procedure.

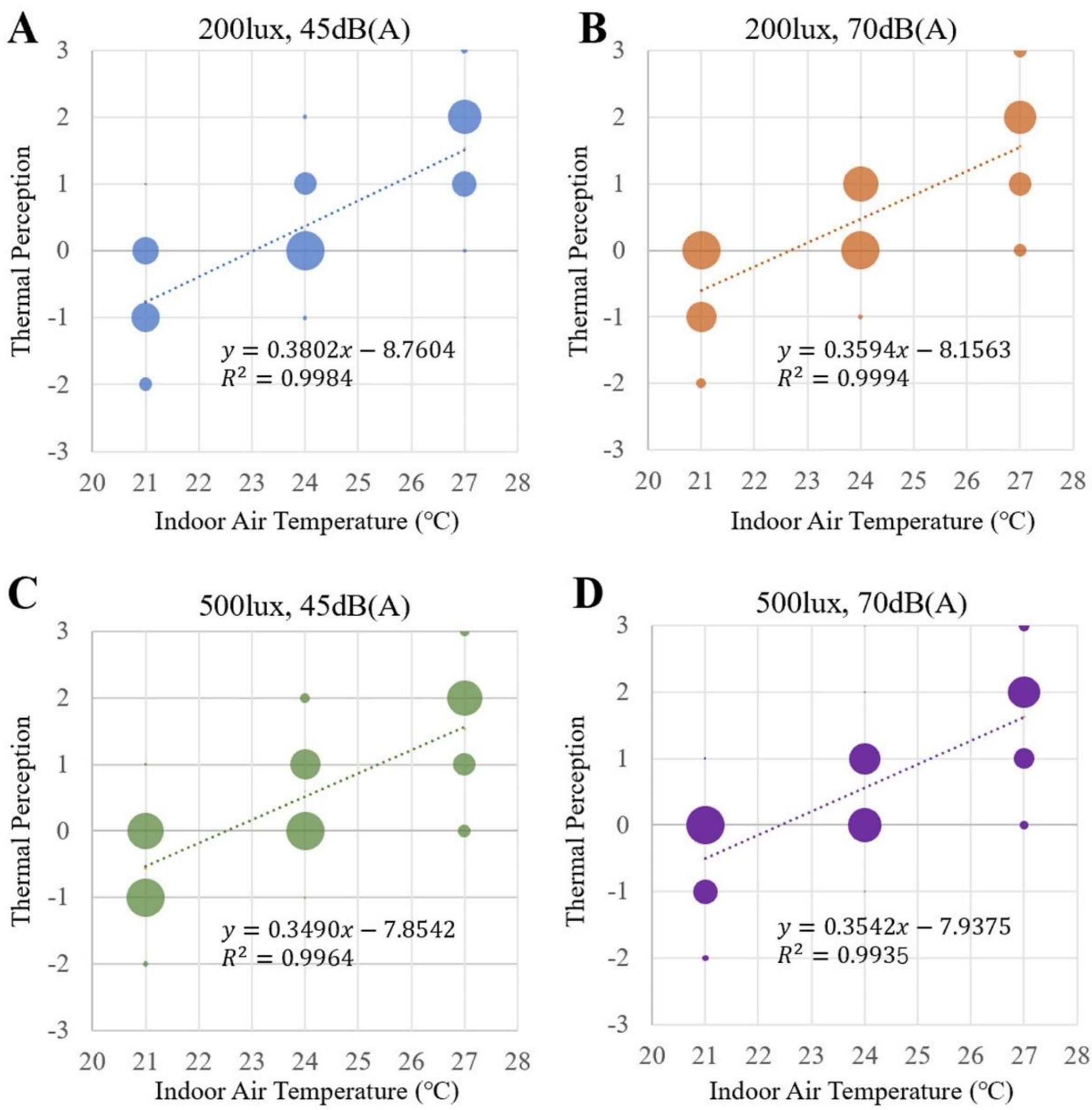


Fig. 3-1. Thermal perception votes and linear regression of the mean votes of four different visual and acoustic combinations: (A) 200lux and 45dBA, (B) 200lux and 70dBA, (C) 500lux and 45dBA and (D) 500lux and 70dBA

According to the results of one-way ANOVA, the significance of the sum of squares between groups was 0.000, less than the significance level of 0.05. Therefore, it could be concluded that different temperatures had a significant influence on the participants' perception of the thermal environment.

Fig. 3-2. demonstrates the results of multiple comparisons between different temperatures within each thermal group. The red mark indicated that the mean difference of this pair was significant. Therefore, it could be seen that the mean difference of thermal perception of 21℃, 24℃ and 27℃

was obvious. In addition, it could also prove that the subject's thermal perception would increase significantly with the increase of temperature.

Table 3-2

Test of homogeneity of variances and ANOVA results about thermal perception for each thermal group

Test of Homogeneity of Variances

	Thermal Group I Dark+Quiet	Thermal Group II Dark+Noisy	Thermal Group III Bright+Quiet	Thermal Group IV Bright+Noisy
Levene Statistic	0.964	2.603	2.201	1.094
Sig.	0.385	0.079	0.138	0.339

ANOVA

F	64.892	58.204	56.867	56.583
Sig.	0.000	0.000	0.000	0.000

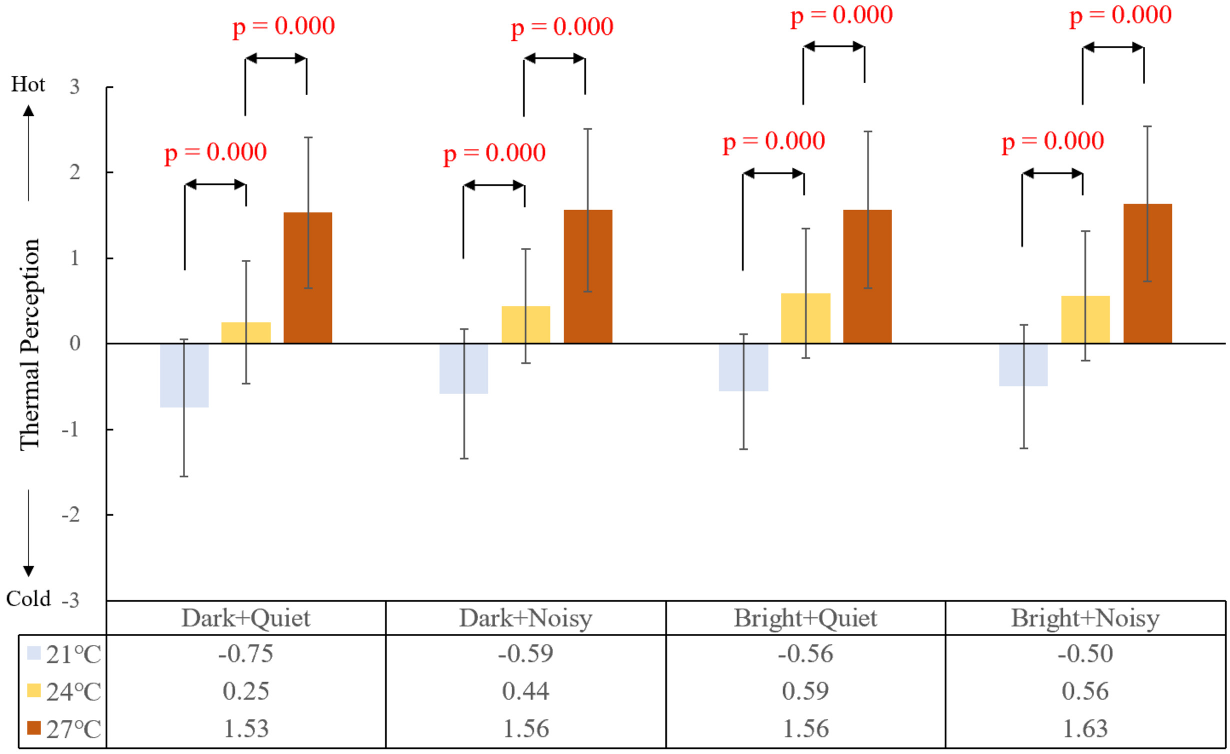


Fig. 3-2. Results of comparison between adjacent temperatures about thermal perception for each thermal group

3.2 Influence mechanism of thermal environment on thermal satisfaction

The results of the participants' thermal satisfaction for different thermal groups are shown in Table 3-1. According to the results, the average thermal satisfaction at 21℃ for all four thermal groups were in the range between -0.59 and -0.31, which indicated that the participants were slightly dissatisfied about this thermal environment. For the temperature of 24℃, the results showed that the participants' satisfaction about thermal environment were around 0.5, which can be interpreted as slightly satisfied. When the temperature increased from 24℃ to 27℃, the average thermal satisfaction dropped to around -0.5, which represented that the occupants were slightly dissatisfied about the thermal environment of 27℃. Through analyzing the tendency of average values of thermal satisfaction under different acoustic and visual environment combinations, it can be found that the relationship between thermal satisfaction of the participants and indoor air temperature can be regarded as a parabola. And the peak satisfaction rate appeared around 24℃.

In order to analyze whether there existed a significant difference about the thermal satisfaction between the pair of adjacent temperature, one-way ANOVA was conducted. The results of ANOVA for each thermal group are shown in Table 3-3.

According to the results of the test of homogeneity of variables, the significance of Levene variance homogeneity test was greater than the significance level of 0.05 only for thermal group of dark and noisy. Therefore, for dark and noise thermal group, it could be considered that the variance between the sample data was homogeneous. In the post hoc analysis, because of the homogeneity of variance, Tukey HSD test was used for multiple comparison procedure. However, for the other three thermal groups, the significance value of Levene variance homogeneity test was less than the significance level of 0.05. Therefore, the variance between the sample data was unequal and Dunnett's all-pairs comparison test (Dunnett’s T3) was used to analyze the difference between adjacent pair of temperatures within thermal group.

According to the results of one-way variance analysis, the significance of the sum of squares between groups was less than the significance level of 0.05. Therefore, it can be concluded that different temperatures had a significant influence on the participants' satisfaction of the thermal environment.

For the results of multiple comparisons between adjacent pair of temperatures within thermal group (Fig. 3-3), the red mark indicated that the mean difference of this pair was significant. Therefore, it can be seen that with the increase of the temperature from 21℃ to 24℃, the thermal satisfaction score significantly increased. But opposite trend was found when the temperature continued to increase from 24℃ to 27℃.

Table 3-3

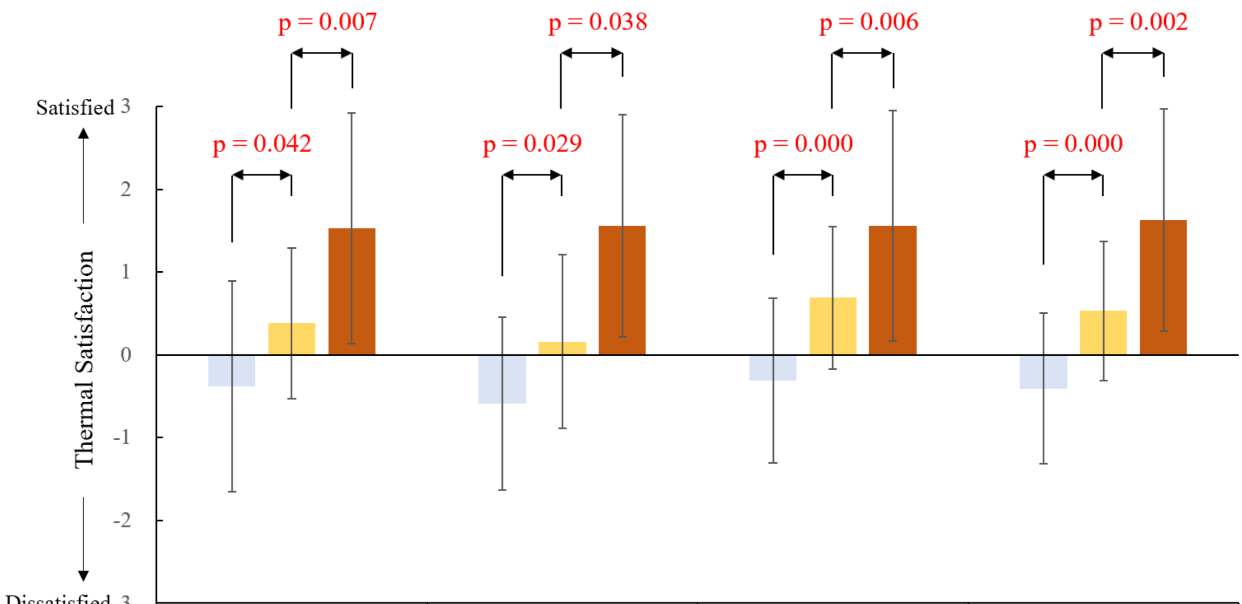
Test of homogeneity of variances and ANOVA results about thermal satisfaction for each thermal group

Test of Homogeneity of Variances

	Thermal Group I Dark+Quiet	Thermal Group II Dark+Noisy	Thermal Group III Bright+Quiet	Thermal Group IV Bright+Noisy
Levene Statistic	3.224	3.000	4.733	4.449
Sig.	0.044	0.055	0.011	0.014

ANOVA

	Thermal Group I Dark+Quiet	Thermal Group II Dark+Noisy	Thermal Group III Bright+Quiet	Thermal Group IV Bright+Noisy
F	5.070	4.327	8.210	9.009
Sig.	0.008	0.016	0.001	0.000



	Dark+Quiet	Dark+Noisy	Bright+Quiet	Bright+Noisy
21°C	-0.38	-0.59	-0.31	-0.41
24°C	0.38	0.16	0.69	0.53
27°C	1.53	1.56	1.56	1.63

Fig. 3-3. Results of comparison between adjacent temperatures about thermal satisfaction for each thermal group

When the thermal comfort was calculated in this experiment, the concept of actual percentage of dissatisfaction, which was calculated as the proportion of people who chose the "very dissatisfied" or "dissatisfied" options about the thermal satisfaction voting to the total number of the participants. Therefore, it was necessary to understand the relationship between actual percentage of dissatisfaction and thermal environment.

Fig. 3-4 demonstrates the scatter plot of the actual percentage of dissatisfaction about thermal environment for different environment conditions. The regression line was drawn for each thermal group with the same visual and acoustic environment. From the figure, it can be seen that the actual percentage of dissatisfaction was the lowest when the temperature was 24℃, while the most dissatisfaction occurred when the temperature was 27℃. The optimal temperature of the lowest points for the above four parabolic curve were between 22℃ and 23℃. When the temperature increased from 21℃ to the optimal temperature, the actual percentage of dissatisfaction decreased. Once the temperature exceeded the optimal temperature, the actual percentage of dissatisfaction increased significantly.

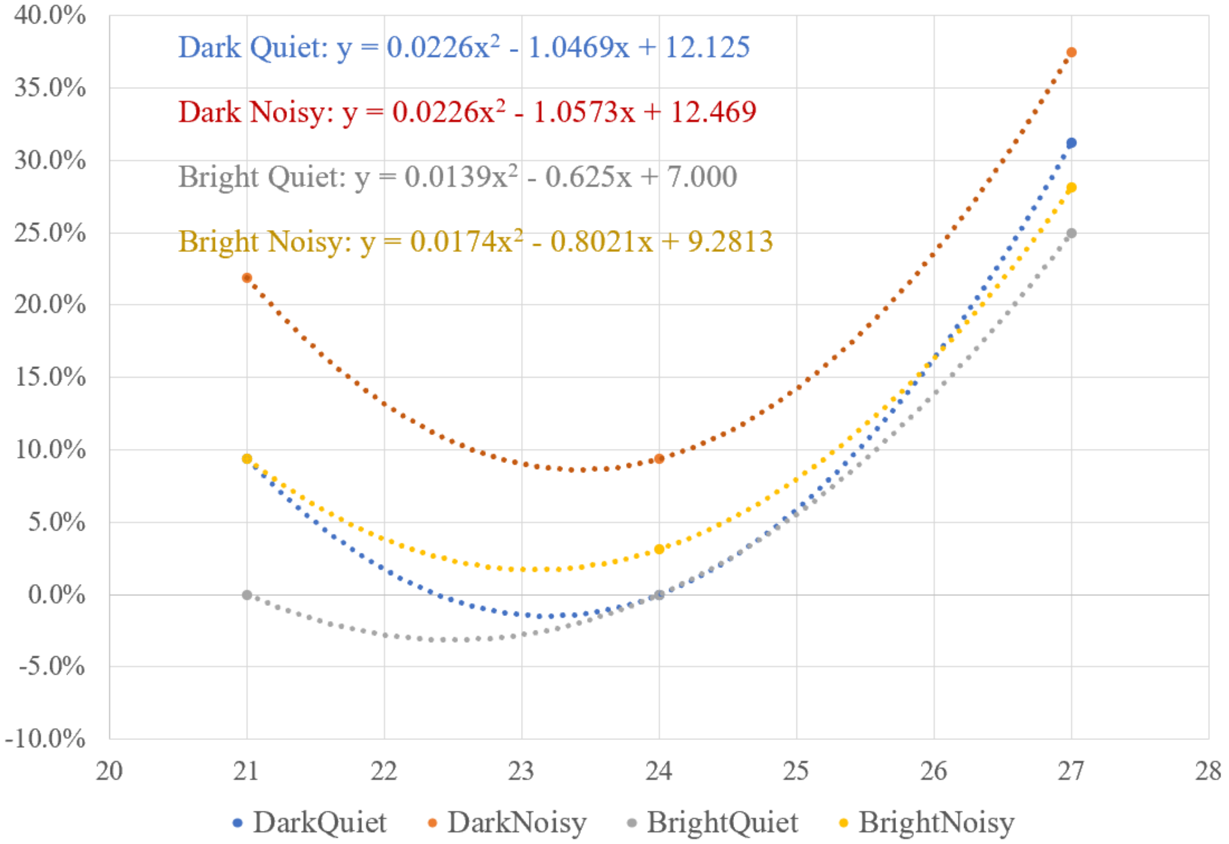


Fig. 3-4. Scatter plot of the actual percentage of dissatisfaction about thermal environment for different environment conditions

3.3 Influence mechanism of thermal environment on acoustic perception

In order to analyze the effect of thermal environment on acoustic perception, one-way ANOVA was used, and the results are shown in Table 3-4. From the test of homogeneity of variables for different thermal groups, it can be seen that the significance of Levene variance homogeneity test were greater than the significance level of 0.05 for all four thermal groups. Therefore, it can be considered that the variance between the sample data of each thermal group was homogeneous. According to the results of one-way analysis of variance, the significance of the sum of squares between groups was far larger than the significance level of 0.05. Therefore, the influence of thermal environment on acoustic perception was not significant, and subsequent multi comparison analysis was not required.

Table 3-4

Test of homogeneity of variances and ANOVA results about acoustic perception for each thermal group

Test of Homogeneity of Variances

	Thermal Group I Dark+Quiet	Thermal Group II Dark+Noisy	Thermal Group III Bright+Quiet	Thermal Group IV Bright+Noisy
Levene Statistic	0.208	1.767	0.313	0.459
Sig.	0.812	0.176	0.732	0.633

ANOVA

	Thermal Group I Dark+Quiet	Thermal Group II Dark+Noisy	Thermal Group III Bright+Quiet	Thermal Group IV Bright+Noisy
F	0.304	0.906	0.294	0.722
Sig.	0.739	0.408	0.746	0.488

3.4 Influence mechanism of thermal environment on acoustic satisfaction

One-way ANOVA was used to analyze the effect of thermal environment on acoustic satisfaction. The results are shown in Table 3-5. According to the test of homogeneity of variables for different thermal groups, it can be seen that the significance of Levene variance homogeneity test were larger than the significance level of 0.05 for all four thermal groups. Therefore, it can be considered that the variance between the sample data of each thermal group was homogeneous.

According to the results of one-way analysis of variance, only for thermal group of dark and noisy, the significance of the sum of squares between groups was less than the significance level of 0.05. Therefore, for thermal group of dark and noisy, post hoc analysis was required. And because of the homogeneity of variance, Tukey HSD test was used for multiple comparison procedure.

The multiple comparison results showed that only for pair comparison between temperature of 21℃ and 27℃, the significance value of Tukey HSD test was 0.023, which was less than 0.05. However, since 21℃ and 27℃ were not adjacent temperature, therefore, this result was meaningless. And for the two adjacent temperature pairs, both of the significance values of Tukey HSD test were larger than 0.05. This indicated that even though the significance of ANOVA was less than 0.05, through post-hoc analysis, thermal environment had no effect on acoustic satisfaction.

Table 3-5

Test of homogeneity of variances and ANOVA results about acoustic satisfaction for each thermal group, and comparison between adjacent temperatures for Dark and Noisy group

Test of Homogeneity of Variances

	Thermal Group I Dark+Quiet	Thermal Group II Dark+Noisy	Thermal Group III Bright+Quiet	Thermal Group IV Bright+Noisy
Levene Statistic	2.737	3.009	0.184	0.123
Sig.	0.070	0.054	0.832	0.885

ANOVA

F	0.261	3.996	0.117	0.647
Sig.	0.771	0.022	0.889	0.526

Multi Comparison in Dark+Noisy Group

Post-Hoc Analysis Method	I	J	Mean Difference (I-J)	Standard Error	Sig.
Tukey HSD	21	24	0.125	0.221	0.839
	24	27	0.594	0.221	0.023
	21	27	0.469	0.221	0.092

3.5 Influence mechanism of thermal environment on visual perception

One-way ANOVA was used in this section to analyze the effect of thermal environment on acoustic satisfaction. The results are shown in Table 3-6. From the test of homogeneity of variables for different thermal groups, it can be seen that the significance of Levene variance homogeneity test were larger than the significance level of 0.05 for all different combinations of visual and acoustic environment.

According to the results of one-way analysis of variance, only for bright and noisy group, the significance of the sum of squares between groups was less than the significance level of 0.05. Therefore, post hoc analysis was required. And because of the homogeneity of variance, Tukey HSD test was used for multiple comparison procedure. The multiple comparison results showed that when the temperature increased from 24°C to 27°C, the visual perception increased 0.719 level with significance of 0.011.

Table 3-6

Test of homogeneity of variances and ANOVA results about visual perception for each thermal group, and comparison between adjacent temperatures for Bright and Noisy group

Test of Homogeneity of Variances

	Thermal Group I Dark+Quiet	Thermal Group II Dark+Noisy	Thermal Group III Bright+Quiet	Thermal Group IV Bright+Noisy
Levene Statistic	0.034	0.106	0.598	0.308
Sig.	0.966	0.900	0.552	0.735

ANOVA

F	0.493	1.318	0.857	4.377
Sig.	0.612	0.273	0.428	0.015

Multi Comparison in Bright+Noisy Group

Post-Hoc Analysis Method	I	J	Mean Difference (I-J)	Standard Error	Sig.
Tukey HSD	21	24	0.125	0.244	0.223
	24	27	0.594	0.244	0.011
	21	27	0.469	0.244	0.408

3.6 Influence mechanism of thermal environment on visual satisfaction

In order to analyze the influence of thermal environment on visual satisfaction, ANOVA was adopted in this experiment. The results of homogeneity test for different groups are in Table 3-7. Only for bright and noisy condition, the significance of Levene variance homogeneity test was less than 0.05, where the original hypothesis that the variance was homogeneous should be refused.

Table 3-7

Test of homogeneity of variances and ANOVA results about visual satisfaction for each thermal group

Test of Homogeneity of Variances

	Thermal Group I Dark+Quiet	Thermal Group II Dark+Noisy	Thermal Group III Bright+Quiet	Thermal Group IV Bright+Noisy
Levene Statistic	0.310	0.312	0.518	4.324
Sig.	0.734	0.732	0.598	0.016

ANOVA

F	0.333	1.025	0.176	1.197
Sig.	0.717	0.363	0.839	0.307

According to the results of one-way analysis of variance, the significance of the sum of squares between groups was far larger than the significance level of 0.05. Therefore, the influence of thermal environment on visual satisfaction was not significant, and subsequent multi comparison analysis was not required.

3.7 Influence mechanism of thermal environment on research performance

In this experiment, two indicators were used to calculate the research performance, which were the answering accuracy and response time of the performance test. For this section, these two indicators together with the relative research performance index were considered as the dependent variables. And the one-way ANOVA test was used to examine whether the thermal environment would affect the research performance.

3.7.1 The effect of thermal environment on answer accuracy of performance test

Table 3-8 shows the homogeneity test results and ANOVA of answering accuracy for all four thermal groups. The results showed that the significance value of Levene variance homogeneity test was greater than the significance level of 0.05, which proved the variance of answering accuracy were all homogeneous. The F factor between the groups were all larger than 0.05, which indicated that the difference of answering accuracy caused by the thermal environment was not significant and there was no need for further comparison.

Table 3-8

Test of homogeneity of variances and ANOVA results about answer accuracy of performance test for each thermal group

Test of Homogeneity of Variances

	Thermal Group I Dark+Quiet	Thermal Group II Dark+Noisy	Thermal Group III Bright+Quiet	Thermal Group IV Bright+Noisy
Levene Statistic	0.133	0.220	0.820	1.428
Sig.	0.875	0.803	0.444	0.245

ANOVA

F	0.403	0.327	0.805	0.286
Sig.	0.669	0.772	0.450	0.752

3.7.2 The effect of thermal environment on response time of performance test

Table 3-9 demonstrates the ANOVA results about the response time for different visual and acoustic environment combinations. The results showed that for dark and noisy group, p value of Levene variance homogeneity test was 0.034 < 0.05. This indicated that the variance of data for dark and noisy group was unequal. Because of that, Dunnett T3 method was used to conduct the post-hoc comparison. The variance of data for the other thermal groups were examined as homogeneous, where Tukey HSD method was selected for post-hoc comparison. The significance values between the groups of variance analysis were all less than 0.05, except for the bright and quiet thermal group. This proved the thermal environment had the effect on answering speed of participants for thermal groups other than bright and quiet group. And the data of these three groups were qualified to conduct the post-hoc comparison using the corresponding methods mentioned above.

Table 3-9

Test of homogeneity of variances and ANOVA results about response time of performance test for each thermal group

Test of Homogeneity of Variances

	Thermal Group I Dark+Quiet	Thermal Group II Dark+Noisy	Thermal Group III Bright+Quiet	Thermal Group IV Bright+Noisy
Levene Statistic	0.196	3.503	0.624	0.538
Sig.	0.822	0.034	0.871	0.422

ANOVA

F	59.943	5.965	2.143	32.058
Sig.	0.000	0.004	0.123	0.000

According to the multi comparison results, for dark and quiet thermal group, the answering speed decreased with the temperature increased from 21℃ to 27℃. For dark and noisy group, only when temperature increased from 21℃ to 24℃, the answering speed decreased. For bright and noisy group, both the p value for two adjacent temperature pairs were larger than 0.05, which meant the influence of temperature on response time at this situation was not significant.

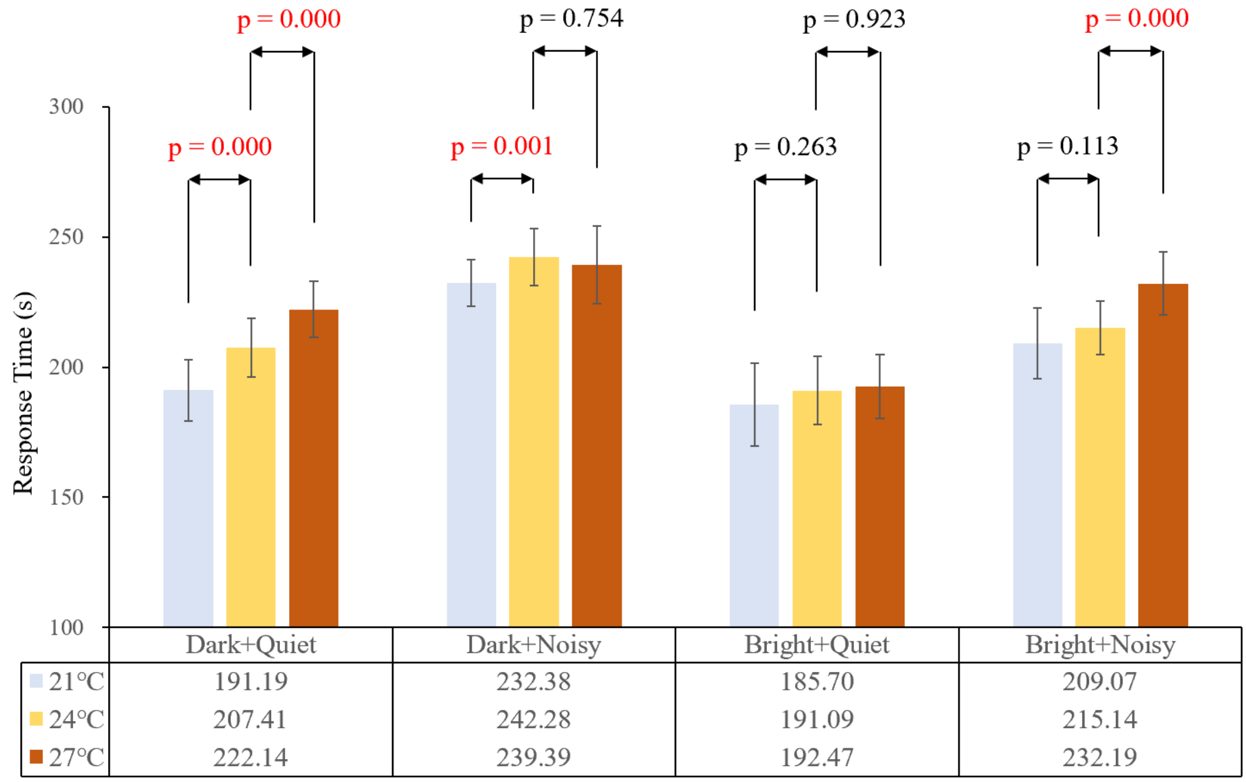


Fig. 3-5. Results of comparison between adjacent temperatures about response time of performance test for each thermal group

3.7.3 The effect of thermal environment on RPI of performance test

The relative research performance index of each environment condition was calculated according to Eq. 2-2 and Eq. 2-3. The ANOVA results of relevant RPI within each thermal group are shown in Table 3-10. According to the results of the test of homogeneity of variables, the significance values of Levene variance homogeneity test were greater than the significance level of 0.05 for both dark quiet and bright quiet conditions. For these two thermal groups, the variance between the sample data was homogeneous and Tukey HSD test was used for multiple comparison procedure. For dark noisy and bright noisy groups, the variance of the data was not equal, thus, Dunnett T3 method was used to conduct the post-hoc comparison. From the F-test results, the p values of all four thermal groups were less than 0.05, which indicated that the entire sample was qualified for variance analysis.

From the post-hoc analysis results, it can be seen that the p values for adjacent temperature pairs for dark and quiet thermal group were less than 0.05, which indicated that thermal condition indeed had affect the researcher's research performance.

$$Performance\ (PI) = Accuracy^{0.5} \times Speed^{0.5} \times 100 = \frac{Accuracy^{0.5}}{Reaction\ Time^{0.5}} \times 100 \quad (Eq.2-2)$$

$$RPI_{ij} = \frac{n \times PI_{ij}}{\sum_{j=1}^{n} PI_{ij}} \times 100\% \quad (Eq.2-3)$$

Table 3-10

Test of homogeneity of variances and ANOVA results about RPI of performance test for each thermal group

Test of Homogeneity of Variances

	Thermal Group I Dark+Quiet	Thermal Group II Dark+Noisy	Thermal Group III Bright+Quiet	Thermal Group IV Bright+Noisy
Levene Statistic	0.347	7.309	0.406	5.666
Sig.	0.708	0.001	0.667	0.005

ANOVA

F	60.468	5.862	4.198	24.091
Sig.	0.000	0.004	0.018	0.000

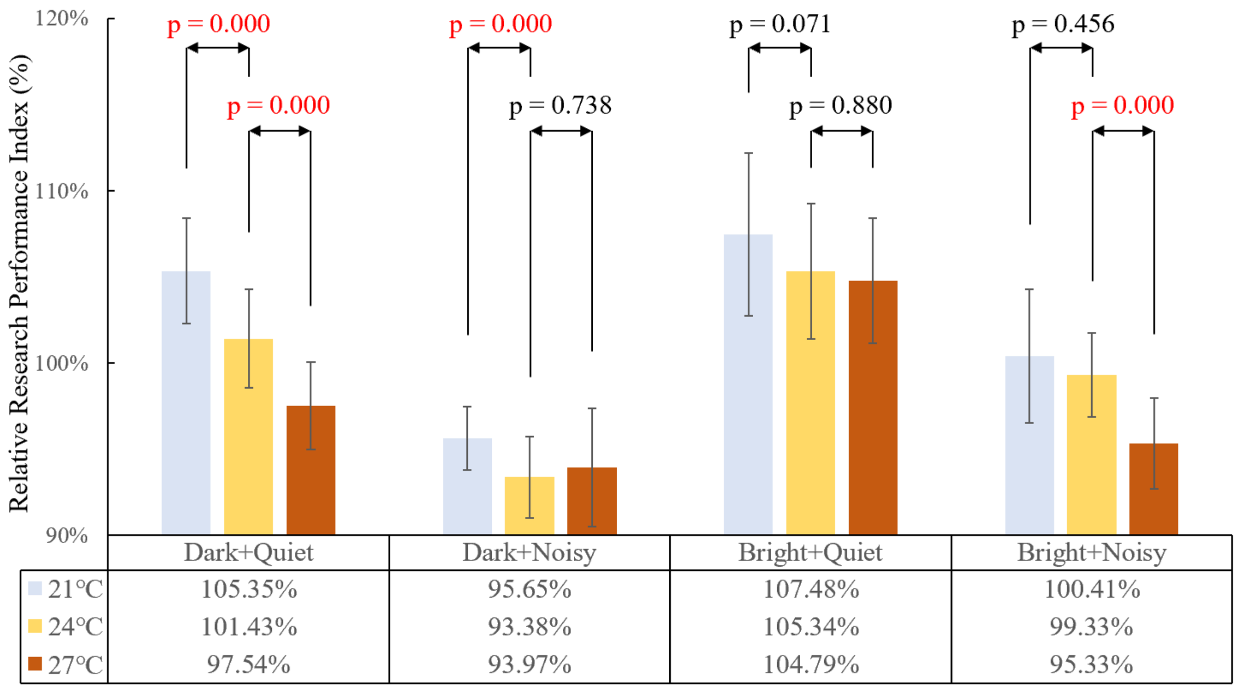


Fig. 3-6. Results of comparison between adjacent temperatures about RPI of performance test for each thermal group

Chapter IV

Influence mechanism of acoustic environment on environmental perception, satisfaction, and research performance

For the open-plan office environment, background noise intensity is one of the main factors affecting the indoor environmental perception, indoor environmental satisfaction and productivity. For the research facilities with strict requirements for noise level, the influence on occupants' perception and performance caused by the change of acoustic environment is more significant. Therefore, it is necessary to understand the influence mechanism of acoustic environment on environmental perception, satisfaction and research performance.

In this chapter, based on the results of the subjective questionnaire, the influence mechanism of background noise intensity on the participants' environmental perception and satisfaction was qualitatively analyzed. In addition, according to the performance test results of the participants, whether the change of background noise level affected the researchers' scientific performance was also qualitatively analyzed.

4.1 The influence of acoustic environment on acoustic perception and satisfaction

In order to compare the effects of different acoustic environments on acoustic perception and satisfaction, 12 environment conditions were divided into six acoustic groups according to different thermal and visual environment combinations. For each acoustic group, the thermal and visual physical parameters were the same, but the acoustic physical parameter was different. Fig. 4-1 and Fig. 4-2 show the voting results of the participants about acoustic perception and acoustic satisfaction based on different acoustic groups.

The results showed that the mean value of acoustic perception was in the range from 0.31 to 0.78 for acoustic environment of 45dB(A). This indicated that the average feeling of participants about background noise level 45dB(A) was neutral or slightly quiet. According to the acoustic satisfaction results, the participants' average satisfaction about 45dB(A) was between 0.53 and 0.91. This indicated that the participants were slightly satisfied with this acoustic environment.

There existed some difference between the actual acoustic perception and satisfaction with the expectations at noise level 45dB(A). One reasonable explanation is that according to the American National Standards Institute (ANSI) and European standard EN15251, the one-hour steady-state background noise levels should not exceed 40dB(A) for the scientific facilities [90, 91]. Because the controlled research office in this experiment was classified as open-plan office, where the typing noise by operating the computer could not be avoided. Therefore, even though all the participants were asked to keep quiet during the experiment, the minimum background noise intensity can be achieved in controlled research office was around 45dB(A), which was slighter higher than the required noise level from standard. Because of that, the average acoustic perception and average acoustic satisfaction were lower than the expectation.

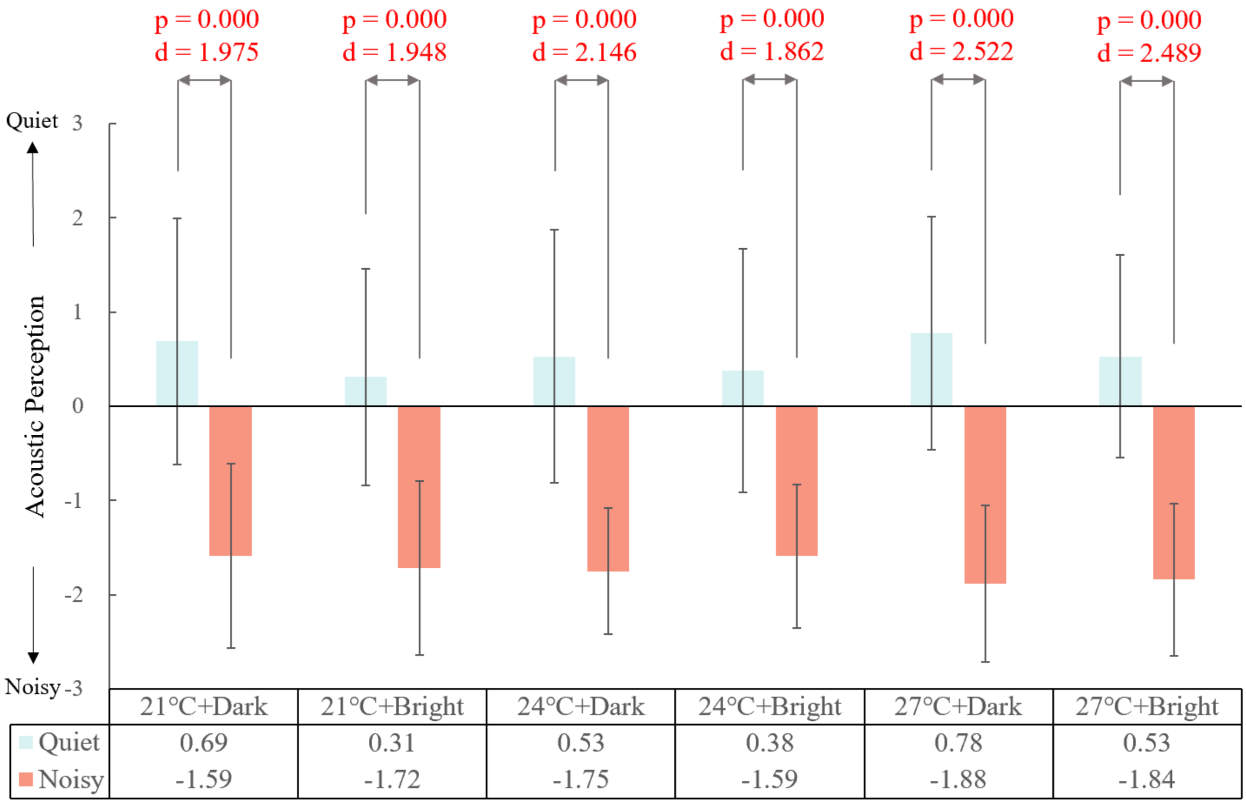
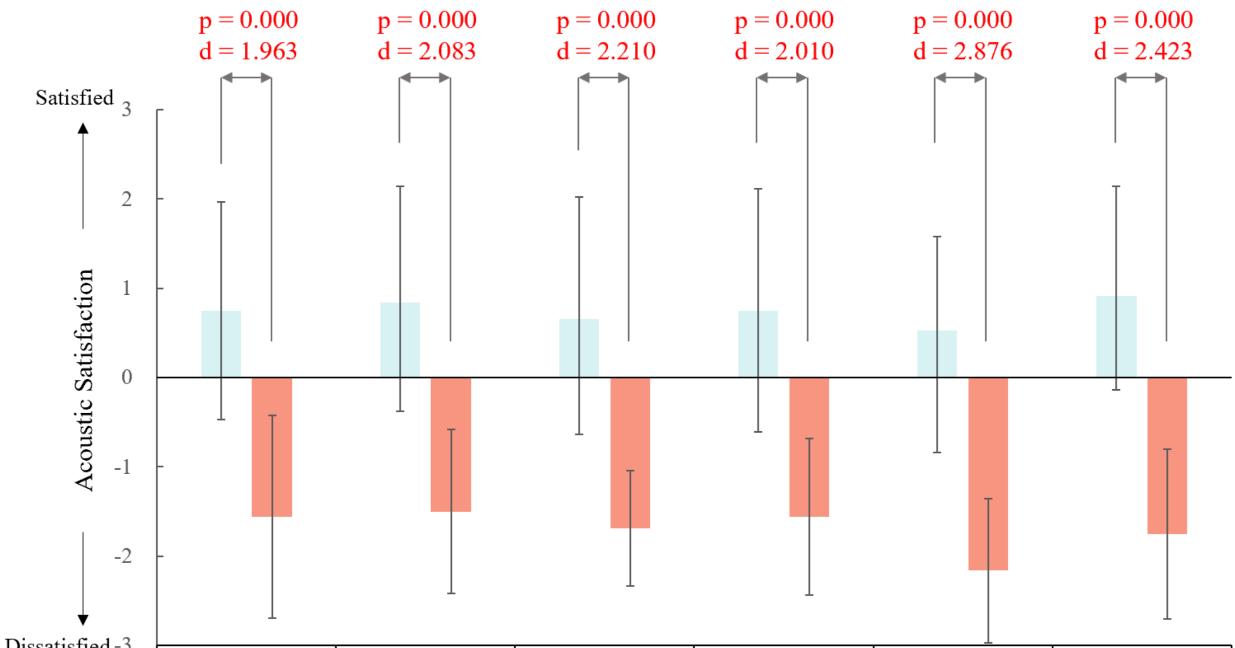


Fig. 4-1. Results of acoustic perception and paired sample t-test results about influence of acoustic environment on acoustic perception for each acoustic group

For the background noise intensity of 75dB(A), the mean value of acoustic perception decreased to the range from -1.88 to -1.59, where the participants generally believed that this acoustic environment was noisy. And the mean value of acoustic satisfaction was also decreased to the range from -2.16 to -1.50. This indicated that the participants felt dissatisfied about 75dB(A) acoustic environment. This was consistent with the expectation of employees' perception about noisy open-plan office condition.

The paired sample t-test results about acoustic perception and acoustic satisfaction for each acoustic group are also shown in Fig. 4-1 and Fig. 4-2 respectively. The results showed that the significance value for all six acoustic groups were less than 0.05 with effect size larger than 0.8. The mean difference between quiet condition and noisy condition were around 2 levels. This indicated that the background noise intensity had a significant impact on participants' acoustic perception.

According to paired sample t-test about acoustic satisfaction, for every combination of thermal and visual environment, the participants' satisfaction about the acoustic environment increased with the decrease of the background noise intensity (all $p < 0.05$). The increase range was between 2.313 and 2.688 levels. This showed that the acoustic environment had a significant impact on acoustic satisfaction.



	21°C+Dark	21°C+Bright	24°C+Dark	24°C+Bright	27°C+Dark	27°C+Bright
Quiet	0.75	0.84	0.66	0.75	0.53	0.91
Noisy	-1.56	-1.50	-1.69	-1.56	-2.16	-1.75

Fig. 4-2. Results of acoustic satisfaction and paired sample t-test results about influence of acoustic environment on acoustic satisfaction for each acoustic group

One possible explanation is that with the increase of background noise intensity, human sympathetic nerve activity also increases. This further affects the irritability and negative emotion of occupants, and finally reduces the comfort level of the occupants. Another possible explanation is that when the same noise acts on participants for a long time, it will cause a significant reduction in auditory receptivity. This is so-called auditory fatigue. When auditory fatigue happens to the occupants after a long-time noise, the comfort level about acoustic environment of the participants would decrease.

4.2 The influence of acoustic environment on thermal perception and satisfaction

Table 4-1 shows the paired sample t-test results of the thermal perception of participants for each acoustic group. The results showed that only for 21℃ dark and 24℃ dark environment, there existed significant difference of thermal perception when the average background level changed ($t (31) = -2.490$, $p = 0.018 < 0.05$ and $t (31) = -2.252$, $p = 0.032 < 0.05$). The effect size for 21℃ dark environment was -0.328, and for 24℃ dark environment was -0.274. Both absolute values were within the range of 0.2 to 0.5. This indicated that influence of acoustic environment on thermal perception at these two specific acoustic groups was small.

One possible reason is that 21℃ and 24℃ achieve cool comfort and warm comfort respectively. At this time, visual and acoustic parameters become the main factors affecting the thermal perception. And people tend to be more sensitive in dark environments. Therefore, at 21℃ dark and 24℃ dark environments, the acoustic environment has a significant influence on thermal perception.

In addition, for all six acoustic groups, the mean difference of thermal perception between quiet condition and noisy condition was less than zero. This indicated that quiet environment can make the participants feel cooler, while the noisy environment can make the participants feel hotter.

The paired sample t-test results of background noise intensity on participants' thermal satisfaction are shown in Table 4-2. The results showed that although the thermal satisfaction of personnel in quiet environment was higher than that in noisy environment under all six combinations of thermal and visual environments, the gap between quiet and noisy environments was not obvious (all $p > 0.05$). This showed that background noise intensity was not a secondary factor affecting participants' thermal satisfaction.

Table 4-1

Results of thermal perception and paired sample t-test results about influence of acoustic environment on thermal perception for each acoustic group

	Environment Condition	Thermal Perception	Paired Sample T-test (Quiet - Noisy)				
			Mean	SD	t	Sig.	Cohen's d
Acoustic Group 1	A (21°C+Dark+Quiet) B (21°C+Dark+Noisy)	-0.75 ± 0.80 -0.50 ± 0.72	-0.250	0.568	-2.490	0.018	-0.328
Acoustic Group 2	C (21°C+Bright+Quiet) D (21°C+Bright+Noisy)	-0.56 ± 0.67 -0.50 ± 0.72	-0.063	0.435	-0.812	0.423	-0.086
Acoustic Group 3	E (24°C+Dark+Quiet) F (24°C+Dark+Noisy)	0.25 ± 0.72 0.44 ± 0.67	-0.188	0.471	-2.252	0.032	-0.274
Acoustic Group 4	G (24°C+Bright+Quiet) H (24°C+Bright+Noisy)	0.56 ± 0.76 0.59 ± 0.76	-0.031	0.695	-0.254	0.801	-0.040
Acoustic Group 5	I (27°C+Dark+Quiet) J (27°C+Dark+Noisy)	1.53 ± 0.88 1.56 ± 0.95	-0.031	0.474	-0.373	0.712	-0.033
Acoustic Group 6	K (27°C+Bright+Quiet) L (27°C+Bright+Noisy)	1.53 ± 0.92 1.63 ± 0.91	-0.094	0.466	-1.139	0.263	-0.110

Table 4-2

Results of thermal satisfaction and paired sample t-test results about influence of acoustic environment on thermal satisfaction for each acoustic group

	Environment Condition	Thermal Satisfaction	Paired Sample T-test (Quiet - Noisy)				
			Mean	SD	t	Sig.	Cohen's d
Acoustic Group 1	A (21°C+Dark+Quiet) B (21°C+Dark+Noisy)	-0.28 ± 1.28 -0.59 ± 1.04	0.313	1.230	1.484	0.161	0.266
Acoustic Group 2	C (21°C+Bright+Quiet) D (21°C+Bright+Noisy)	-0.31 ± 1.00 -0.41 ± 0.91	0.094	0.734	0.722	0.476	0.105
Acoustic Group 3	E (24°C+Dark+Quiet) F (24°C+Dark+Noisy)	0.38 ± 0.91 0.16 ± 1.05	0.219	1.211	1.022	0.315	0.224
Acoustic Group 4	G (24°C+Bright+Quiet) H (24°C+Bright+Noisy)	0.69 ± 0.86 0.53 ± 0.84	0.156	1.139	0.776	0.444	0.188
Acoustic Group 5	I (27°C+Dark+Quiet) J (27°C+Dark+Noisy)	-0.56 ± 1.39 -0.56 ± 1.34	0.000	1.481	0.000	1.000	0.000
Acoustic Group 6	K (27°C+Bright+Quiet) L (27°C+Bright+Noisy)	-0.25 ± 1.39 -0.47 ± 1.34	0.219	0.792	1.561	0.129	0.161

4.3 The influence of acoustic environment on visual perception and satisfaction

Table 4-3 shows the paired sample t-test results about the influence of acoustic environment on visual perception between quiet and noisy conditions in all six acoustic groups. The results showed that the increase of background noise intensity would reduce the visual perception in 24°C bright ($t(31) = 2.339$ with $p = 0.026 < 0.05$) and 27°C dark environments ($t(31) = 2.104$ with $p = 0.044 <$

0.05). These were two extreme environments. For 24°C bright environment, the thermal environment reached warm comfort and visual environment reached visual comfort. At this time, the acoustic parameter was the only factor affecting visual perception. On the contrary, for 27°C dark environment, participants felt discomfort for both thermal and visual aspects. Because of this, the participants became more sensitive about the environment. Therefore, the change of background noise intensity would make significant influence on visual perception. The effect size for 24°C bright environment was 0.416, and for 27°C dark environment was 0.278. Both absolute values were within the region of 0.2 to 0.5. This indicated that influence of acoustic environment on visual perception at these two specific acoustic groups was small.

Table 4-3

Results of visual perception and paired sample t-test results about influence of acoustic environment on visual perception for each acoustic group

	Environment Condition	Visual Perception	Paired Sample T-test (Quiet - Noisy)				
			Mean	SD	t	Sig.	Cohen's d
Acoustic Group 1	A (21°C+Dark+Quiet) B (21°C+Dark+Noisy)	-1.03 ± 1.03 -1.16 ± 0.92	0.125	0.609	1.161	0.255	0.133
Acoustic Group 2	C (21°C+Bright+Quiet) D (21°C+Bright+Noisy)	1.28 ± 1.02 1.22 ± 0.98	0.063	0.564	0.626	0.536	0.060
Acoustic Group 3	E (24°C+Dark+Quiet) F (24°C+Dark+Noisy)	-1.22 ± 0.91 -1.22 ± 0.91	0.000	0.803	0.000	1.000	0.000
Acoustic Group 4	G (24°C+Bright+Quiet) H (24°C+Bright+Noisy)	1.19 ± 0.93 0.81 ± 0.90	0.375	0.907	2.339	0.026	0.416
Acoustic Group 5	I (27°C+Dark+Quiet) J (27°C+Dark+Noisy)	-1.25 ± 0.92 -1.50 ± 0.88	0.250	0.672	2.104	0.044	0.278
Acoustic Group 6	K (27°C+Bright+Quiet) L (27°C+Bright+Noisy)	1.50 ± 0.98 1.53 ± 1.05	-0.031	0.595	-0.297	0.768	-0.030

This section also studied the influence of the change of acoustic environment on participants' visual satisfaction under different thermal and visual environments (Table 4-4). The results of paired sample t-test showed that, for acoustic group 21°C bright and 24°C bright, with the increase of background noise intensity, the participants' visual satisfaction decreased about 0.5 level (t (31) = 2.247 with $p = 0.032 < 0.05$ and t (31) = 2.79 with $p = 0.009 < 0.05$). The effect size for 21°C bright environment was 0.280, indicating that for this acoustic group, the influence of acoustic environment on visual satisfaction was small. And the effect size for 24°C bright environment was 0.513. This demonstrated that for 24°C bright condition, acoustic environment can exert medium influence on visual satisfaction.

A reasonable explanation is that participants achieved cool comfort and warm comfort in the 21℃ and 24℃ bright environments respectively, and the visual environment also reaches the optimal condition, where noise level becomes a secondary factor affecting visual satisfaction.

For other thermal and visual environments, although the significance values of paired sample t-test were greater than 0.05, it was still found that the visual satisfaction decreased with the increase of background noise intensity.

Table 4-4

Results of visual satisfaction and paired sample t-test results about influence of acoustic environment on visual satisfaction for each acoustic group

	Environment Condition	Visual Satisfaction	Paired Sample T-test (Quiet - Noisy)				
			Mean	SD	t	Sig.	Cohen's d
Acoustic Group 1	A (21°C+Dark+Quiet)	-0.81 ± 1.03	0.031	1.121	0.158	0.876	0.028
	B (21°C+Dark+Noisy)	-0.84 ± 1.14					
Acoustic Group 2	C (21°C+Bright+Quiet)	1.00 ± 1.22	0.344	0.865	2.247	0.032	0.280
	D (21°C+Bright+Noisy)	0.66 ± 1.21					
Acoustic Group 3	E (24°C+Dark+Quiet)	-0.88 ± 1.19	0.031	0.933	0.190	0.851	0.024
	F (24°C+Dark+Noisy)	-0.91 ± 1.28					
Acoustic Group 4	G (24°C+Bright+Quiet)	0.88 ± 1.41	0.625	1.264	2.798	0.009	0.513
	H (24°C+Bright+Noisy)	0.25 ± 1.02					
Acoustic Group 5	I (27°C+Dark+Quiet)	-1.03 ± 1.09	0.219	0.751	1.648	0.109	0.188
	J (27°C+Dark+Noisy)	-1.25 ± 1.24					
Acoustic Group 6	K (27°C+Bright+Quiet)	0.81 ± 1.23	0.125	0.108	1.161	0.255	0.087
	L (27°C+Bright+Noisy)	0.69 ± 1.51					

4.4 The influence of acoustic environment on research performance

The section studied whether the change of background noise intensity would affect the researchers' research performance under each thermal and visual environment combination. According to the paired sample t-test between acoustic environment and answer accuracy from performance test of the participants (Table 4-5), only for 21℃ bright environment, the average answer accuracy which the participants accomplished in quiet condition was 1.406 points higher than that accomplished in noisy condition ($t\ (31) = 2.948$ with $p = 0.006 < 0.05$). The Cohen's d value of this acoustic group was 0.327, which was in the region between 0.2 and 0.5. This indicated that the effect between acoustic environment and answer accuracy for acoustic group 21℃ bright was small. For other acoustic groups, all significance value was greater than 0.05, which meant that the change of background noise intensity had no significant impact on the answer accuracy of the participants.

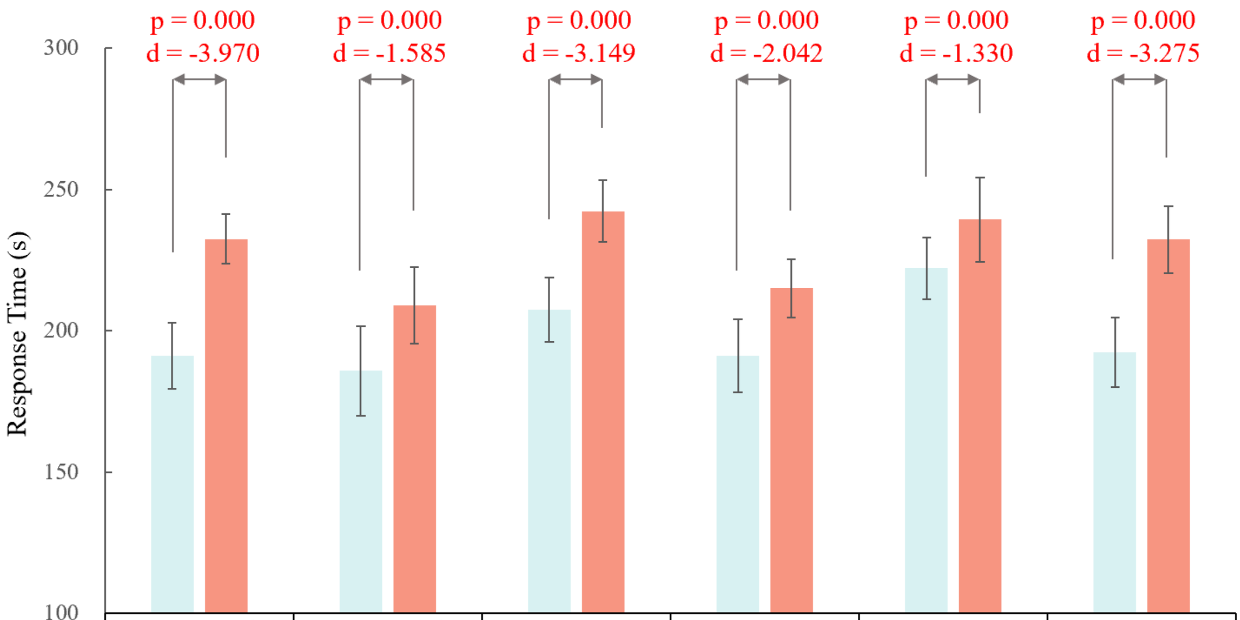
Table 4-5

Results of answer accuracy of performance test and paired sample t-test results about influence of acoustic environment on answer accuracy for each acoustic group

	Environment Condition	Answer Accuracy	Paired Sample T-test (Quiet - Noisy)				
			Mean	SD	t	Sig.	Cohen's d
Acoustic Group 1	A (21°C+Dark+Quiet) B (21°C+Dark+Noisy)	94.81 ± 3.72 95.16 ± 3.96	-0.344	1.619	-1.201	0.239	-0.091
Acoustic Group 2	C (21°C+Bright+Quiet) D (21°C+Bright+Noisy)	95.56 ± 3.48 94.16 ± 4.96	1.406	2.698	2.948	0.006	0.327
Acoustic Group 3	E (24°C+Dark+Quiet) F (24°C+Dark+Noisy)	95.38 ± 3.61 94.50 ± 4.17	0.875	3.338	1.483	0.148	0.226
Acoustic Group 4	G (24°C+Bright+Quiet) H (24°C+Bright+Noisy)	94.66 ± 3.73 94.94 ± 4.09	-0.281	3.448	-0.461	0.648	-0.072
Acoustic Group 5	I (27°C+Dark+Quiet) J (27°C+Dark+Noisy)	94.53 ± 4.14 94.41 ± 3.99	0.125	2.733	0.259	0.798	0.030
Acoustic Group 6	K (27°C+Bright+Quiet) L (27°C+Bright+Noisy)	94.41 ± 4.26 94.34 ± 3.82	0.063	3.047	0.116	0.908	0.017

According to the paired sample t-test results of influence of acoustic environment on answer response time of performance test (Fig. 4-3), all the significance value for all six acoustic groups were less than 0.05 and the absolute value of effect size was all larger than 0.8. Therefore, there existed a significant difference in answer speed between quiet environment and noisy environment for all six acoustic groups. It can be seen all the mean value of difference between quiet condition and noisy condition were less than 0, which indicated that the participants could answer faster in quiet condition than that in noisy condition.

When the thermal condition was 21℃ and the visual condition was 200lux, the response time of the participants was most affected by the background noise intensity, and the response time in quiet condition was 17.7% shorter than that in noisy condition. When the thermal condition was 27℃ and the visual condition was 200lux, the participants' answering speed was least affected by the noise level, where the time to complete the test was shortened only 7.6%.



	21°C+Dark	21°C+Bright	24°C+Dark	24°C+Bright	27°C+Dark	27°C+Bright
Quiet	191.19	185.72	207.44	191.13	222.06	192.44
Noisy	232.38	209.00	242.28	215.06	239.38	232.19

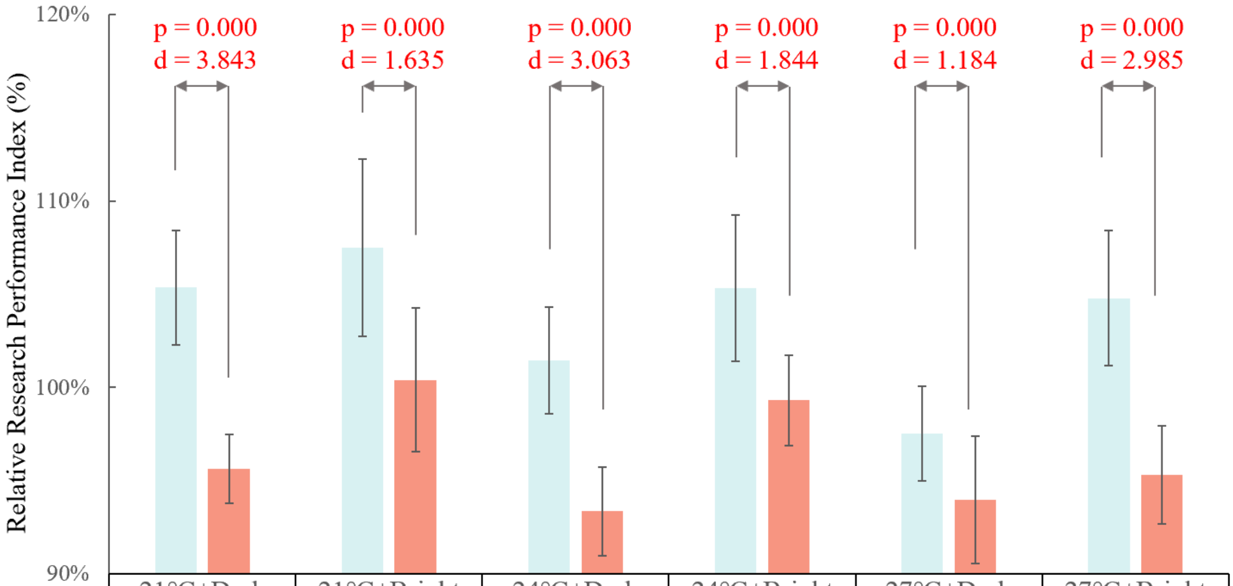
Fig. 4-3. Results of response time of performance test and paired sample t-test results about influence of acoustic environment on response time for each acoustic group

The relative performance index was calculated using Eq. 2-2 and Eq. 2-3. According to the paired sample t-test (Fig. 4-4), the significance value of all the thermal and visual combinations were less than 0.05 with effect size larger than 0.8. And the mean value of difference between quiet and noisy condition was negative. Therefore, with the increase of background noise intensity, the researchers' research performance decreased significantly. This was in line with the influence trend of acoustic environment on answer accuracy and response time.

$$Performance\ (PI) = Accuracy^{0.5} \times Speed^{0.5} \times 100 = \frac{Accuracy^{0.5}}{Reaction\ Time^{0.5}} \times 100 \quad (Eq. 2-2)$$

$$RPI_{ij} = \frac{n \times PI_{ij}}{\sum_{j=1}^{n} PI_{ij}} \times 100\% \quad (Eq. 2-3)$$

Same as the condition in paired sample t-test analysis of response time, when the thermal environment was 27℃ and the visual condition was 200lux, the relative research performance was least affected by noise level, and only increase 3.57%. On the contrary, for 21℃ 200lux environment, the Cohen's d value was 3.843, which was the largest. This indicated that the impact of acoustic environment on research performance was the most significant with a 9.70% increase.



	21°C+Dark	21°C+Bright	24°C+Dark	24°C+Bright	27°C+Dark	27°C+Bright
Quiet	105.36%	107.49%	101.43%	105.33%	97.54%	104.79%
Noisy	95.65%	100.41%	93.36%	99.32%	93.97%	95.33%

Fig. 4-4. Results of RPI of performance test and paired sample t-test results about influence of acoustic environment on RPI for each acoustic group

Chapter V

Influence mechanism of visual environment on environmental perception, satisfaction and research performance

At present, the research on the influence of visual environment on environment comfort and research efficiency is still very limited. Therefore, this chapter qualitatively analyzed the impact of different visual environments on researchers' indoor environmental perception and satisfaction under different thermal and acoustic combinations according to the data collected from subjective questionnaires and physical environment monitoring. At the same time, according to the performance test results of researchers, the effects of different visual environments on researchers' research performance were qualitatively analyzed.

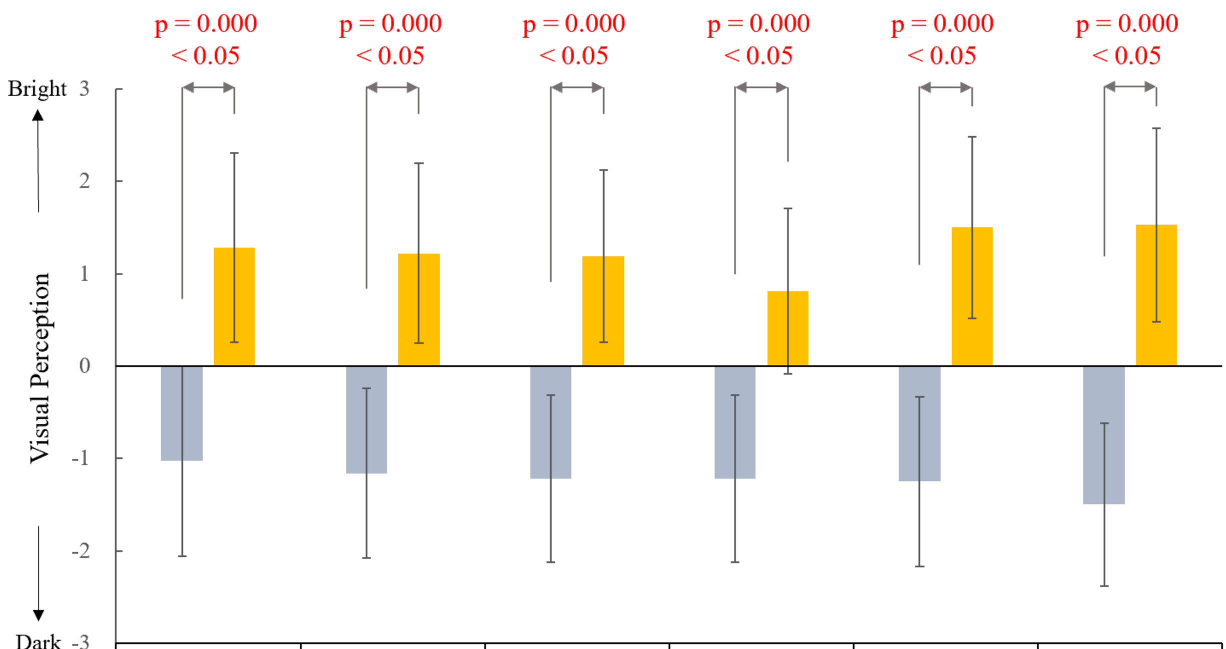
5.1 Influence mechanism of visual environment on visual perception and satisfaction

Similar to the analysis of acoustic environment on environmental perception and satisfaction, 12 environment conditions were divided into six visual groups according to different thermal and acoustic environment combinations, so as to compare the effects of different acoustic environments on acoustic perception and satisfaction. For each visual group, the thermal and acoustic environment remained same, and the only difference was the visual physical parameters.

The voting results of the visual perception of the controlled research office under different thermal and acoustic combinations are shown in Fig. 5-1. The voting results showed that under all six thermal and acoustic combinations, the average visual perception of the participants to 200lux environment was between -1.50 and -1.03, indicating that the participants' subjective perception of 200lux was dark to slightly dark. On the contrary, the average visual perception of the participants to 500lux was between 0.81 and 1.53, indicating that the participants generally believed that the environment of 500lux was slightly bright to bright.

Fig. 5-2 shows the participants’ visual satisfaction of the controlled research office under 12 environment conditions. According to the average value of visual satisfaction, for all six visual groups, the average distribution of researchers' visual satisfaction about 200lux visual environment was between -1.25 and -0.81. This indicated that researchers generally hold a slightly dissatisfied attitude towards low illumination environment regardless of the external thermal and acoustic environment. The average distribution of researchers' visual satisfaction with 500lux visual environment was between 0.25 and 1.00, which showed that researchers were slightly satisfied with the high illumination level.

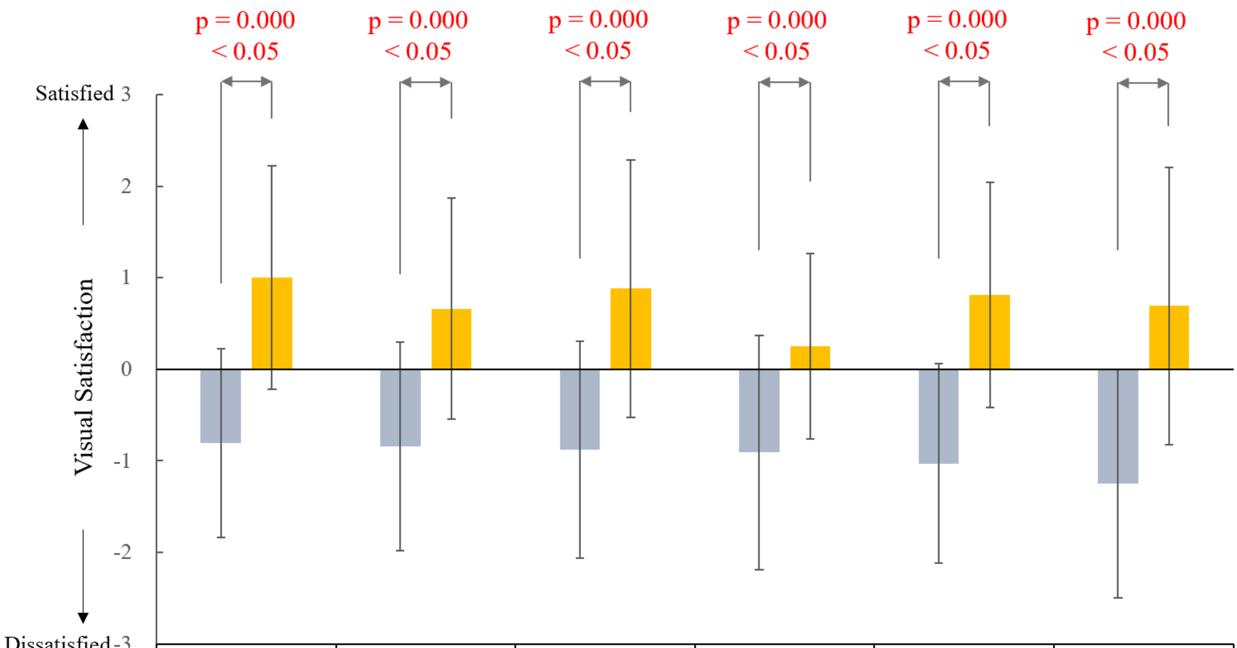
The paired sample t-test results of participants' visual perception within each visual group are also shown in Fig. 5-1. The results clearly showed that under the same thermal and acoustic environment, the participants' visual perception about the visual environment of 500lux was significantly higher than that about the environment of 200lux, where all significance values were less than 0.05. Since all Cohen’s d value were larger than 0.8, this indicated that the influence of visual environment on visual perception was remarkable. The mean difference of visual perception within each visual group was between 2.031 and 3.031 levels, which further proved that high illumination level could greatly increase the visual perception of the participants.



	21°C+Quiet	21°C+Noisy	24°C+Quiet	24°C+Noisy	27°C+Quiet	27°C+Noisy
Dark	-1.03	-1.16	-1.22	-1.22	-1.25	-1.50
Bright	1.28	1.22	1.19	0.81	1.50	1.53

Fig. 5-1. Results of visual perception and paired sample t-test results about influence of visual environment on visual perception for each visual group

In order to test whether the indoor visual environment had an impact on the researchers' visual satisfaction, each group of data with same thermal and acoustic physical parameters was brought into paired sample t-test. The pair sample t-test results about influence of visual environment on visual satisfaction are also shown in Fig. 5-2. The results showed that all significance values of all six visual groups were less than 0.05, which showed that there was a significant difference in the average visual satisfaction between 200lux visual environment and 500lux visual environment. The effect size was also calculated using Cohen's d. The results showed that the effect size for all visual groups were larger than 0.8, which can be regarded as large effect. This indicated that the influence of visual environment on visual perception was remarkable. In addition, the mean difference between low illuminance conditions and high illuminance conditions for all the thermal and visual environment combinations were between 1.500 and 1.938. This can be interpreted as: with the improvement of visual environment from low illumination to high illumination, the participants' visual satisfaction improved by nearly two levels.



	21°C+Quiet	21°C+Noisy	24°C+Quiet	24°C+Noisy	27°C+Quiet	27°C+Noisy
Dark	-0.81	-0.84	-0.88	-0.91	-1.03	-1.25
Bright	1.00	0.66	0.88	0.25	0.81	0.69

Fig. 5-2. Results of visual satisfaction and paired sample t-test results about influence of visual environment on visual satisfaction for each visual group

5.2 Influence mechanism of visual environment on thermal perception and satisfaction

In order to study the effect of visual environment on participants' thermal perception under different thermal and acoustic conditions, paired sample t-test was used (Table 5-1). The results of paired t-test showed that the participants' subjective thermal perception increased significantly with the increase of illumination level under the conditions of 24 centigrade with 45dB(A) and 24 centigrade with 70dB(A) (both significance value $p < 0.05$). The effect size was calculated using Cohen's d, where absolute value of Cohen's d for the above two visual groups were both within the range of 0.2 to 0.5. This indicated the effect of visual environment on thermal perception for 24 centigrade with 45dB(A) and 24 centigrade with 70dB(A) were small. Under other thermal and acoustic conditions, the effect of illumination on participants' thermal perception was not statistically significant.

This is mainly because under the conditions of 24 centigrade quiet and noisy conditions, the thermal environment reached the warm comfort, so the influence of the visual environment change on the participants' thermal perception begins to appear. Under other conditions, the thermal environment is not optimal. Therefore, the thermal environment is still the major impact on thermal perception, and the impact of visual environment change is not significant.

Table 5-1

Results of thermal perception and paired sample t-test results about influence of visual environment on thermal perception for each visual group

	Environment Condition		Paired Sample T-test for Thermal Perception (Dark - Bright)				
			Mean	SD	t	Sig.	Cohen's d
Visual Group 1	A C	(21°C+Dark+Quiet) (21°C+Bright+Quiet)	-0.125	0.421	-1.679	0.103	-0.168
Visual Group 2	B D	(21°C+Dark+Noisy) (21°C+Bright+Noisy)	-0.094	0.588	-0.902	0.374	-0.122
Visual Group 3	E G	(24°C+Dark+Quiet) (24°C+Bright+Quiet)	-0.344	0.745	-2.609	0.014	-0.461
Visual Group 4	F H	(24°C+Dark+Noisy) (24°C+Bright+Noisy)	-0.188	0.471	-2.252	0.032	-0.257
Visual Group 5	I K	(27°C+Dark+Quiet) (27°C+Bright+Quiet)	0.000	0.568	0.000	1.000	0.000
Visual Group 6	J L	(27°C+Dark+Noisy) (27°C+Bright+Noisy)	-0.063	0.354	-1.000	0.325	-0.075

In addition, for all six groups of thermal and acoustic environment combinations, the average value of difference about thermal perception between dark condition and bright condition was below 0. This indicated that when the visual environment improved from low illuminance to high illuminance, subjects would feel a little bit hotter.

One possible explanation is that the desk lamp was used in this experiment to adjust the illuminance level. When the desk lamp is switched on, the electric current gets through the wire and reaches the semiconductor chip. At this time, the electron and electron hole are pushed into the quantum well, where electron hole recombination happened. Because of the movements of free electron, there is a change in the energy level as the voltage drops from the conduction band to the valance band, with a release of energy [92]. Part of the light energy will transfer to heat, and would transmit to the participants, which will make the participants feel hotter.

Paired sample t-test was conducted to study the effect of illuminance level on participants' thermal satisfaction using the subjective votes of thermal satisfaction for all six groups of different thermal and acoustic environments. The results are summarized in Table 5-2. From the paired sample t-test results, it can be seen that the subjects were more satisfied when the illuminance level was 500lux. This trend only existed when the thermal condition was in warm comfort (24°C temperature). At this situation, the significance value for quiet condition was 0.048 with absolute of Cohen's d of 0.351. The significance value for noisy condition was 0.016 with absolute of Cohen's d of 0.389. Based on the Cohen's d value for both conditions, the effect size were both small. For other thermal situation, the influence of visual environment on participants' thermal satisfaction was not statistically significant.

Table 5-2

Results of thermal satisfaction and paired sample t-test results about influence of visual environment on thermal satisfaction for each visual group

	Environment Condition	Thermal Satisfaction	Paired Sample T-test for Thermal Satisfaction (Dark - Bright)				
			Mean	SD	t	Sig.	Cohen's d
Visual Group 1	A (21°C+Dark+Quiet) C (21°C+Bright+Quiet)	-0.31 ± 1.00 -0.28 ± 1.28	-0.031	0.861	-0.205	0.839	-0.026
Visual Group 2	B (21°C+Dark+Noisy) D (21°C+Bright+Noisy)	-0.59 ± 1.04 -0.41 ± 0.91	-0.188	0.859	-1.235	0.226	-0.184
Visual Group 3	E (24°C+Dark+Quiet) G (24°C+Bright+Quiet)	0.38 ± 0.91 0.69 ± 0.86	-0.313	0.859	-2.058	0.048	-0.351
Visual Group 4	F (24°C+Dark+Noisy) H (24°C+Bright+Noisy)	0.16 ± 1.05 0.53 ± 0.84	-0.375	0.833	-2.547	0.016	-0.389
Visual Group 5	I (27°C+Dark+Quiet) K (27°C+Bright+Quiet)	-0.56 ± 1.39 -0.25 ± 1.39	-0.313	1.061	-1.667	0.106	-0.223
Visual Group 6	J (27°C+Dark+Noisy) L (27°C+Bright+Noisy)	-0.56 ± 1.34 -0.47 ± 1.34	-0.094	0.995	-0.533	0.598	-0.067

From the mean difference between dark and bright conditions, it can be seen the satisfaction of the participants about the dark visual environment was less than that about bright visual environment, even though the difference was not that significant. This indicated that under the same thermal and acoustic environment, high level of illuminance would make the participants more comfort about the temperature.

The results of thermal satisfaction based on visual environment was consistent with the effect of visual environment on thermal perception. When thermal environment reached warm comfort, the influence of illuminance level began to play a decisive role.

5.3 Influence mechanism of visual environment on acoustic perception and satisfaction

Table 5-3 shows the paired sample t-test results of visual environment on participants' acoustic perception under different acoustic and thermal combinations. The results showed that only in the quiet environment of 21 centigrade, the significance value was 0.008, which was far less than 0.05. Since Cohen's d value was 0.309, which is in the range of 0.2 to 0.5, the paired sample t-test effect was small. Therefore, for quiet environment of 21 centigrade, the participants' subjective acoustic perception was affected by the indoor visual environment. In other acoustic and thermal combinations, the change of illumination level had no significant effect on the participants' acoustic perception.

In addition, from the paired sample t-test results, it can be concluded that the average acoustic perception of participants in dark environment was lower than that in bright environment for all six visual groups. This proved that in dark environment, participants believed that the environment was noisier than in quiet environment with the same thermal and acoustic condition.

One possible reason is that in dark conditions, participants' ability to obtain external information through vision is weakened. Therefore, the participants need to rely more on hearing and other senses to collect information in order to make up for the information loss due to bad visual environment. When more information is received through auditory organs, more background noise will also be collected. Therefore, the participants would feel noisier when the visual condition is dark. The other possible reason is that in the participants is more prone to generate sense of fear to the outside world in dark environment. This makes the participants more sensitive to the surrounding environment. When there is some irrelevant sound from the outside, like the background noise, it will cause excessive perception to the participants.

Table 5-3

Results of acoustic perception and paired sample t-test results about influence of visual environment on acoustic perception for each visual group

	Environment Condition	Acoustic Perception	Paired Sample T-test for Acoustic Perception (Dark - Bright)				
			Mean	SD	t	Sig.	Cohen's d
Visual Group 1	A (21°C+Dark+Quiet) C (21°C+Bright+Quiet)	0.69 ± 1.31 0.31 ± 1.15	0.375	0.751	2.823	0.008	0.309
Visual Group 2	B (21°C+Dark+Noisy) D (21°C+Bright+Noisy)	-1.59 ± 0.98 -1.72 ± 0.92	0.125	0.492	1.438	0.161	0.137
Visual Group 3	E (24°C+Dark+Quiet) G (24°C+Bright+Quiet)	0.53 ± 1.34 0.38 ± 1.29	0.156	1.110	0.796	0.432	0.114
Visual Group 4	F (24°C+Dark+Noisy) H (24°C+Bright+Noisy)	-1.59 ± 0.76 -1.75 ± 0.67	0.156	0.884	1.000	0.325	0.224
Visual Group 5	I (27°C+Dark+Quiet) K (27°C+Bright+Quiet)	0.78 ± 1.24 0.53 ± 1.08	0.250	0.803	1.761	0.088	0.216
Visual Group 6	J (27°C+Dark+Noisy) L (27°C+Bright+Noisy)	-1.84 ± 0.81 -1.88 ± 0.83	0.031	0.309	0.571	0.572	0.049

This section also studied the effect of the visual environment on participants' acoustic satisfaction. The relevant results for all six visual groups are in Table 5-4. According to the paired sample t-test, under the 27 centigrade thermal environment, for both dark and bright conditions, the significance value were less than 0 (quiet condition: $t(31) = -2.175$, $p = 0.037 < 0.05$ and noisy condition $t(31) = -2.881$, $p = 0.007 < 0.05$). This indicated that the increase of illuminance level from 200lux to 500lux would improve the participants' acoustic satisfaction by 0.5 level when the temperature was 27 centigrade. And at these situations, the absolute value of Cohen’s d for both quiet and noisy conditions were in the range of 0.2 to 0.5, which indicated that the influence effect was small.

In other thermal and acoustic environmental combinations, although the change of illuminance level had limited impact on acoustic satisfaction, it could still be found that with the deterioration of visual environment, researchers' acoustic satisfaction also decreased.

This was consistent with the effect of visual environment on acoustic perception. As discussed earlier, this is because people are more sensitive to sound in a dark environment. Another reasonable explanation for the obvious impact of illuminance level on acoustic satisfaction in a thermal environment of 27 degree Celsius is that when the temperature reaches the warm discomfort zone, the tolerance to the environment of the participants will reduce because the participants had to endure the thermal discomfort caused by temperature. Therefore, any slight deterioration of the visual environment will cause participants to feel extremely uncomfortable, thus reducing the score of acoustic satisfaction.

Table 5-4

Results of acoustic satisfaction and paired sample t-test results about influence of visual environment on acoustic satisfaction for each visual group

	Environment Condition	Acoustic Satisfaction	Paired Sample T-test for Acoustic Satisfaction (Dark - Bright)				
			Mean	SD	t	Sig.	Cohen's d
Visual Group 1	A (21°C+Dark+Quiet) C (21°C+Bright+Quiet)	0.75 ± 1.22 0.84 ± 1.30	-0.094	0.856	-0.619	0.540	-0.072
Visual Group 2	B (21°C+Dark+Noisy) D (21°C+Bright+Noisy)	-1.56 ± 1.13 -1.50 ± 0.92	-0.063	0.914	-0.387	0.701	-0.058
Visual Group 3	E (24°C+Dark+Quiet) G (24°C+Bright+Quiet)	0.66 ± 1.36 0.75 ± 1.37	-0.094	0.963	-0.551	0.586	-0.066
Visual Group 4	F (24°C+Dark+Noisy) H (24°C+Bright+Noisy)	-1.69 ± 0.64 -1.56 ± 0.88	-0.125	0.793	-0.892	0.379	-0.169
Visual Group 5	I (27°C+Dark+Quiet) K (27°C+Bright+Quiet)	0.53 ± 1.05 0.91 ± 1.23	-0.375	0.976	-2.175	0.037	-0.333
Visual Group 6	J (27°C+Dark+Noisy) L (27°C+Bright+Noisy)	-2.16 ± 0.81 -1.75 ± 0.95	-0.406	0.798	-2.881	0.007	-0.465

5.4 Influence mechanism of visual environment on research performance

In order to study the effects of different visual environments on the research performance of participants, the paired sample t-test was conducted for six visual groups based on performance test results collected under different thermal and acoustic environments. The relevant results are shown in Table 5-5, Fig. 5-3 and Fig. 5-4.

5.4.1 The effect of visual environment on answer accuracy

The results of paired sample t-test (Table 5-5) on the answer accuracy according to illuminance level showed that in the thermal environment of 21 degree Celsius, the accuracy of participants completing the performance test in the 500lux condition was higher than that in the 200lux condition (quiet condition: $t\ (31) = -2.436$, $p = 0.021 < 0.05$ and noisy condition: $t\ (31) = 2.133$, $p = 0.041 < 0.05$). For the thermal environment of 24 centigrade and 27 centigrade, there was no significant difference in the answer accuracy of subjects between low illumination level and high illumination level.

This is because the average outdoor temperature was between negative 17.9 centigrade and negative 7.4 centigrade. Thus, the participants generally wore thick sweaters, thick trousers and thick shoes. The clothing coefficient was 1.05, nearly two times of clothing coefficient for indoor summer environment. Therefore, in a relative cool environment, the influence of thermal environment becomes the minimized and the influence of visual environment becomes to appear. This is also proven in Chapter 7, where the weight of the thermal index is highest, and the weight of the visual index is a little bit lower than that, but far larger than the weight of acoustic index.

Table 5-5

Paired sample t-test results about influence of visual environment on answer accuracy of performance test for each visual group

	Environment Condition	Answer Accuracy	Paired Sample T-test for Answer Accuracy (Dark - Bright)				
			Mean	SD	t	Sig.	Cohen's d
Visual Group 1	A (21°C+Dark+Quiet) C (21°C+Bright+Quiet)	94.81 ± 3.72 95.56 ± 3.48	-0.750	1.741	-2.436	0.021	-0.208
Visual Group 2	B (21°C+Dark+Noisy) D (21°C+Bright+Noisy)	95.16 ± 3.96 94.16 ± 4.96	1.000	2.652	2.133	0.041	0.223
Visual Group 3	E (24°C+Dark+Quiet) G (24°C+Bright+Quiet)	95.38 ± 3.61 94.66 ± 3.73	0.719	3.134	1.297	0.204	0.196
Visual Group 4	F (24°C+Dark+Noisy) H (24°C+Bright+Noisy)	94.50 ± 4.17 94.94 ± 4.09	-0.438	2.793	-0.886	0.382	-0.107
Visual Group 5	I (27°C+Dark+Quiet) K (27°C+Bright+Quiet)	94.53 ± 4.14 94.41 ± 4.26	0.125	3.250	0.218	0.829	0.029
Visual Group 6	J (27°C+Dark+Noisy) L (27°C+Bright+Noisy)	94.41 ± 3.99 94.34 ± 3.82	0.063	2.972	0.119	0.906	0.018

5.4.2 The effect of visual environment on response time of performance test

According to the results in Fig. 5-3, except the 21°C quiet environment, the significance value for the other five visual groups was less than 0.05. This indicated that the change of visual environment had a significant impact on the participants' response time for these five different thermal and acoustic environment combinations. And from the mean difference, it can be seen that in dark environment, the participants needed more time to accomplish the performance test than that in bright environment.

One possible explanation is that participants are eager to collect more information in a short time because of the desire to master information. If the illuminance is not enough, the information collection process will be obstructed. And the participants need to spend more time and energy for the information collection, which will cause the fatigue. This impact is more significant for the scientific research tasks which needs lots of accurate and complex operations. Therefore, the participants need to pay more time to accomplish the same quantity of tasks in dark environment than that in bright environment.

For the environment of 21°C quiet, the thermal environment and acoustic environment reached the comfort zone respectively. The impact caused by insufficient light source would be reduced accordingly, so the mean difference between response time in dark environment and bright environment was similar.

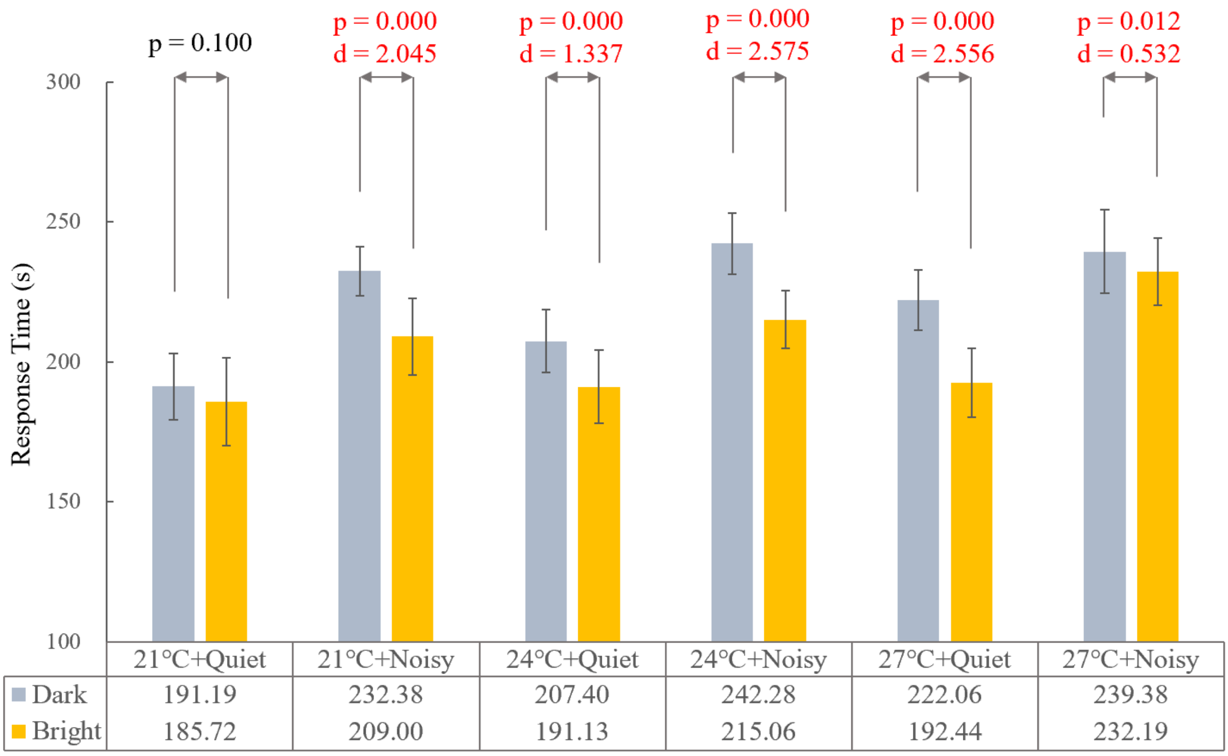


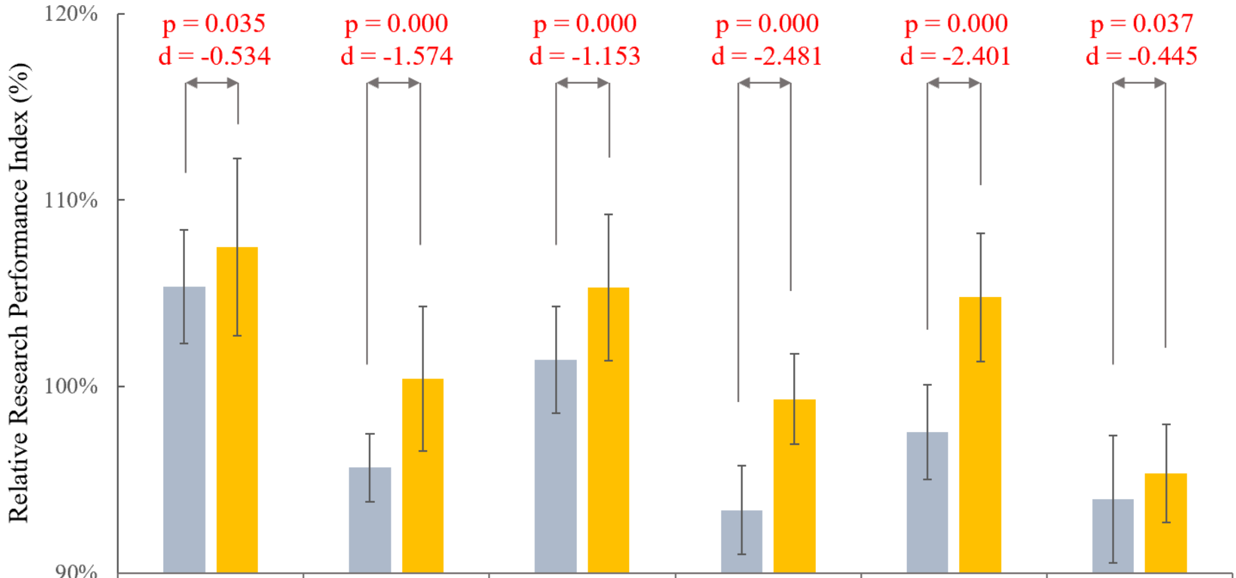
Fig. 5-3. Paired sample t-test results about influence of visual environment on response time of performance test for each visual group

5.4.3 The effect of visual environment on relative research performance

The relative research performance index of each environment condition was calculated according to Eq. 2-2 and Eq. 2-3. The comparison results of relevant RPI within each visual group are shown in Fig. 5-4. The results showed that under all six thermal and acoustic environment combinations, the participants' relative research performance would increase by 1.36% to 7.25% with the increase of illumination level. And the significance values for all six visual groups were less than 0.05, this indicated that the appropriate indoor visual environment played a significant role in improving the researchers' research efficiency. This was also consistent with the previous analysis about the visual environment on the participants' answer accuracy and response time.

$$Performance\ (PI) = Accuracy^{0.5} \times Speed^{0.5} \times 100 = \frac{Accuracy^{0.5}}{Reaction\ Time^{0.5}} \times 100 \quad (Eq. 2-2)$$

$$RPI_{ij} = \frac{n \times PI_{ij}}{\sum_{j=1}^{n} PI_{ij}} \times 100\% \quad (Eq. 2-3)$$



	21°C+Quiet	21°C+Noisy	24°C+Quiet	24°C+Noisy	27°C+Quiet	27°C+Noisy
Dark	105.36%	95.64%	101.43%	93.36%	97.54%	93.97%
Bright	107.49%	100.41%	105.33%	99.32%	104.79%	95.33%

Fig. 5-4 Paired sample t-test results about influence of visual environment on RPI for each visual group

Chapter VI

Indoor Environmental Index Equation

With the development of society and the improvement of living standards, the requirements for living and working environment have changed from only meeting the most basic functions to seeking a more comfortable environment. How to meet the increasing demand for indoor comfort has become an important topic in the field of sustainable development of modern architecture. Indoor environment quality is considered to be an important index for the sustainable development of buildings. It is calculated based on the subjective voting results of environmental satisfaction about indoor thermal, visual and acoustic environment, so as to reflect comfort level of occupants to the indoor environment. Because it is impossible to conduct the subjective test to every indoor environment, and the subjective voting results are not easy to quantify. Therefore, it is particularly important to develop a mathematical model which can directly evaluate the indoor environment quality according to the physical parameters of the indoor environment.

From Chapter III to Chapter V, this paper qualitatively analyzed the effect of indoor thermal environment, acoustic environment and visual environment on occupants' environment satisfaction, respectively. However, it is relatively difficult to quantitatively analyze the relationship between physical parameters of indoor environment and occupants' satisfaction. This is because a single environmental indicator will be affected by various environmental physical quantities [41]. For example, the thermal comfort index of indoor environment is not only affected by the physical parameters of thermal environment such as temperature and humidity, but also affected by physical parameters of visual and acoustic environment, such as luminance and average background noise intensity.

Among the existing relevant models, Wong's multivariate logistic model, Iordache's IEQ model and Ncube's IEQ model are three classis mathematical model for predicting occupants' comfort based on environment physical parameters [20, 43, 93]. Among them, Wong's multivariate logistic model is developed based on the subjective evaluation about indoor environmental conditions from 293 occupancies in a typical air-conditioned office in Hong Kong. The equation of Wong's multivariate logistic model is listed from Eq. 6-1 to Eq. 6-5:

$$Thermal\ Index: \phi_1 = 1 - \frac{PPD}{100} \quad (Eq.6-1)$$

$$IAQ\ Index: \phi_2 = 1 - \frac{1}{2}\left(\frac{1}{1+\exp(3.118-0.00215\zeta_2)} - \frac{1}{1+\exp(3.230-0.00117\zeta_2)}\right), 500 \leq \zeta_2 1800\ ppm \quad (Eq.6-2)$$

$$Visual\ Index: \phi_4 = 1 - \frac{1}{1+\exp(-1.018+0.00558\zeta_4)}, 200 \leq \zeta_4 \leq 1600\ lux \quad (Eq.6-3)$$

$$Acoustic\ Index: \phi_3 = 1 - \frac{1}{1+\exp(9.540-0.134\zeta_3)}, 45 \leq \zeta_3 \leq 72\ dBA \quad (Eq.6-4)$$

$$Overall\ IEQ: \theta = 1 - \frac{1}{1+\exp(-15.02+\sum_{i=1}^{4} K_i\phi_i)}, K_1 = 6.09, K_2 = 4.88, K_3 = 4.74, K_4 = 3.70 \quad (Eq.6-5)$$

Iordache's IEQ model is a multiple non-linear regression models developed based on the data from university classroom and professors' office in Romania. The equation of Iordache's IEQ model is listed from Eq.6-6 to Eq.6-10:

$$Thermal\ Index: I_{th} = \begin{cases} 28.57\theta_o - 514, & \theta_o \leq 21.5 \\ -28.57\theta_o + 800, & \theta_o \geq 24.5 \end{cases} \quad (Eq.6-\ 6)$$

$$IAQ\ Index: I_{IAQ} = 3.125Q_{air} - 12.5 \quad (Eq.6-7)$$

$$Visual\ Index: I_v = 0.33E_{av} \quad (Eq.6-8)$$

$$Acoustic\ Index: I_a = -3.33L_{pi} + 200 \quad (Eq.6-9)$$

$$Overall\ IEQ: I_{IEQ} = \frac{1}{4}\left(I_{th} + I_a + I_v + I_{IAQ}\right) \quad (Eq.6-10)$$

Ncube's IEQ model is a multiple regression model developed based on the surveyed input data from 68 occupants in two selected office buildings in UK. It is used to quick assess the environmental performance of the air-conditioned office alongside energy performance. The Equation of Ncube's IEQ Model is from Eq. 6-11 to Eq. 6-15.

$$Thermal\ Index: TC_{index} = 100 - PPD \quad (Eq.6-\ 11)$$

$$IAQ\ Index: IAQ_{index} = 100 - PD_{IAQ}, where\ PD_{IAQ} = 395 \times \exp\left(-15.15 \times C_{CO_2}^{-0.25}\right) \quad (Eq.6-12)$$

$$Visual\ Index: L_{index} = -176.16x^2 + 738.4x - 690.29, x = \ln(\ln(lux)) \quad (Eq.6-13)$$

$$Acoustic\ Index: AC_{index} = 100 - PD_{ACc}, where$$

$$PD_{ACc} = 2 \times (Actual_{SoundPressureLevel} - Design_{SoundPressureLevel}) \quad (Eq.6-14)$$

$$IEQ_{index} = 0.30TC_{index} + 0.36IAQ_{index} + 0.18AC_{index} + 0.16L_{index} \quad (Eq. 6-15)$$

However, there are several shortcomings for these three mathematical models. On the one hand, when establishing a single environmental index, these three models only considered the impact of its corresponding environmental physical parameter, ignoring the impact of other environmental physical parameters. According to the correlation analysis between satisfaction in this chapter, there existed correlation between different aspects of environmental satisfaction. Therefore, when establishing each environmental index equation, it is necessary to comprehensively consider the impact of all environmental aspects on the index.

On the other hand, Wong's multivariate logistic model, Iordache's IEQ model and Ncube's IEQ model were established based on the data of working environment, learning environment and living environment. Their applicability in the research facilities has not been fully tested. In addition, some studies pointed out that the coefficient of environmental indexes in the IEQ equation were different for different building usages [94, 95]. For example, Wong et al. and Lee et al. pointed out that the importance of acoustic environment on working environment was higher than that of thermal or visual environment. Therefore, the coefficient of acoustic index in IEQ equation should be higher than the other two indexes [20, 96].

In this experiment, three environmental indexes were used to evaluate the indoor environment quality of controlled research office, which were thermal comfort index, acoustic comfort index and visual comfort index. Each comfort index needed to establish the relationship with all the environment physical parameters. This was accomplished by improving the existing mathematical equations of environmental prediction. Therefore, this chapter first illustrated the comparison between three existing mathematical models and the actual voting results of environmental satisfaction. And the most appropriate prediction equation for each environmental comfort was selected. Secondly, the correlation among three environmental satisfaction was analyzed based on the actual satisfaction voting results. Finally, the optimal equation corresponding to each environmental index was improved by adding the parameters of other environmental aspects, so as to make it more in line with the actual research environment.

6.1 Prediction equation of environmental comfort index

6.1.1 Prediction equation of thermal comfort index

In order to obtain the prediction equation of thermal comfort index, the difference between the actual thermal comfort of the subjects and the thermal comfort index obtained from three mathematical models was compared under different environment conditions. According to the research of Fanger, for each environment condition, the actual thermal comfort = 100 – actual percentage of dissatisfaction about thermal environment [97]. And the actual percentage of dissatisfaction was the calculated as the proportion of people who chose the "very dissatisfied" or "dissatisfied" options in the thermal satisfaction voting to the total number of the subjects. The calculation results are summarized in Table 6-1.

Table 6-1

Summary of thermal comfort indexes calculated from three mathematic models (mean value ± standard deviation) and actual thermal comfort for different environmental conditions

Environment Condition	Thermal Comfort Index (Wong)	Thermal Comfort Index (Ncube)	Thermal Comfort Index (Iordache)	Actual Thermal Comfort
A (21°C+Dark+Quiet)	91.50 ± 1.73	91.50 ± 1.73	85.91 ± 13.33	90.6
B (21°C+Dark+Noisy)	91.75 ± 2.63	91.75 ± 2.63	86.38 ± 15.56	78.1
C (21°C+Bright+Quiet)	92.25 ± 1.71	92.25 ± 1.71	90.84 ± 11.41	100.0
D (21°C+Bright+Noisy)	91.00 ± 2.00	91.00 ± 2.00	82.64 ± 11.44	90.6
E (24°C+Dark+Quiet)	91.50 ± 1.73	91.50 ± 1.73	98.83 ± 1.79	100.0
F (24°C+Dark+Noisy)	91.50 ± 1.91	91.50 ± 1.91	97.40 ± 3.58	90.6
G (24°C+Bright+Quiet)	93.00 ± 1.41	93.00 ± 1.41	99.77 ± 0.46	100.0
H (24°C+Bright+Noisy)	93.25 ± 2.36	93.25 ± 2.36	99.29 ± 1.41	96.9
I (27°C+Dark+Quiet)	70.00 ± 4.76	70.00 ± 4.76	22.66 ± 11.57	68.8
J (27°C+Dark+Noisy)	70.00 ± 2.94	70.00 ± 2.94	25.04 ± 8.91	62.5
K (27°C+Bright+Quiet)	71.50 ± 4.12	71.50 ± 4.12	26.71 ± 13.89	75.0
L (27°C+Bright+Noisy)	74.00 ± 5.83	74.00 ± 5.83	33.37 ± 15.22	71.9

The mathematical equations for predicting thermal comfort index in three mathematical models are shown in Eq. 6-1, Eq. 6-6 and Eq. 6-11 respectively. Both Wong's multivariate logistic model and Ncube's model used predicted percentage of dissatisfaction (PPD) when predicting thermal comfort. Essentially they are the same equation. PPD was calculated through Fanger's thermal comfort model, and the calculation formula is shown in Appendix 6-1 [97, 98]. When calculating the PPD, some parameters needed to be set. In this experiment, the relevant parameters were set as follows:

(a) In the experiment, there was no external wind source, so the indoor air flow speed was set as 0.1m/s;

(b) The participants carried out relevant scientific research during the experiment, including reading the literature, analyzing the data and typing. Therefore, the metabolic rate was set to 1.1met;

(c) According the clothing data in the subjective questionnaire, the subjects generally wore normal indoor clothes for winter, including long sleeved thick sweaters, thick trousers, thermal underwear, thick stockings and thick shoes. This is because in the whole experimental stage, the maximum outdoor average temperature was minus 7.4 degrees Celsius, and the minimum was minus 17.9 degrees Celsius (See Appendix 6-2). The seat was an ordinary office chair. With the help of "CBE Thermal Comfort Tool", the clothing level for this experiment was calculated to be 1.05 [99, 100].

θ_o was used to calculate the thermal comfort index in Iordache's model, which is operative temperature. It was calculated using Eq. 6-16, where θ_i is the indoor air temperature, θ_{mr} is the mean radiant temperature for indoor environment, h_r is linear radiative heat transfer coefficient and h_c is convective heat transfer coefficient. The indoor air temperature was the temperature measured in this experiment. Because of the window shading and the heat insulating materials around the exterior wall of the controlled research office, the influence of solar radiation during the experience period was reduced to the minimum. Therefore, the mean radian temperature was approximately equal to the indoor air temperature in the controlled research office. By bring θ_i and θ_{mr} into Eq. 6-16, θ_o was calculated equal to θ_i. In addition, when the operative temperature was between 21.5 to 24.5 centigrade, the thermal comfort index was set to 100 in Iordache's model [43].

$$\theta_o = \frac{h_r\theta_{mr} + h_c\theta_i}{h_r + h_c} \quad (Eq. 6-16)$$

In this experiment, participants were divided into four experiment groups. The thermal physical parameters measured for each experiment group under different environmental conditions are shown in Table 6-2. For each mathematical model, under every environment condition, through bringing the environment physical parameters into thermal equation, the thermal comfort index for each experiment group was obtained. Afterwards, the thermal comfort index for total subjects under each environment condition was calculated by taking the geometric average of the four groups of thermal comfort indexes. The corresponding results are shown in Table 6-1. In order to make the comparison more intuitive, the index calculated from Wong's multivariate logistic model was enlarged by 100 times in this experiment.

Table 6-2

Summary of thermal physical parameters (mean value ± standard deviation) for different environmental conditions

Environment Condition	Group 1 Air Temperature (°C)	Group 1 Relative Humidity (%)	Group 2 Air Temperature (°C)	Group 2 Relative Humidity (%)
A (21°C+Dark+Quiet)	21.1 ± 0.35	42.0 ± 2.72	20.4 ± 0.06	43.1 ± 2.57
B (21°C+Dark+Noisy)	20.4 ± 0.29	44.2 ± 0.44	21.5 ± 0.21	44.6 ± 1.95
C (21°C+Bright+Quiet)	21.0 ± 0.12	39.0 ± 1.49	20.7 ± 0.21	36.3 ± 1.21
D (21°C+Bright+Noisy)	20.3 ± 0.10	38.7 ± 1.10	21.2 ± 0.26	36.6 ± 2.89
E (24°C+Dark+Quiet)	23.9 ± 0.23	41.5 ± 1.99	24.6 ± 0.06	42.4 ± 0.90
F (24°C+Dark+Noisy)	23.6 ± 0.31	39.7 ± 0.75	24.6 ± 0.26	41.6 ± 1.59
G (24°C+Bright+Quiet)	23.6 ± 0.21	42.1 ± 3.11	23.4 ± 0.15	38.5 ± 1.59
H (24°C+Bright+Noisy)	24.6 ± 0.00	42.3 ± 2.19	24.2 ± 0.21	35.1 ± 0.25
I (27°C+Dark+Quiet)	27.5 ± 0.17	38.1 ± 3.71	26.7 ± 0.26	38.9 ± 2.19
J (27°C+Dark+Noisy)	27.2 ± 0.12	38.7 ± 1.44	27.2 ± 0.35	36.9 ± 2.48
K (27°C+Bright+Quiet)	27.5 ± 0.35	36.8 ± 2.22	27.5 ± 0.15	34.9 ± 1.97
L (27°C+Bright+Noisy)	26.5 ± 0.12	36.5 ± 0.46	27.4 ± 0.26	36.5 ± 2.26

Environment Condition	Group 3 Air Temperature (°C)	Group 3 Relative Humidity (%)	Group 4 Air Temperature (°C)	Group 4 Relative Humidity (%)
A (21°C+Dark+Quiet)	21.0 ± 0.15	40.7 ± 1.06	21.6 ± 0.32	36.2 ± 2.01
B (21°C+Dark+Noisy)	20.7 ± 0.35	39.1 ± 1.95	21.5 ± 0.31	45.0 ± 3.15
C (21°C+Bright+Quiet)	21.6 ± 0.00	34.8 ± 1.35	21.7 ± 0.35	40.7 ± 0.93
D (21°C+Bright+Noisy)	21.1 ± 0.25	43.6 ± 0.90	21.0 ± 0.06	44.5 ± 0.17
E (24°C+Dark+Quiet)	24.5 ± 0.06	45.5 ± 2.31	24.1 ± 0.44	35.1 ± 0.98
F (24°C+Dark+Noisy)	24.8 ± 0.21	38.1 ± 1.50	24.1 ± 0.26	42.4 ± 2.69
G (24°C+Bright+Quiet)	24.5 ± 0.12	36.6 ± 3.37	23.9 ± 0.06	45.2 ± 3.05
H (24°C+Bright+Noisy)	23.3 ± 0.15	39.2 ± 0.69	23.3 ± 0.23	37.8 ± 0.95
I (27°C+Dark+Quiet)	27.1 ± 0.38	35.5 ± 1.33	27.6 ± 0.31	40.9 ± 2.27
J (27°C+Dark+Noisy)	27.4 ± 0.29	43.7 ± 3.30	26.7 ± 0.12	45.6 ± 1.10
K (27°C+Bright+Quiet)	26.6 ± 0.38	40.5 ± 4.44	26.7 ± 0.12	41.8 ± 0.36
L (27°C+Bright+Noisy)	27.2 ± 0.12	42.5 ± 4.83	26.3 ± 0.46	36.5 ± 0.56

In order to examine which mathematic model is more suitable for predicting thermal comfort in this experiment, the thermal comfort indexes calculated from three mathematical models and the actual thermal comfort of the subjects were compared using paired sample T-test. The results are shown in Fig. 6-1. Because there were 12 different environment conditions, the sample size N = 12. According to the results of pair sample T-test, there was no significant difference between thermal comfort prediction from Wong's multivariate logistic model and Ncube's model with the actual thermal comfort of the subjects (both t (11) = 0.168, p = 0.870 > 0.05). However, for the Iordache's model, the pair sample T-test results showed that t (11) = 2.372 with p = 0.037 < 0.05. This indicated that there existed significant difference between thermal comfort index predicted by Iordache's model and the actual thermal comfort. Because the prediction of thermal comfort index by Wong's multivariate logistic model and Ncube's model is essentially the same equation, in this experiment, Ncube's model was used to calculate the thermal comfort index.

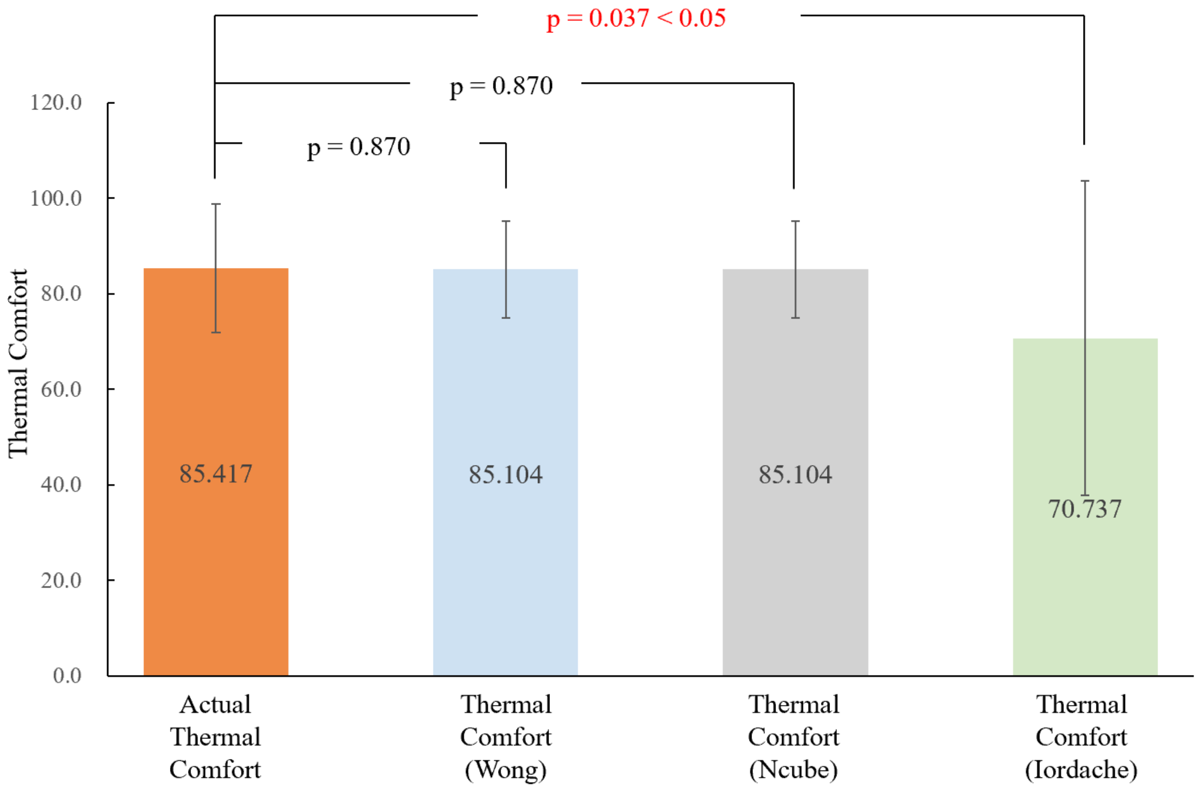


Fig. 6-1. Paired sample t-test results between thermal comfort indexes from three mathematical models and actual thermal comfort

6.1.2 Prediction equation of acoustic comfort index

The acoustic physical parameters measured for each experimental group under different environmental conditions are shown in Table 6-3. Through comparing difference between the actual acoustic comfort of the subjects and the acoustic comfort indexes obtained from three mathematical models under different environment conditions, the equation for calculating the acoustic comfort index was found out. Same as the thermal part, the actual acoustic comfort was set as 100 minus actual percentage of dissatisfaction about acoustic environment. And the actual percentage of dissatisfaction was set as the proportion of the people who chose "very dissatisfied" or "dissatisfied" options about acoustic satisfaction to the total number of the subjects. The results are summarized in Table 6-4.

Table 6-3

Summary of acoustic physical parameters (mean value ± standard deviation) for different environmental conditions

Environment Condition	Group 1	Group 2	Group 3	Group 4
	Average Background Noise Level (dB(A))	Average Background Noise Level (dB(A))	Average Background Noise Level (dB(A))	Average Background Noise Level (dB(A))
A (21°C+Dark+Quiet)	44.3 ± 3.3	44.1 ± 1.7	41.6 ± 2.6	44.9 ± 2.5
B (21°C+Dark+Noisy)	69.0 ± 2.3	75.0 ± 1.5	74.7 ± 3.9	75.5 ± 3.0
C (21°C+Bright+Quiet)	39.4 ± 1.0	46.0 ± 1.2	39.0 ± 3.7	40.2 ± 1.3
D (21°C+Bright+Noisy)	69.8 ± 1.9	69.9 ± 3.3	70.5 ± 1.0	67.9 ± 1.7
E (24°C+Dark+Quiet)	42.5 ± 2.1	40.5 ± 1.8	47.3 ± 2.3	40.2 ± 2.6
F (24°C+Dark+Noisy)	72.0 ± 1.7	69.4 ± 3.3	70.0 ± 1.2	73.7 ± 1.9
G (24°C+Bright+Quiet)	46.0 ± 3.7	47.9 ± 2.0	39.0 ± 3.4	38.5 ± 2.6
H (24°C+Bright+Noisy)	69.0 ± 3.3	75.1 ± 4.6	72.4 ± 2.1	72.2 ± 1.6
I (27°C+Dark+Quiet)	41.8 ± 3.5	46.6 ± 3.3	39.8 ± 5.8	40.9 ± 1.9
J (27°C+Dark+Noisy)	73.5 ± 1.4	70.9 ± 1.5	75.8 ± 2.2	75.1 ± 1.9
K (27°C+Bright+Quiet)	41.8 ± 4.0	45.8 ± 3.2	38.2 ± 4.5	40.4 ± 2.9
L (27°C+Bright+Noisy)	77.0 ± 0.9	72.1 ± 2.8	75.1 ± 2.3	72.2 ± 1.7

Table 6-4

Summary of acoustic comfort indexes calculated from three mathematic models (mean value ± standard deviation) and actual acoustic comfort for different environmental conditions

Environment Condition	Acoustic Comfort Index (Wong)	Acoustic Comfort Index (Ncube)	Acoustic Comfort Index (Iordache)	Actual Acoustic Comfort
A (21°C+Dark+Quiet)	97.52 ± 0.44	92.63 ± 2.93	100.00 ± 0.00	100.0
B (21°C+Dark+Noisy)	42.31 ± 10.09	32.90 ± 6.13	39.44 ± 10.21	37.5
C (21°C+Bright+Quiet)	98.11 ± 0.96	96.90 ± 5.97	100.00 ± 0.00	100.0
D (21°C+Bright+Noisy)	55.60 ± 3.75	40.99 ± 2.29	52.91 ± 3.81	46.9
E (24°C+Dark+Quiet)	97.71 ± 1.11	94.75 ± 6.58	100.00 ± 0.00	96.9
F (24°C+Dark+Noisy)	49.74 ± 6.49	37.45 ± 3.90	47.02 ± 6.50	34.4
G (24°C+Bright+Quiet)	97.48 ± 1.48	93.06 ± 8.16	100.00 ± 0.00	93.8
H (24°C+Bright+Noisy)	46.84 ± 8.22	35.69 ± 4.99	44.08 ± 8.31	43.8
I (27°C+Dark+Quiet)	97.84 ± 0.96	95.36 ± 5.88	100.00 ± 0.00	100.0
J (27°C+Dark+Noisy)	41.45 ± 7.09	32.39 ± 4.35	38.59 ± 7.24	18.8
K (27°C+Bright+Quiet)	98.03 ± 0.87	96.01 ± 5.25	100.00 ± 0.00	100.0
L (27°C+Bright+Noisy)	40.61 ± 7.63	31.83 ± 4.80	37.65 ± 8.00	31.3

For three mathematical models, the equation of the relationship between acoustic comfort and environment physical parameters are shown in Eq. 6-4, Eq. 6-9 and Eq. 6-14 respectively. For Wong's multivariate logistic model, when calculating the acoustic comfort index, ζ_3 was used, which was the average background noise level measured in this experiment. Ncube's model used PD_{ACc} as an intermediate variable when predicting the acoustic thermal index. And PD_{ACc} was regarded as percentage of dissatisfaction with acoustic environment, which needed to be calculated from Actual Sound Pressure Level and Design Sound Pressure Level. Actual sound pressure level was the measured background noise intensity in this experiment. According to the *Environmental Quality Standard for Noise (GB3096)* published by Chinese government, the research facility belongs to Class-I environmental functional area, which needed to be particularly quiet. And the daytime noise limit must below 55dB(A) [101]. American National Standards Institute (ANSI) required that for core learning spaces, the one-hour steady-state background noise levels should not exceed 40dB(A) [90]. The European standard EN15251 also recommended the average background noise levels should not exceed 40dB(A) for the scientific facilities [91]. Therefore, the design sound pressure level was set to 40dB(A) in this experiment. The interior sound pressure level L_{pi} was adopted in Iordache's model when establishing the equation for predicting acoustic comfort. In order to calculate L_{pi}, the office structure and material properties of wall and window should be considered. The Appendix 6-3 shows the specific calculation method for L_{pi}.

In order to obtain the acoustic comfort indexes of three mathematical models for the total sample, it was necessary to bring different environment physical parameters of the four experiment groups into Eq.6-4, Eq.6-9 and Eq.6-14 to obtain the acoustic comfort indexes of each group respectively. For each mathematical model, the acoustic comfort indexes of each group were geometrically averaged to obtain the acoustic comfort indexes of the overall sample under each environment condition. The corresponding results are shown in Table 6-5. Also, in order to facilitate comparison, the acoustic comfort index obtained from Wong's multivariate logistic model was enlarged by 100 times in this experiment.

The paired sample t-test was conducted between the acoustic comfort index predicted by the three mathematical models and the actual acoustic comfort of the subjects, so as to test whether the relevant mathematical models can accurately predict the actual acoustic comfort. The relevant results are shown in Fig. 6-2. The results indicated that only the significance value of Ncube's model was greater than 0.05 ($t(11) = 1.156$, $p = 0.272 > 0.05$). This meant that there was no significant difference between the acoustic comfort calculated by Ncube's model and the actual acoustic comfort of the subject. And Eq. 6-14 can be used as the prediction equation of acoustic comfort in this experiment. For the other two models, both significance value of paired sample t-test were less than 0.05 ($t(11) = -2.202$, $p = 0.0499 < 0.05$ and $t(11) = -2.645$, $p = 0.023 < 0.05$). And the mean difference was less than zero. This indicated that the acoustic comfort indexes calculated by Wong's multivariate logistic model and Iordache's model were significantly greater than the actual indoor acoustic comfort. Therefore, the acoustic equation in Wong's multivariate logistic model and Iordache's model cannot be used in this experiment.

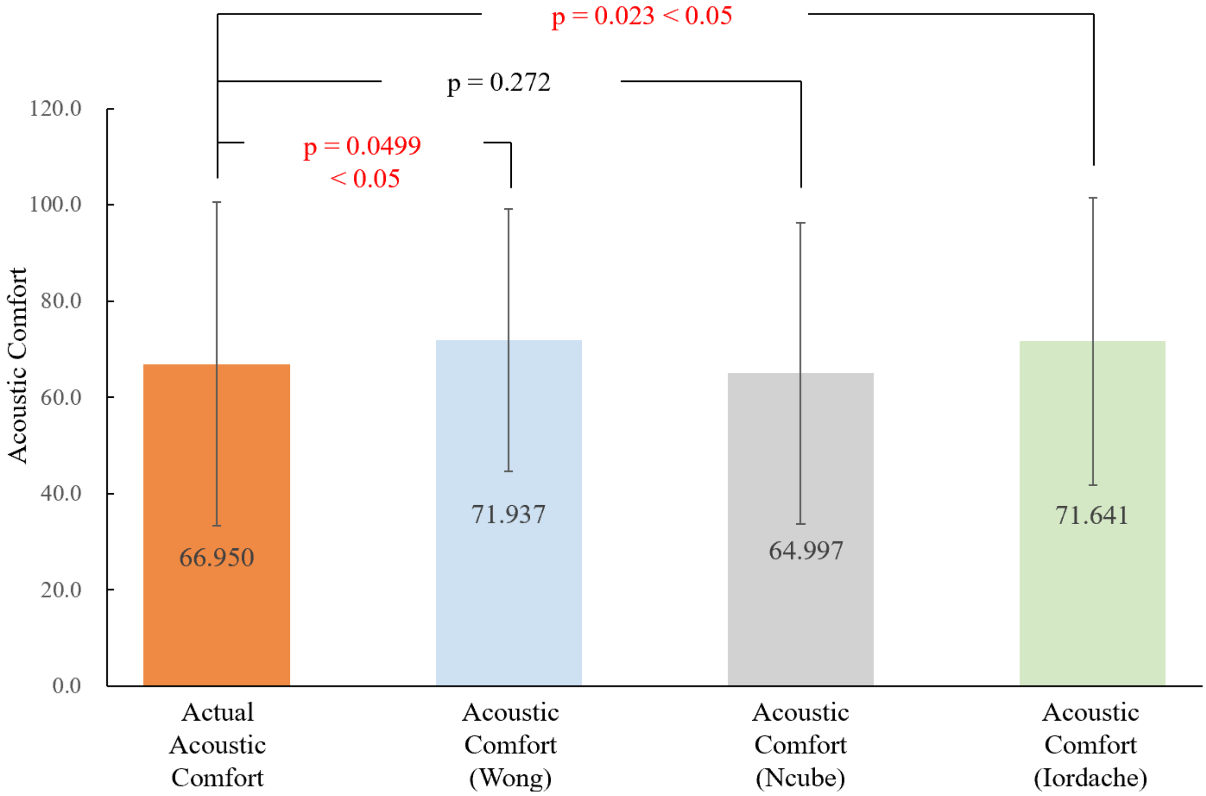


Fig. 6-2. Paired sample t-test results between acoustic comfort indexes from three mathematical models and actual acoustic comfort

6.1.3 Prediction equation of visual comfort index

This section mainly discussed which mathematical model can accurately evaluate the indoor visual comfort of the research facilities. This needed to compare the difference between the actual visual comfort of the subjects and the visual comfort index obtained by the three mathematical models. Similar to the thermal environment and acoustic environment, the actual visual comfort = 100 – actual percentage of dissatisfaction about visual environment. And actual percentage of dissatisfaction was regarded as the proportion of people who chose "very dissatisfied" or "dissatisfied" options about visual satisfaction to the total number of the participants. The relevant results are shown in Table 6-5.

The mathematical equations describing the relationship between visual comfort and environment physical parameters in three mathematical models are shown in Eq. 6-3, Eq. 6-8 and Eq. 6-13. In this experiment, each experiment group conducted the experiment for 90 minutes under each environment condition. At the beginning and end of the experiment, the desktop illumination intensity was measured respectively, and the average value of the two measurements was set as the measured illuminance level of the desktop. The visual physical parameters measured for each experiment group under different environment conditions are shown in Table 6-6.

When calculating the visual comfort index, the variable ζ_4 used in Wong's multivariate logistic model, the variable lux used in Ncube's model and the variable E_{av} used in Iordache's model were the measured luminance level of the desktop in this experiment.

Under each environment condition, the visual physical parameters for each experiment group were brought into the Eq. 6-3, Eq. 6-8 and Eq. 6-13 to get the visual comfort index for this experiment group. Through geometric averaging the four-group visual comfort indexes, the visual comfort index for entire subjects were obtained under each environment condition. The corresponding results are shown in Fig.6-3. The visual comfort index calculated from Wong's multivariate logistic model needed to enlarge 100 times in order to make the comparison more intuitive.

The visual comfort index calculated by the three mathematical models were compared with the actual visual comfort of the subjects by paired sample t-test, and the results are shown in Fig. 6-3. The purpose was to determine which model can more accurately predict the actual visual comfort in the research facility. According to the paired sample t-test result, there existed significant difference between the actual visual comfort of the subjects and the visual comfort calculated by the corresponding equations of Wong's multivariate logistic model and Ncube's model, both significance values were less than 0.05. For both models, the difference of the mean value were above +10, which indicated that the prediction of visual comfort using Wong's multivariate logistic model and Ncube's model were significantly too small. For the Iordache's model, the paired t-test results showed that t (11) = -0.800 with p = 0.441 > 0.05. Therefore, the null hypothesis that there existed a difference between the visual comfort index from model and actual visual comfort can be rejected. In this experiment, the visual equation in Iordache's model was selected to evaluate the visual comfort of research facilities.

Table 6-5

Summary of visual physical parameters (mean value ± standard deviation) for different environmental conditions

Environment Condition	Group 1	Group 2	Group 3	Group 4
	Luminance Level on the desk (lux)	Luminance Level on the desk (lux)	Luminance Level on the desk (lux)	Luminance Level on the desk (lux)
A (21°C+Dark+Quiet)	242.5 ± 17.7	180.0 ± 15.6	199.0 ± 1.4	181.0 ± 5.7
B (21°C+Dark+Noisy)	223.0 ± 4.2	203.5 ± 16.3	213.5 ± 3.5	234.0 ± 4.2
C (21°C+Bright+Quiet)	532.5 ± 4.9	491.0 ± 9.9	523.5 ± 31.8	487.0 ± 21.2
D (21°C+Bright+Noisy)	526.0 ± 9.9	470.5 ± 13.4	504.5 ± 21.9	539.0 ± 15.6
E (24°C+Dark+Quiet)	185.5 ± 2.1	167.5 ± 7.8	204.5 ± 7.8	206.5 ± 9.2
F (24°C+Dark+Noisy)	162.0 ± 8.5	222.5 ± 6.4	161.5 ± 0.7	200.0 ± 2.8
G (24°C+Bright+Quiet)	526.0 ± 9.9	473.5 ± 12.0	484.0 ± 5.7	529.0 ± 0.0
H (24°C+Bright+Noisy)	456.5 ± 16.3	551.0 ± 25.5	469.5 ± 10.6	479.5 ± 0.7
I (27°C+Dark+Quiet)	188.5 ± 7.8	179.0 ± 25.5	176.0 ± 7.1	199.0 ± 52.3
J (27°C+Dark+Noisy)	213.0 ± 11.3	189.5 ± 3.5	189.0 ± 19.8	197.0 ± 19.8
K (27°C+Bright+Quiet)	493.5 ± 10.6	504.0 ± 7.1	506.5 ± 17.7	460.0 ± 2.8
L (27°C+Bright+Noisy)	525.5 ± 19.1	503.5 ± 9.2	518.0 ± 7.1	475.5 ± 17.7

Table 6-6

Summary of visual comfort indexes calculated from three mathematic models (mean value ± standard deviation) and actual visual comfort for different environmental conditions

Environment Condition	Visual Comfort Index (Wong)	Visual Comfort Index (Ncube)	Visual Comfort Index (Iordache)	Actual Visual Comfort
A (21°C+Dark+Quiet)	52.52 ± 4.04	50.90 ± 3.86	66.21 ± 9.65	81.3
B (21°C+Dark+Noisy)	55.01 ± 1.80	53.54 ± 1.61	72.11 ± 4.30	71.9
C (21°C+Bright+Quiet)	86.00 ± 1.53	70.98 ± 0.68	100.00 ± 0.00	96.9
D (21°C+Bright+Noisy)	86.06 ± 2.05	71.01 ± 0.90	100.00 ± 0.00	93.8
E (24°C+Dark+Quiet)	51.19 ± 2.55	49.65 ± 2.92	63.03 ± 6.04	68.8
F (24°C+Dark+Noisy)	50.56 ± 4.18	48.65 ± 4.74	61.55 ± 9.91	62.5
G (24°C+Bright+Quiet)	85.60 ± 1.96	70.81 ± 0.86	100.00 ± 0.00	93.8
H (24°C+Bright+Noisy)	84.52 ± 2.86	70.34 ± 1.27	100.00 ± 0.00	93.8
I (27°C+Dark+Quiet)	50.44 ± 1.45	48.92 ± 1.65	61.26 ± 3.43	62.5
J (27°C+Dark+Noisy)	52.05 ± 1.56	50.68 ± 1.58	65.05 ± 3.70	53.1
K (27°C+Bright+Quiet)	84.79 ± 1.59	70.45 ± 0.70	100.00 ± 0.00	100.0
L (27°C+Bright+Noisy)	85.81 ± 1.53	70.90 ± 0.68	100.00 ± 0.00	90.6

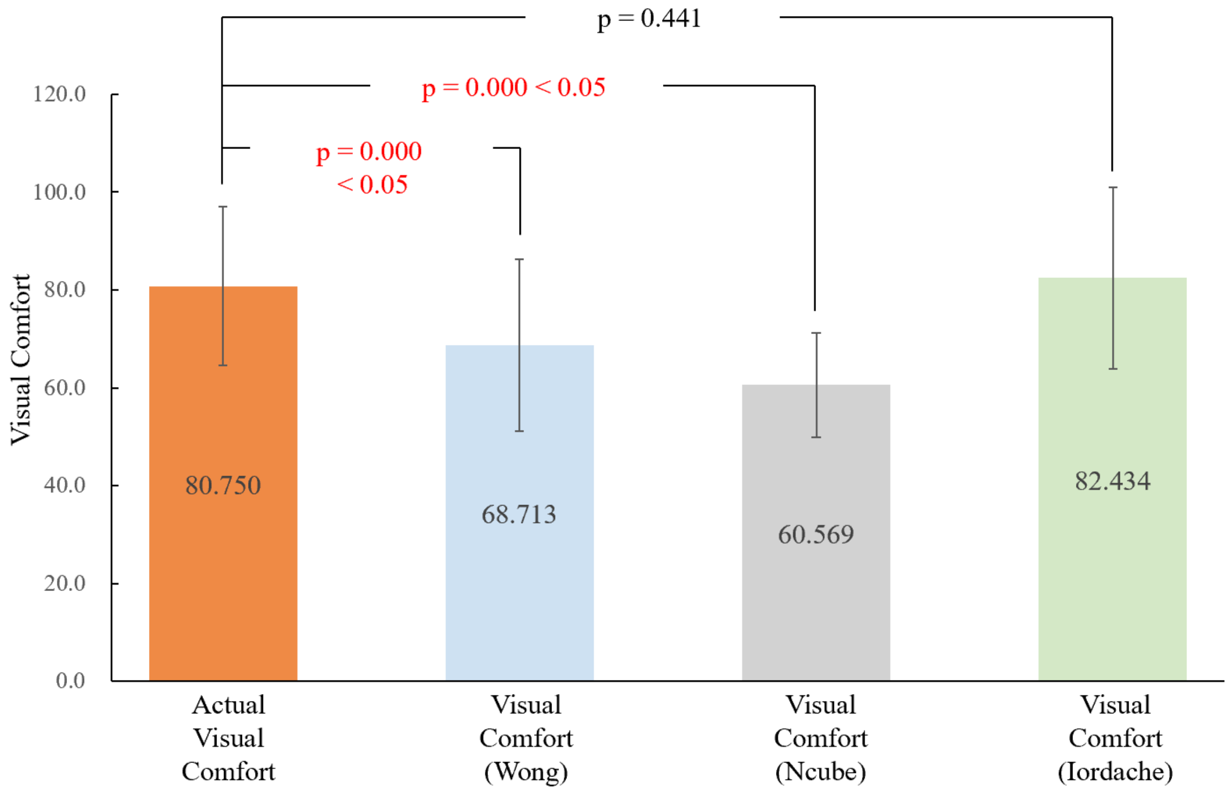


Fig. 6-3. Paired sample t-test results between visual comfort indexes from three mathematical models and actual visual comfort

6.1.4 Summary

Section 6.1.1, 6.1.2 and 6.1.3 evaluated the differences between the comfort indexes calculated from three mathematical models and the actual comfort of the subjects in thermal environment, acoustic environment and visual environment respectively. At the end of each section, the most suitable equation to predict the environmental comfort was selected. Through unifying the symbols in the equation, the prediction equations are summarized in Eq. 6-17, Eq. 6-18 and Eq. 6-19.

$$Thermal\ Comfort\ Index: T_{index-ori} = 100 - PPD \quad (Eq. 6-17)$$

$$Acoustic\ Comfort\ Index: A_{index-ori} = 100 - PD_{ACc}, where$$

$$PD_{ACc} = 2 \times (Actual_{SoundPressureLevel} - Design_{SoundPressureLevel}) \quad (Eq. 6-18)$$

$$Visual\ Index: V_{index-ori} = 0.33E_{av} \quad (Eq. 6-19)$$

6.2 Correlation Analysis

In the subjective questionnaire, thermal satisfaction, acoustic satisfaction and visual satisfaction were scored from - 3 to 3, where "- 3" represented strongly dissatisfied about the environment and "3" represented that the participants were very satisfied with the environment. In order to verify the correlation between the three indoor environmental variables, it was necessary to analyze the correlation of thermal satisfaction, acoustic satisfaction and visual satisfaction of the entire samples. The sample size for correlation analysis was $N = 32 \times 12 = 384$. The corresponding results are shown in Table 6-7.

The results showed that the correlation coefficient between thermal comfort and visual comfort was 0.215 with p value as 0.000. The correlation coefficient between thermal comfort and acoustic comfort was 0.143 with p value as 0.005. And the correlation coefficient between visual comfort and acoustic comfort was 0.165 and the significance value was 0.001. Because the significance value of correlation analysis among three comforts were all less than 0.01, there existed obvious correlation between thermal comfort, acoustic comfort and visual comfort under 99% of confidence level. The Pearson correlation factors all fell in the region 0.1 to 0.4, which indicated that the correlation among all three environmental comforts were weak and positive.

Table 6-7

Correlation analysis results of thermal, acoustic and visual comfort

Correlation

		Thermal Satisfaction	Visual Satisfaction	Acoustic Satisfaction
Thermal Satisfaction	Preason Correlation	1.000	0.215	0.143
	Sig.		0.000	0.005
	N	384	384	384
Visual Satisfaction	Preason Correlation	0.215	1.000	0.165
	Sig.	0.000		0.001
	N	384	384	384
Acoustic Satisfaction	Preason Correlation	0.143	0.165	1.000
	Sig.	0.005	0.001	
	N	384	384	384

Because the environment satisfaction was used to calculate the actual environment comfort of the subject, and the actual comfort can be predicted using environment physical parameters. When establishing the prediction equation of comfort of a single environmental index, it was necessary to consider not only the corresponding environment physical parameters, but also the influence of other environment physical parameters.

6.3 Improvement of prediction equation

Although Eq. 6-17, Eq. 6-18 and Eq. 6-19 can predict the corresponding environmental comfort level using environment physical parameters, there was still a certain gap between the predicted results and actual environment comfort. In addition, according to the analysis of Chapter 6.2, there existed a correlation between thermal comfort, visual comfort and acoustic comfort. When establishing the environmental comfort prediction equation, the physical parameters from all the environment aspects needed to be considered. Therefore, the prediction equation Eq. 6-17, Eq. 6-18 and Eq. 6-19 needed to be improved by adding the other environment physical parameters to make it more in line with the actual application environment.

6.3.1 Improvement of thermal prediction equation

In order to improve the prediction equation of thermal comfort, multiple linear regression analysis was conducted. The independent variables were the thermal comfort index, acoustic comfort index and visual comfort index obtained from Eq. 6-17, Eq. 6-18 and Eq. 6-19 under each environment condition. The dependent variable was the actual thermal comfort of the subjects. The regression results are shown in Table 6-8.

According to the regression results, the adjusted $R^2 = 0.882$ showed that the fitting effect of regression model was very good and can explain 88.2% of the variance of dependent. Variance analysis (ANOVA) showed that $p = 0.000 < 0.05$, indicating that there existed linear relationship between actual thermal comfort with thermal comfort index, acoustic comfort index and visual comfort index calculated from models. The t-test for regression coefficient showed that the significance value for coefficient of thermal comfort index, coefficient of acoustic comfort index and the constant were less than 0.05. This meant that thermal comfort index, visual comfort index and constant had a significant impact on predicting the actual thermal comfort. The p value for the coefficient of visual comfort index was 0.178, which was larger than 0.05. This showed that the influence of visual comfort index on predicting the actual thermal comfort was not significant.

According to the collinearity diagnosis, it can be seen that all three VIF values were less than 5, which proved that no collinear problem found for all three independent variables.

Table 6-8

Regression analysis results of thermal prediction equation

Goodness of Fit					
R	0.956	R Square	0.914	Adjusted R Square	0.882
ANOVA					
F	28.302	Sig.	0.000		

T-test for Coefficient				
	Coefficient	t	Sig	VIF
Constant	-31.209	-2.389	0.044	
Thermal Comfort Index	1.143	8.297	0.000	1.012
Visual Comfort Index	0.129	1.703	0.127	1.013
Acoustic Comfort Index	0.134	2.988	0.017	1.000

Residual Analysis					
Mean	6.18E-15	SD	0.853	Durbin-Watson	1.362

After the linear regression analysis, the Independence and normality of residual needed to be analyzed. In order to test the independence between residuals, Durbin-Watson test was used. The results showed that D-W value was 1.362, which fell into the region between 1 and 3. This indicated that the residuals were independent of each other. The normal distribution test results of residuals are shown in Fig. 6-4(A). The mean value of the residuals was 6.18×10^{-15} and the standard derivation was 0.853. Since the mean value was close to 0 and the standard derivation was close to 1, the residuals were regarded as normal distribution. Fig. 6-4(B) demonstrated the P-P diagram of normal distribution test for residuals. The figure showed that all the residual points were located on both sides of the straight line $y = x$, and no obvious dispersion appeared. This also indicated that all residual points were normally distributed with no obvious abnormal points.

Although visual comfort index had no significant contribution on predicting the actual comfort, it was retained in the improved thermal comfort equation in order to ensure the prediction accuracy. Therefore, the improved thermal comfort equation is listed in Eq.6-20. And the maximum value the improved thermal index was set as 100.

$$T_{index-improved} = 1.143 \times T_{index-ori} + 0.129 \times V_{index-ori} + 0.134 \times A_{index-ori} - 31.209$$

$$(Eq. 6-20)$$

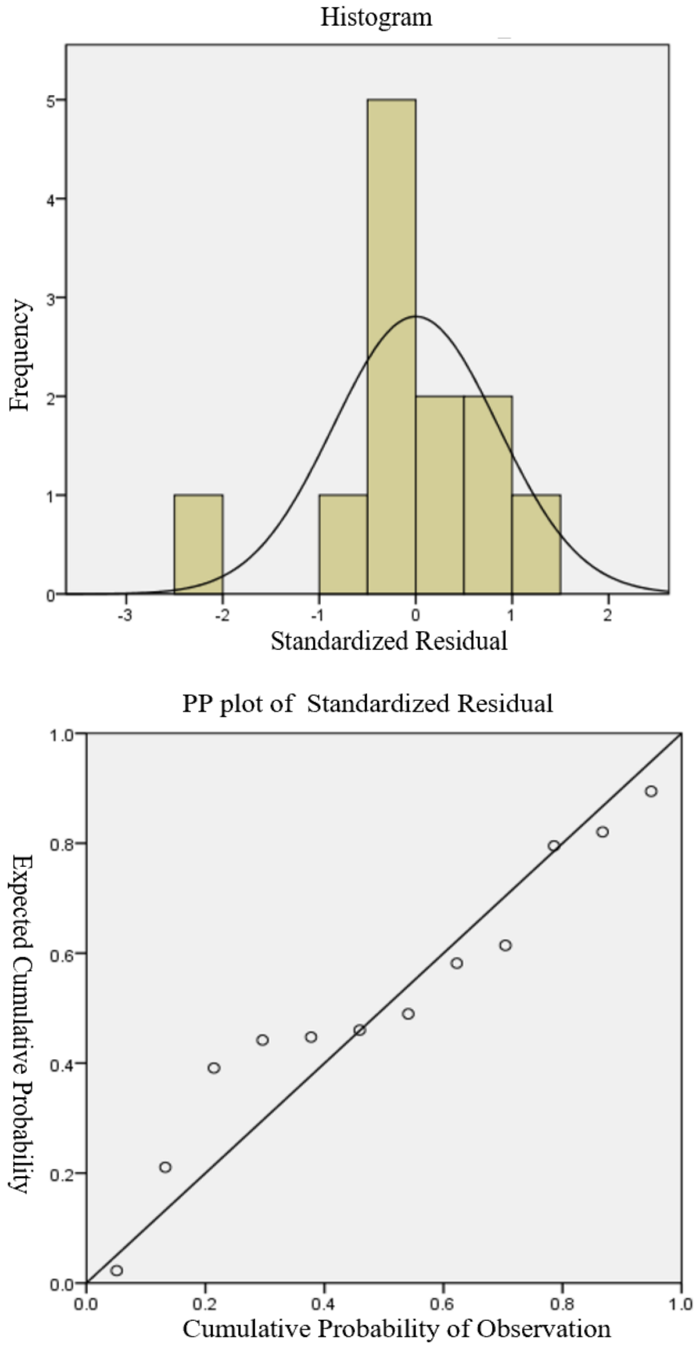


Fig. 6-4. (A) Histogram and normal distribution line of residuals and from thermal regression (B) P-P plot for standardized residual from thermal regression

Fig.6-5 demonstrated the scatter plot between the thermal comfort predicted using improved thermal comfort equation and the actual thermal comfort of the subjects under each environment condition. Through comparing the scatter plot with the straight line $y = x$, it can be found that all the points fell on both sides of the straight line, which indicated that the improved equation predicted thermal comfort well.

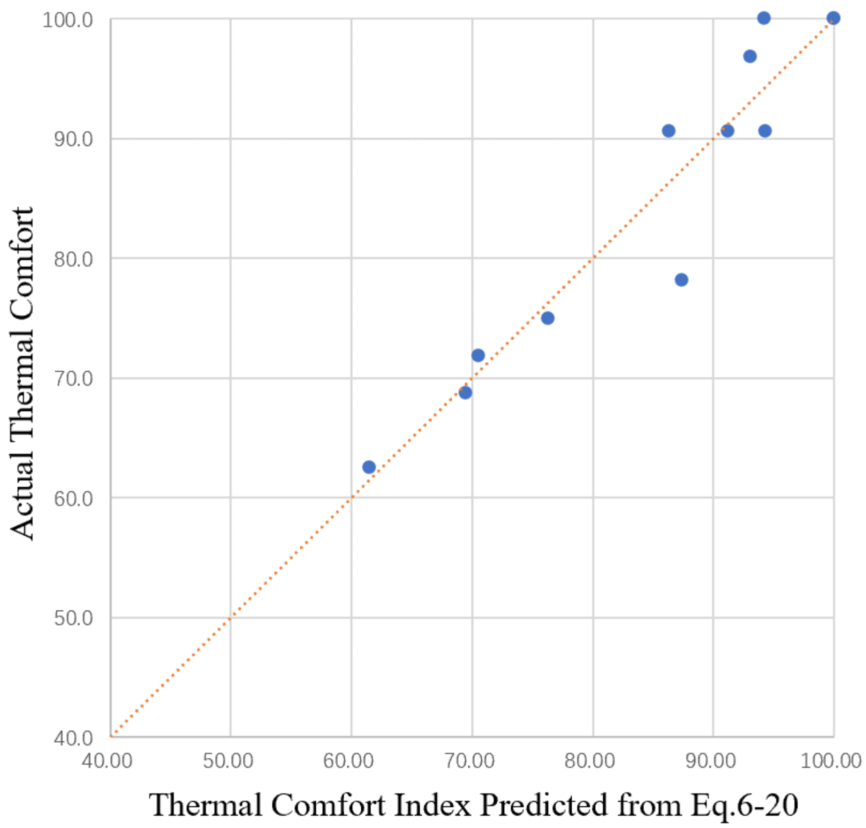


Fig. 6-5. Scatter plot between the thermal comfort predicted using improved thermal comfort equation and the actual thermal comfort

6.3.2 Improvement of acoustic prediction equation

Multiple linear regression analysis was conducted in order to improve the prediction equation of acoustic comfort. Same as Section 6.3.1, the independent variables were the thermal comfort index, acoustic comfort index and visual comfort index calculated from Eq. 6-17, Eq. 6-18 and Eq. 6-19. The dependent variable changed to the actual acoustic comfort of the subjects. Table 6-9 shows the relevant regression analysis results.

The resulted showed that the goodness of fit R = 0.990 and the adjusted R^2 = 0.974. This indicated that the fitting degree of regression model to the observed values was very high, and all the independent variables of the regression equation can explain 97.4% variance of actual acoustic comfort change. Variance analysis results showed that significance value was 0.000, which was less than 0.05. This further proved that the thermal comfort index, acoustic comfort index and visual comfort index can explain the actual acoustic comfort through linear fitting.

The t-test results of the regression coefficient showed only the coefficient of the acoustic comfort index had a significance value less than 0.05, which indicated that the acoustic comfort index played an important role when predicting the actual acoustic comfort. The t-test significance value of the coefficient of thermal comfort and visual comfort, as well as the constant were all greater than 0.05. This indicated that these two variables and constant had no statistical significance in predicting the actual acoustic comfort in the regression equation. The collinearity diagnosis results showed that no collinear problem existed among all three environmental comfort indexes, since the VIF values for all three indexes were less than 5.

Table 6-9

Regression analysis results of acoustic prediction equation

Goodness of Fit					
R	0.990	R Square	0.981	Adjusted R Square	0.974
ANOVA					
F	137.437	Sig.	0.000		
T-test for Coefficient					
		Coefficient	t	Sig	VIF
Constant		-28.914	-1.886	0.096	
Thermal Comfort Index		0.233	1.438	0.188	1.012
Visual Comfort Index		0.085	0.954	0.368	1.013
Acoustic Comfort Index		1.063	20.225	0.000	1.000
Residual Analysis					
Mean	3.10E-15	SD	0.853	Durbin-Watson	2.445

In order to verify the reliability of the regression model, it was necessary to analyze the independence and normality of the residuals. Durbin Watson test was used to test the independence between residuals. The results showed that the D-W value is 2.445, which was between 1 and 3. This indicated that the residuals were independent of each other. The normal distribution test results of residuals were shown in Fig.6-6(A). The mean value of residuals was 3.10×10^{-15}, which was close to 0. And the standard derivation was 0.853, which was close to 1. From the mean value and standard derivation of residuals, the residuals can be regarded as normally distributed. The P-P diagram in Fig. 6-6(B) can also be used for the normal distribution test of residuals. It can be seen from the figure that the residual values of 12 samples fell near the straight line $y = x$ without obvious abnormal points. This also indicated that all residual values were normally distributed.

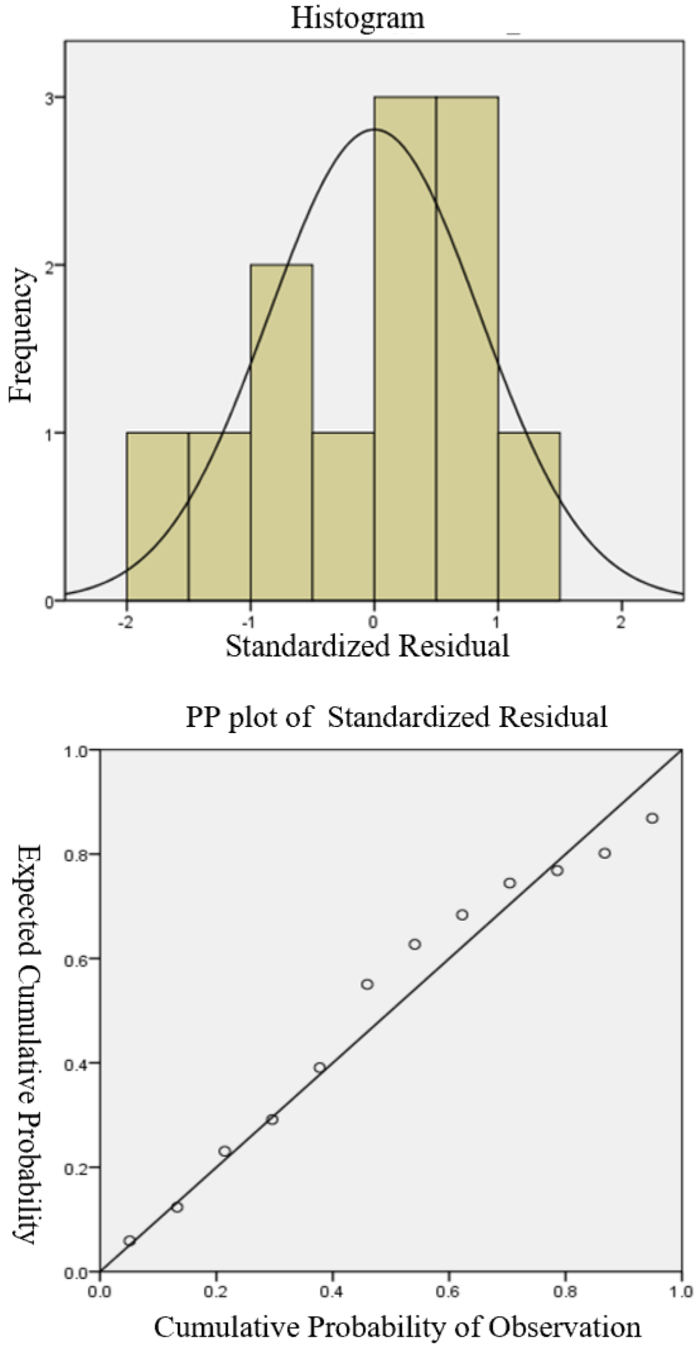


Fig. 6-6. (A) Histogram and normal distribution line of residuals from acoustic regression and (B) P-P plot for standardized residual from acoustic regression

For the improved acoustic comfort equation, the acoustic comfort index, thermal comfort index, visual comfort index and constant were considered in order to ensure the accuracy. The improved acoustic comfort equation is demonstrated in Eq. 6-21. And the maximum value the improved acoustic comfort index was set as 100.

$$A_{index-improved} = 1.063 \times A_{index-ori} + 0.233 \times T_{index-ori} + 0.085 \times V_{index-ori} - 28.914 \quad (Eq. 6-21)$$

Fig. 6-7 shows the scatter diagram between the improved acoustic comfort index calculated by the above equation and the actual acoustic comfort of the subjects under each environment condition. By comparing the scatter plot with the straight line $y = x$, it can be found that all points fall on both sides of the straight line, indicating well-fit of the improved acoustic equation.

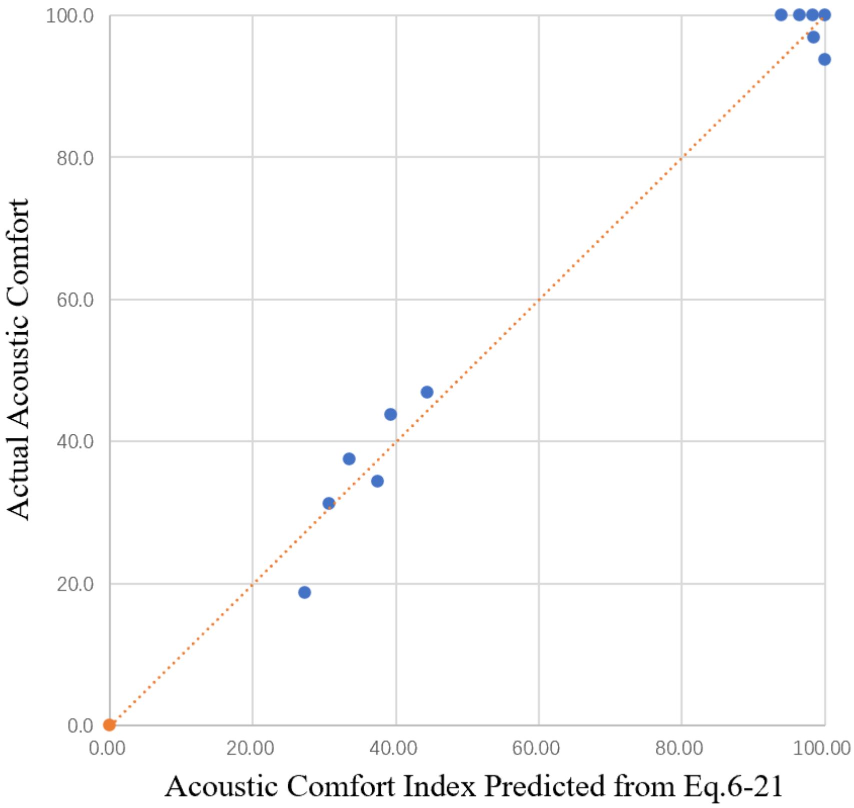


Fig. 6-7. Scatter plot between the acoustic comfort predicted using improved acoustic comfort equation and the actual acoustic comfort

6.3.3 Improvement of visual prediction equation

Similar to Section 6.3.1 and Section 6.3.2, in order to improve the visual comfort equation, multiple linear regression analysis was adopted in this section. The independent variables were still the thermal comfort index, acoustic comfort index and visual comfort index obtained from Eq. 6-17, Eq. 6-18 and Eq. 6-19. The dependent variable was the actual comfort of the subjects about the visual environment. The relevant regression analysis results are shown in Table 6-10.

According to the fitting results of the regression analysis, the goodness of fit R = 0.965, indicating that the improved regression model of visual comfort index had a high fitting degree to the observed values. Adjusted R^2 = 0.905 showed that thermal comfort index, acoustic comfort index and visual comfort index can explain the variance change of 90.5% of the actual visual comfort. The analysis of variance showed that significance value p = 0.000 < 0.05, which further proved that the actual visual comfort can be evaluated by linear fitting of thermal comfort index, acoustic comfort index and visual comfort index.

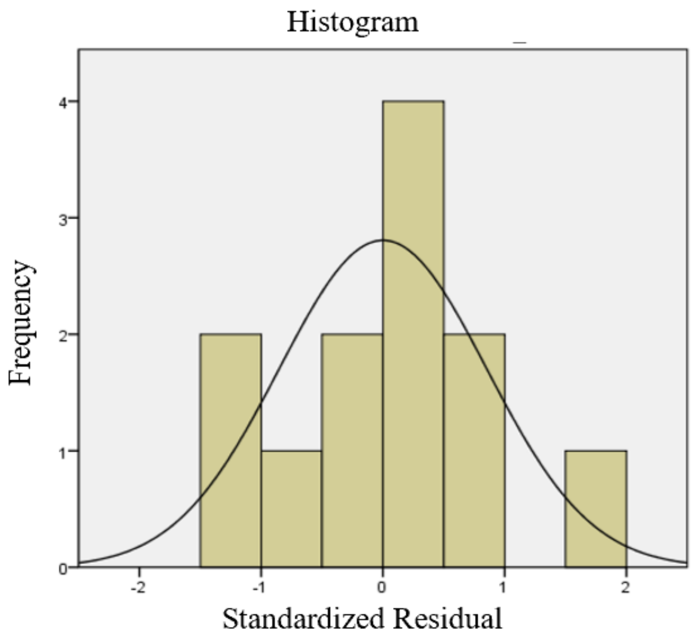
The t-test results of regression coefficients showed that the visual comfort index and acoustic comfort index had a significant impact on the prediction of actual visual comfort in the regression equation (t (11) = 9.690 with p = 0.000 < 0.05 and t (11) = 2.576 with p = 0.033 < 0.05). For the thermal comfort index, t (11) = 1.702, where the significance value equaled to 0.127, larger than 0.05, so the thermal comfort index had no statistical significance on the prediction of actual visual comfort in the regression equation. Similarly, the significance value of the constant was also greater than 0.05, which had no statistical significance on the prediction of actual visual comfort. The collinearity diagnosis results showed all VIF values of three comfort indexes were less than 0.05. This indicated that thermal comfort index, acoustic comfort index and visual comfort index did not have the problem of collinearity.

Table 6-10

Regression analysis results of visual prediction equation

Goodness of Fit					
R	0.965	R Square	0.931	Adjusted R Square	0.905
ANOVA					
F	35.829	Sig.	0.000		
T-test for Coefficient					
		Coefficient	t	Sig	VIF
Constant		-14.266	-1.012	0.341	
Thermal Comfort Index		0.253	1.702	0.127	1.012
Visual Comfort Index		0.793	9.690	0.000	1.013
Acoustic Comfort Index		0.124	2.576	0.033	1.000
Residual Analysis					
Mean	1.51E-15	SD	0.853	Durbin-Watson	1.698

After regression analysis between environmental comfort indexes and actual visual comfort, residuals analysis was conducted in order to verify the reliability of the regression model. Durbin Watson test was used to examine the independence between residuals, and the results showed that the D-W value was 1.698. Because the D-W value was in the region between 1 and 3, it indicated that the residuals were independent of each other.



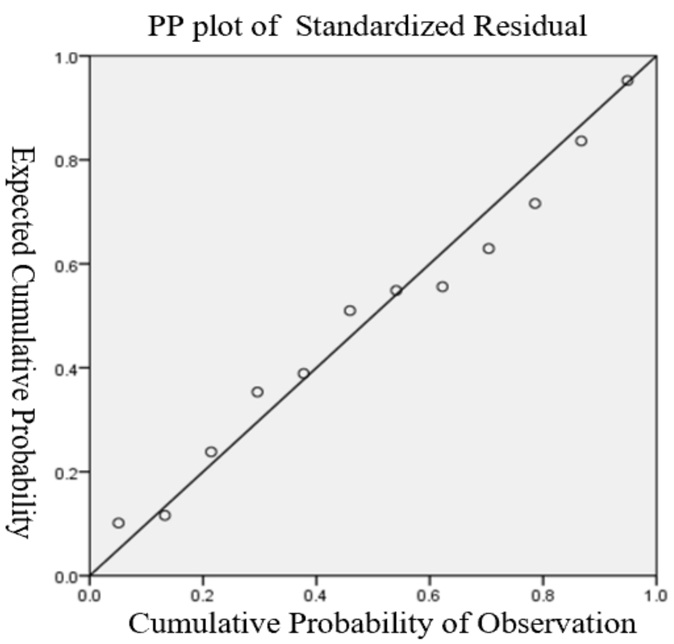


Fig. 6-8. (A) Histogram and normal distribution line of residuals from visual regression and (B) P-P plot for standardized residual from visual regression

The histogram of standardized residual in Fig. 6-8(A) and the P-P diagram of standardized residuals in Fig. 6-8(B) can be used to test whether the residuals obey the normal distribution. According to the results of histogram, the mean value of residuals was 1.51×10^{-15} and the standard deviation of residuals was 0.853. Since the mean value was close to 0, and the standard deviation was around 1, the residuals were judged as normally distributed. According to the P-P diagram, the residual values of 12 samples fell near the straight line $y = x$, and there were no obvious abnormal points, indicating that all residual values obeyed the normal distribution law.

Although the significance values of the coefficient of thermal comfort index and constant were greater than 0.05, in order to ensure the fitting accuracy, the thermal comfort index and constant were retained in the improved prediction equation of visual comfort. The improved prediction equation of visual comfort is demonstrated in Eq.6-22. In order to avoid the situation that visual comfort index was larger than 100, the max score for visual comfort index was set as 100.

$$V_{index-improved} = 0.793 \times V_{index-ori} + 0.124 \times A_{index-ori} + 0.253 \times T_{index-ori} - 14.266 \quad (Eq.6-22)$$

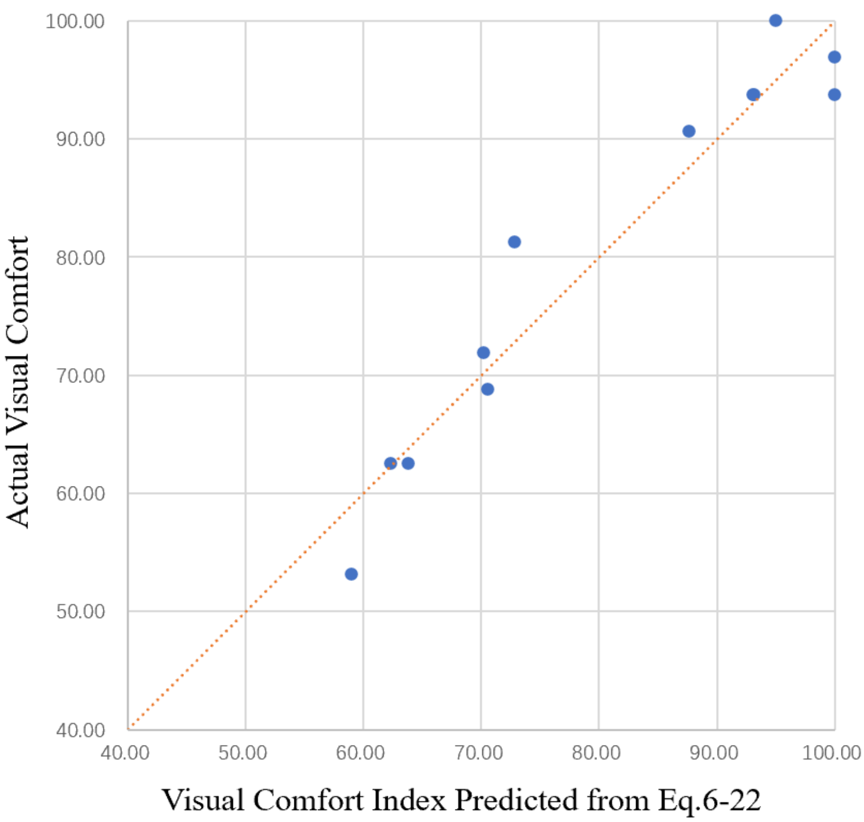


Fig. 6-9. Scatter plot between the visual comfort predicted using improved visual comfort equation and the actual visual comfort

According to the improved prediction equation of visual comfort, the improve visual comfort index in each environment condition was calculated. Taking the improve visual comfort index as the x-axis, and the actual visual comfort as the y-axis, a scatter diagram was plotted (Fig.6-9). By comparing the difference between the scatter plot and the straight line $y = x$, it was found that all points located on both sides of the straight line, which indicated that the improved prediction equation predicted visual comfort well.

6.3.4 Summary

Section 6.3.1, 6.3.2 and 6.3.3 improve the prediction equation for thermal comfort, acoustic comfort and visual comfort respectively. And the fitting degree of each environment equation with the actual environmental comfort had been examined. The improved equations for environmental comfort are summarized as the following:

$$T_{index-improved} = 1.143 \times T_{index-ori} + 0.129 \times V_{index-ori} + 0.134 \times A_{index-ori} - 31.209 \quad (Eq.6-20)$$

$$A_{index-improved} = 1.063 \times A_{index-ori} + 0.233 \times T_{index-ori} + 0.085 \times V_{index-ori} - 28.914 \quad (Eq.6-21)$$

$$V_{index-improved} = 0.793 \times V_{index-ori} + 0.124 \times A_{index-ori} + 0.253 \times T_{index-ori} - 14.266 \quad (Eq.6-22)$$

The improved thermal comfort index, improved acoustic comfort index and improved visual comfort index were treated as the bridge to analyze the relationship between environment physical parameters and research productivity.

Chapter VII

Relationship between environmental comfort index and research performance

Chapter 6 analyzed and compared the difference between the environment comfort indexes obtained from Wong's multivariate-logistic model, Ncube's model and Iordache's model with the actual environmental comfort of the participants. Based on the results from the comparison, the most appropriate prediction equation for each environment was selected. Due to the correlation among three environmental comforts and the facts that the three models were not specially developed for research facilities, the prediction equation of each environmental comfort was improved using multi variable linear regression analysis respectively.

The analysis of this chapter was based on the prediction equation of environmental comfort obtained in Chapter 6. Firstly, the factor analysis was used to calculate the weight of environmental comfort index. Based on the weight, the indoor environment quality equation was established. Secondly, nonlinear regression analysis was carried out, so as to establish the nonlinear equation between the indoor environment quality index and research performance index, which was named as performance prediction equation. Thirdly, through the series connection between performance prediction equation, indoor environment quality equation and improved prediction equation of environmental comfort, the relationship between research performance and environment physical parameters in research facilities was established. And this mathematical model was the main objective of this research.

7.1 Indoor environment quality equation

In order to calculate the weight of thermal comfort index, acoustic comfort index and visual comfort index in indoor environment quality equation, factor analysis was carried out. Since the calculated indexes of 12 different environment condition for 32 participants were used in the factor analysis, the total sample size $N = 32 \times 12 = 384$. Factor analysis required that the sample size need to be five times more than the number of variables and larger than 100. For the factor analysis of this experiment, three variables were analyzed. The sample size was 384, which was larger than

15 (five times the number of variables). The sample size was also larger than 100. Therefore, the sample size satisfied the requirements of factor analysis.

Factor analysis also required sample quality, where correlation must exist among the tested variables. According to the discussion in Chapter 6.2, there existed weak and positive correlation among thermal comfort, acoustic comfort and visual comfort. In this section, KMO and Bartlett were adopted to double check whether there existed correlation among the three environmental comfort indexes. According to Table 7-1, the KMO value was 0.572, which was greater than 0.5. And the significance value from Bartlett's test of sphericity was 0.000, which was less than 0.05. From the results of KMO and Bartlett's test, there existed a meaningful correlation among thermal comfort index, acoustic comfort index and visual comfort index. Therefore, the entire sample set met the sample quality requirement, and was appropriate for factor analysis.

Table 7-1

The results of KMO and Bartlett's test of sphericity

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.572
Bartlett's Test of Sphericity	Approx.Chi-Square	33.264
	df	3
	Sig.	0.000

From the communalities list, the extracted variance of all three variables were larger than 0.4, which indicated that it was acceptable to conduct factor analysis and majority information can be remained with acceptable loss. According to total variance explained list shown in Table 7-2, it can be found that only one initial eigenvalue was larger than 1. This demonstrated that there was only one common factor used to summarize all three environmental comfort indexes, which was the indoor environment quality index.

Table 7-2

The results of communalities list and total variance explained list

Communalities

	Initial	Extraction
Thermal Index	1.000	0.687
Visual Index	1.000	0.600
Acoustic Index	1.000	0.461

Extraction Method: Factor Analysis

Table 7-2 continue

The results of communalities list and total variance explained list

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	1.748	58.274	58.274	1.748	58.274	58.274
2	0.750	24.992	83.266			
3	0.502	16.734	100.000			

Extraction Method: Factor Analysis

Table 7-3

Results of component score, normalized component score and standardized component score

	Thermal Comfort Index	Visual Comfort Index	Acoustic Comfort Index	Length of Vector
Component Score	0.829	0.775	0.679	1.322
Normalized Component Score	0.627	0.586	0.513	1.726
Standardized Componet Score	0.363	0.339	0.297	

The component scores of the three environmental comfort indexes are shown in Table 7-3. In order to obtain the weight of the three environmental comfort indexes in indoor environment quality equation, it was necessary to normalize and standardize the component scores. The equations for normalization are shown in Eq. 7-1 and Eq. 7-2.

$$Normalized\ Component\ Score\ Vector = \frac{Component\ Score\ Vector}{Norm\ of\ Component\ Score\ Vector} \quad (Eq.7-1)$$

$$Norm\ of\ Component\ Score\ Vector = \sqrt{\sum Component\ Score^2} \quad (Eq.7-2)$$

Standardization was to unify the normalized component score so that the sum of the three normalized component score equaled to one. The results deduced after standardization are shown in Table 7-3. Therefore, the weight for thermal comfort index was 0.363, the weight for visual comfort index was 0.329 and the weight for acoustic comfort index was 0.297. And the equation to predict indoor environment quality was set as Eq.7-3.

$$IEQ\ Index = 0.363 \times T_{index-improved} + 0.339 \times V_{index-improved} + 0.297 \times A_{index-improved} \quad (Eq. 7-3)$$

From the weight results of environmental comfort index, it can be seen that, for research facilities, thermal comfort index contributed the most impact to the indoor environment quality, followed by visual comfort index. While the weight of the influence caused by acoustic comfort index on indoor environment quality was the smallest.

7.2 Relationship between indoor environment quality and research performance

In order to obtain the relationship between indoor environment quality and research performance, on the one hand, it was necessary to calculate the IEQ index of the participants under different environment conditions. For this experiment, the participants were divided into four experiment groups, each experiment group needed to experience 12 different environment conditions. For the same environment condition, the environment physical parameters experienced by different experiment groups were also different. Therefore, in total, $4 \times 12 = 48$ sets of different environment physical parameters needed to be considered when calculating the IEQ index. For each experiment group, under each environment condition, the thermal comfort index, acoustic comfort index and visual comfort index were calculated through bringing the corresponding set of environment physical parameters into Eq. 6-20, Eq. 6-21 and Eq. 6-22. Afterwards, based on the calculated thermal comfort index, acoustic comfort index and visual comfort index, the IEQ index was obtained for this experiment group under this environment condition using Eq.7-3. The relevant results are shown in Table 7-4.

On the other hand, it was also necessary to calculate the performance index of the participants. Corresponding to the calculation of IEQ index, the experiment group was treated as the base unit when calculating performance index. For one experiment group, under each environment condition, the personal performance index of eight participants in this group should be arithmetically averaged to obtain the average performance index of this experiment group under this environment condition. The corresponding results are shown in Table 7-4.

Table7-4

Results of thermal comfort index, visual comfort index, acoustic comfort index, IEQ index and performance index for each experiment group under 12 environment conditions

	Environment Condition	Thermal Comfort Index	Visual Comfort Index	Acoustic Comfort Index	IEQ Index	Performance Index
Experiment Group 1	A (21°C+Dark+Quiet)	96.46	83.80	96.48	92.08	69.87
	B (21°C+Dark+Noisy)	85.80	71.82	42.78	68.20	63.52
	C (21°C+Bright+Quiet)	100.00	100.00	100.00	99.90	72.19
	D (21°C+Bright+Noisy)	87.99	92.31	43.09	76.03	68.18
	E (24°C+Dark+Quiet)	95.55	69.59	99.00	87.68	67.06
	F (24°C+Dark+Noisy)	88.05	56.38	35.85	61.72	61.41
	G (24°C+Bright+Quiet)	100.00	99.73	95.09	98.35	70.64
	H (24°C+Bright+Noisy)	90.48	93.01	45.20	77.80	66.68
	I (27°C+Dark+Quiet)	66.16	63.98	94.56	73.79	66.39
	J (27°C+Dark+Noisy)	62.49	63.29	28.56	52.62	61.85
	K (27°C+Bright+Quiet)	72.34	94.19	97.85	87.25	69.69
	L (27°C+Bright+Noisy)	74.69	87.99	25.34	64.47	63.79
Experiment Group 2	A (21°C+Dark+Quiet)	90.33	66.75	94.56	83.50	71.07
	B (21°C+Dark+Noisy)	89.10	66.49	30.59	63.97	64.18
	C (21°C+Bright+Quiet)	96.41	98.71	94.05	96.39	73.38
	D (21°C+Bright+Noisy)	92.53	93.29	43.70	78.19	68.67
	E (24°C+Dark+Quiet)	91.84	64.61	100.00	84.94	69.22
	F (24°C+Dark+Noisy)	86.81	71.83	42.04	68.35	63.48
	G (24°C+Bright+Quiet)	100.00	99.26	90.99	96.97	70.98
	H (24°C+Bright+Noisy)	92.33	92.26	32.93	74.57	66.53
	I (27°C+Dark+Quiet)	73.63	62.31	85.85	73.35	65.41
	J (27°C+Dark+Noisy)	63.25	58.02	33.55	52.60	62.89
	K (27°C+Bright+Quiet)	71.33	93.21	89.51	84.08	72.08
	L (27°C+Bright+Noisy)	65.68	86.93	33.72	63.32	63.15
Experiment Group 3	A (21°C+Dark+Quiet)	95.25	73.10	100.00	89.06	70.36
	B (21°C+Dark+Noisy)	85.04	68.16	30.52	63.04	64.43
	C (21°C+Bright+Quiet)	100.00	100.00	100.00	99.90	70.93
	D (21°C+Bright+Noisy)	92.38	93.15	42.53	77.75	66.33
	E (24°C+Dark+Quiet)	91.71	72.60	88.52	84.19	67.44
	F (24°C+Dark+Noisy)	83.96	55.73	39.11	60.98	62.54
	G (24°C+Bright+Quiet)	99.10	100.00	100.00	99.57	70.99
	H (24°C+Bright+Noisy)	95.33	93.45	39.24	77.94	66.85
	I (27°C+Dark+Quiet)	72.91	62.66	99.33	77.21	65.11
	J (27°C+Dark+Noisy)	56.24	55.41	21.90	45.70	63.24
	K (27°C+Bright+Quiet)	81.96	96.66	100.00	92.22	69.85
	L (27°C+Bright+Noisy)	64.91	86.19	27.39	60.92	64.02

Table7-4 continue

Results of thermal comfort index, visual comfort index, acoustic comfort index, IEQ index and performance index for each experiment group under 12 environment conditions

	Environment Condition	Thermal Comfort Index	Visual Comfort Index	Acoustic Comfort Index	IEQ Index	Performance Index
Experiment Group 4	A (21°C+Dark+Quiet)	94.74	67.83	93.82	85.25	70.72
	B (21°C+Dark+Noisy)	90.32	74.35	30.38	67.01	63.92
	C (21°C+Bright+Quiet)	100.00	100.00	100.00	99.90	71.16
	D (21°C+Bright+Noisy)	93.06	93.80	48.11	79.87	65.69
	E (24°C+Dark+Quiet)	97.07	75.65	100.00	90.58	67.78
	F (24°C+Dark+Noisy)	87.00	65.39	32.79	63.48	62.50
	G (24°C+Bright+Quiet)	100.00	100.00	100.00	99.90	69.32
	H (24°C+Bright+Noisy)	95.37	93.49	39.62	78.08	65.80
	I (27°C+Dark+Quiet)	64.55	66.43	96.15	74.50	64.23
	J (27°C+Dark+Noisy)	64.80	59.46	25.40	51.23	63.53
	K (27°C+Bright+Quiet)	79.57	96.06	100.00	91.15	68.92
	L (27°C+Bright+Noisy)	78.24	89.70	36.18	69.55	64.21

After obtaining the IEQ index and the corresponding average performance index of each experiment group under each environment condition, the nonlinear regression analysis was adopted to obtain the performance prediction equation. In the nonlinear regression analysis, IEQ index was the independent variable and average performance index was the dependent variable. The total sample size was equal to the product of number of environment conditions and number of experiment groups, which was calculated as 48.

7.2.1 Curvilinear regression

Because it was not clear which nonlinear model can best fit the relationship between IEQ index and average performance index. One linear fitting models and nine nonlinear fitting models should be tested using curvilinear regression in this experiment with the help of SPSS. The relevant results are summarized in Table 7-5 and figure plot of ten fitting models are in Fig. 7-1. According to variance analysis results, the significance value of all ten fitting methods were all less than 0.05. This indicated that all ten fitting models can well explain relationship between IEQ index and average performance index.

In order to compare the goodness of fit of ten regression models, R^2 of each regression model was calculated. The results showed that the R^2 of quadratic regression model and cubic regression model were the largest among all ten models, both R^2 were 0.813. It needed further analysis to examine which regression model can best predict performance index.

Table 7-5

Summary of regression results of ten fitting models

Model Summary and Estimated Value

Equation	Model Summary					Estimated Value			
	R square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	0.804	188.831	1	46	0.000	51.318	0.200		
Logarithmic	0.771	155.101	1	46	0.000	4.001	14.508		
Inverse	0.713	114.164	1	46	0.000	80.086	-986.888		
Quadratic	0.813	97.647	2	45	0.000	58.862	-0.004	0.001	
Cubic	0.813	98.041	2	45	0.000	57.954	0.000	0.002	-3.32E-06
Compound	0.808	194.143	1	46	0.000	52.931	1.003		
Power	0.777	160.569	1	46	0.000	26.055	0.217		
S Curve	0.720	118.373	1	46	0.000	4.400	-14.795		
Growth	0.808	194.143	1	46	0.000	3.969	0.003		
Exponential	0.808	194.143	1	46	0.000	52.931	0.003		

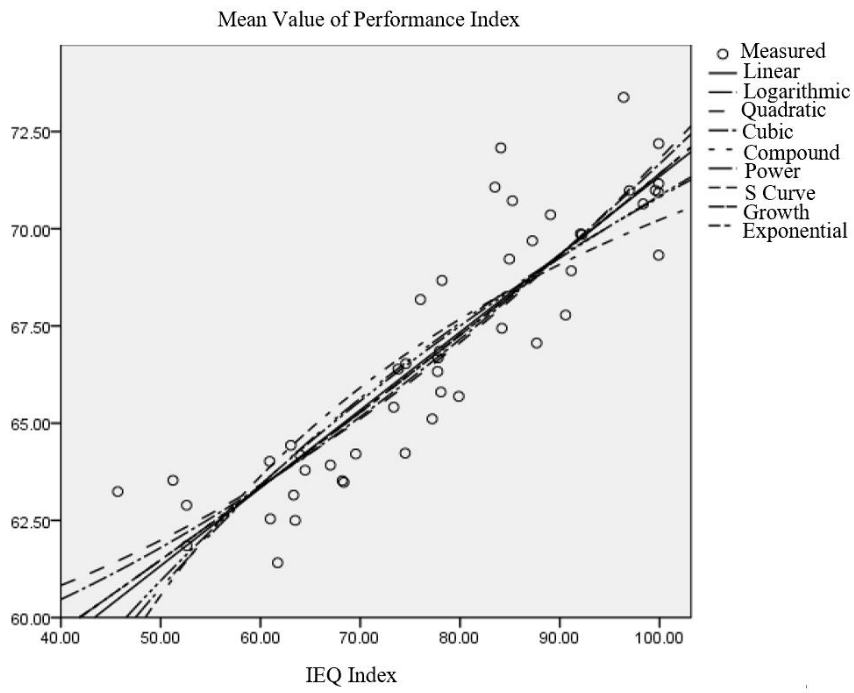


Fig. 7-1. Regression plot of ten fitting models

When conducting the nonlinear regression analysis using curvilinear regression function in SPSS, the nonlinear fitting model needs to be linear processed first. After the linear processing, the linearized fitting model is solved by the least square method. Because of the linearization processing, the accuracy of fitting using curvilinear regression declines. However, for the actual nonlinear regression, the nonlinear fitting model uses Gauss-Newton method to estimate the variables. Afterwards, the expected function is expanded using Taylor series and the coefficient of independent variable is solved iteratively. Therefore, quadratic regression analysis and cubic regression analysis needs to be conducted respectively.

7.2.2 Quadratic regression

According to the results of quadratic regression analysis, after four iterations, the sum of squares due to error had reached the minimum value 94.495. Because the difference between consecutive sum of squares due to error was reduced to the level of 10^{-8}, the iteration was terminated. At this time, the optimal solution for quadratic regression was found. The coefficient of quadratic term was 0.001337, coefficient of linear term was -0.004304 and constant term was 58.8621. The results are shown in Table 7-6. The results of variance analysis of quadratic regression are shown in Table 7-7. The R^2 was 0.813, which showed that the quadratic regression equation can explain 81.3% of the variance of performance index.

Table 7-6

Iteration results of quadratic regression analysis

Iteration History

Iteration Number	Sum of Residual Square	Coefficient		
		a	b	c
1.0	2141352261	1.000	1.000	1.000
1.1	94.495	0.001	-0.004	58.862
2.0	94.495	0.001	-0.004	58.862
2.1	94.495	0.001	-0.004	58.862

Table 7-7

Variance analysis of quadratic regression

ANOVA

Source	Sum of Square	df	Mean Square
Regression	215370.519	3	71790.173
Residual	94.495	45	2.1000
Total Uncorrected	215465.014	48	
Total Corrected	504.590	47	

R square = 1 - sum of square of residual / total corrected = 0.813

Residuals should be analyzed in order to verify the reliability of the quadratic regression model. The normal distribution test results of residuals are shown in Fig. 7-2 (A). The mean value of residuals was 1.01×10^{-10}, and the standard deviation was 1.418. Since the mean value was close to 0 and the standard derivation was close to 1, the residuals were regarded as normal distribution. Fig 7-2(B) demonstrated the P-P diagram of normal distribution test for residuals. The figure showed that all the residual points were located on both sides of the straight line $y = x$, and no obvious dispersion appeared. This also indicated that all residual points were normally distributed with no obvious abnormal points.

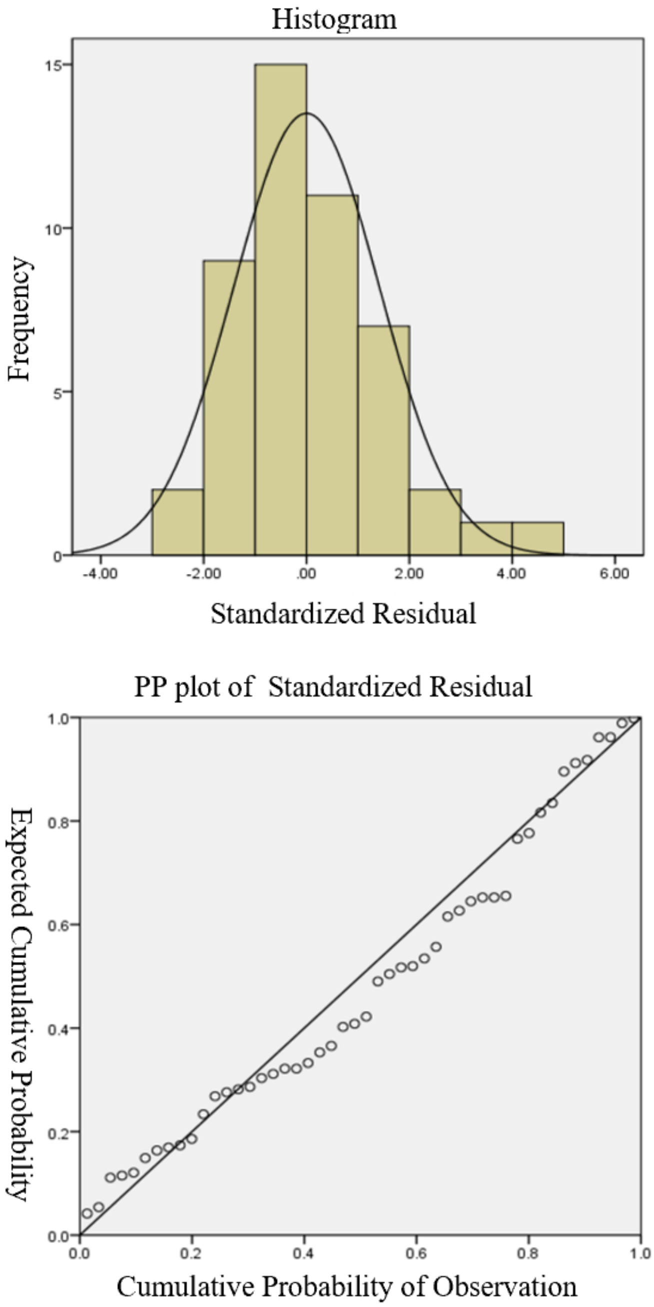


Fig. 7-2. (A) Histogram and normal distribution line of residuals from quadratic regression and (B) P-P plot for standardized residual from quadratic regression

7.2.3 Cubic regression

The cubic regression results are shown in Table 7-8. After five iterations, the sum of squares due to error converged to minimum value of 94.495. The difference between consecutive sum of squares due to error was reduced to the level of 10^{-8}, therefore, the iteration was terminated and the optimum solution was obtained. The coefficient of cubic term was -1.923×10^{-4}, coefficient of quadratic term was 0.0446, coefficient of linear term was -3.161 and constant term was 133.290. Table 7-9 showed the variance analysis of cubic regression, where $R^2 = 0.851$. This indicated that the cubic regression equation can explain 85.1% of the variance of performance index.

Table 7-8

Iteration results of cubic regression analysis

Iteration History

Iteration Number	Sum of Residual Square	Coefficient			
		a	b	c	d
1.0	1.683E+13	1.000	1.000	1.000	1.000
1.1	75.084	0.000	0.045	-3.172	133.535
2.0	75.084	0.000	0.045	-3.172	133.535
2.1	75.083	0.000	0.045	-3.161	133.290
3.0	75.083	0.000	0.045	-3.161	133.290

Table 7-9

Variance analysis of cubic regression

ANOVA

Source	Sum of Square	df	Mean Square
Regression	215389.931	4	53847.483
Residual	75.083	44	1.706
Total Uncorrected	215465.014	48	
Total Corrected	504.590	47	

R square = 1 - sum of square of residual / total corrected = 0.851

After the nonlinear regression between IEQ index and average performance index using cubic fitting model, residuals analysis was conducted in order to verify the reliability of the regression model. The histogram of standardized residual in Fig. 7-3(A) and the P-P diagram of standardized residuals in Fig. 7-3(B) can be used to test whether the residuals obey the normal distribution. According to the results of histogram, the mean value of residuals was -1.29×10^{-9} and the standard deviation of residuals was 1.264. Since the mean value was close to 0, and the standard deviation was around 1, the residuals were judged as normally distributed. According to the P-P diagram, the residual values of 48 samples were located near the straight line $y = x$, and there were no obvious abnormal points, indicating that all residual values obeyed the normal distribution law.

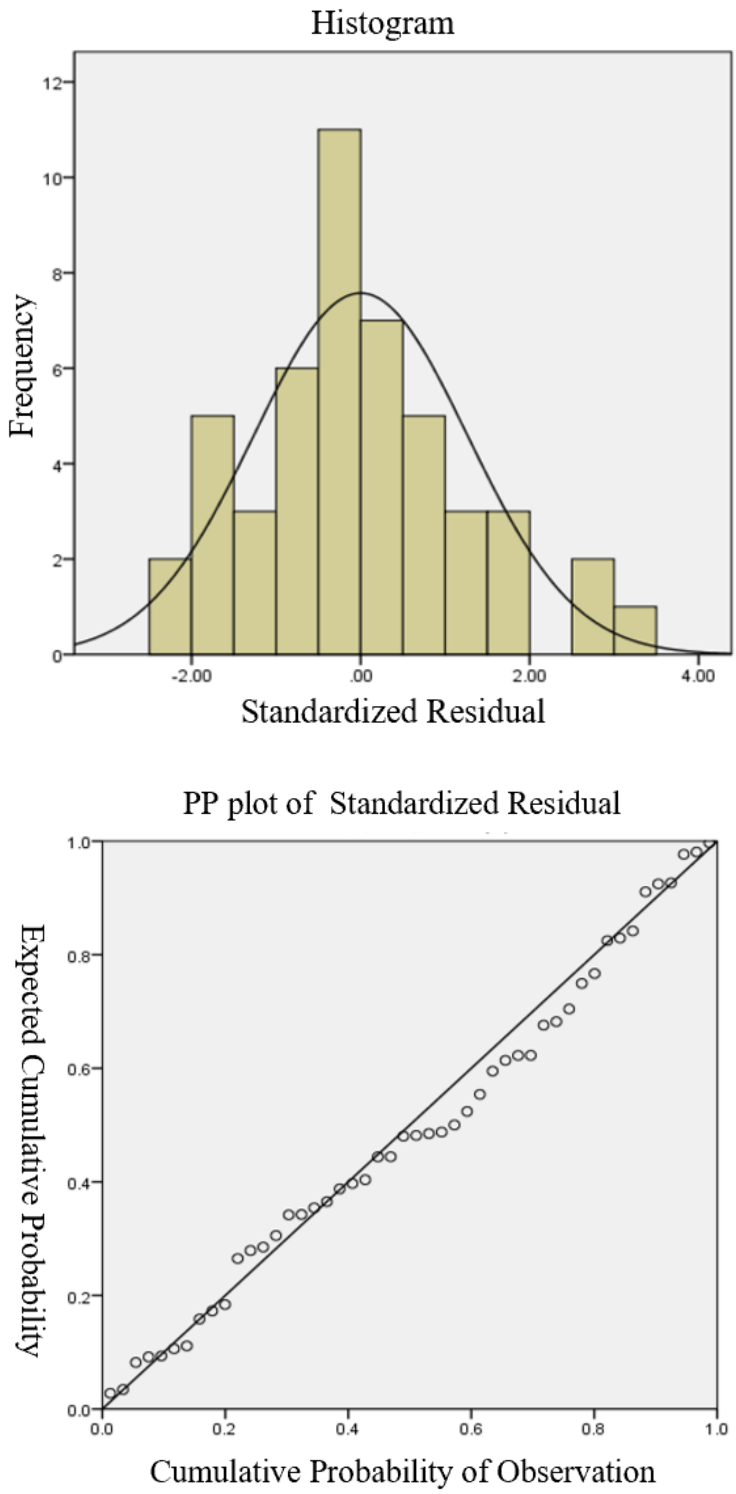


Fig. 7-3. (A) Histogram and normal distribution line of residuals from cubic regression and (B) P-P plot for standardized residual from cubic regression

7.2.4 Performance prediction equation

Through comparing the R^2 value between quadratic regression model (R^2 = 0.813) and cubic regression model (R^2 = 0.851), it can be seen that the fitting degree for cubic regression model was much better than that for quadratic regression model. Therefore, cubic regression model was adopted to obtain the relationship between performance index and IEQ index in this research. The performance prediction equation was set as Eq. 7-4.

$$PI = -1.923 \times 10^{-4} \times IEQ_{Index}^3 + 0.0446 \times IEQ_{Index}^2 - 3.161 \times IEQ_{Index} + 133.290 \quad (Eq.7-4)$$

Fig. 7-4 showed the scatter diagram of PI-IEQ, in which the X-coordinate of the scatter plot was the IEQ index of each experiment group under each environment condition, and the Y-coordinate was the average performance index of the corresponding group. The dotted line in the figure is the cubic regression curve based on Eq. 7-4. It can be seen from the figure that all points located on both sides of the cubic regression curve, and the cubic regression curve was consistent with the trend of scattered points. In addition, there was no obvious abnormal point in the figure. Therefore, the cubic regression curve can well predict the performance index using IEQ index.

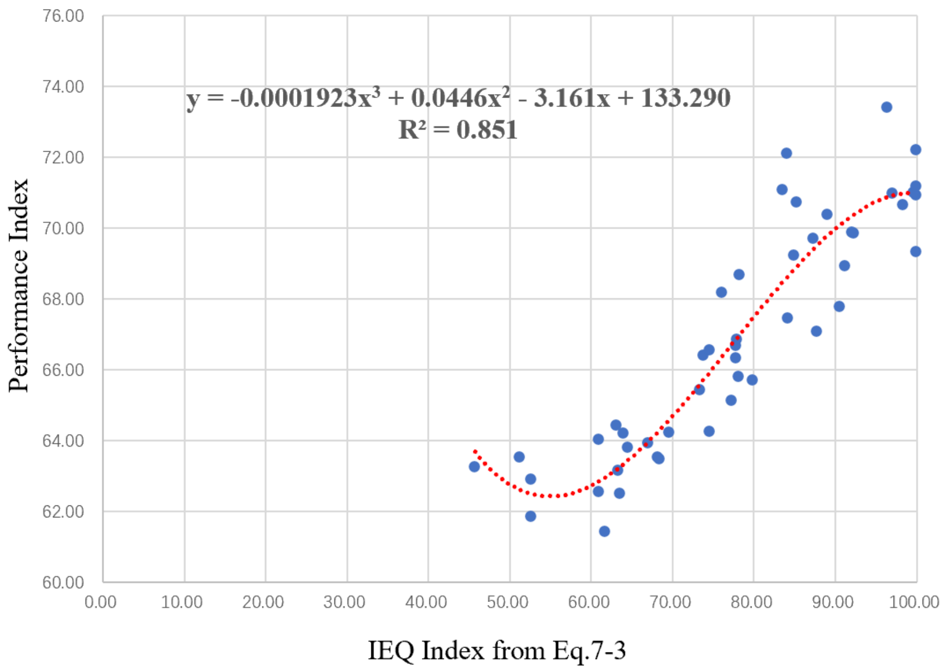


Fig.7-4. Scatter diagram of PI-IEQ and cubic regression curve of performance prediction equation

Eq.7-5 was the derivative function of performance prediction equation, and it was used to judge the increase and decrease trend between performance index and IEQ index. The characteristic roots of the derivative function were 55.0 and 99.6. Fig.7-5 showed the curve of the derivative function. It can be seen from the figure that when the indoor IEQ index increased from 55.0 to 99.6, the researcher's research performance gradually increased from 62.46 to 77.99. This was in line with the expected influence of indoor environment quality on research performance in a comfortable environment zone. When the IEQ index was between 99.6 and 100, the researchers' research performance decreased by 0.002, which was very small and negligible. It was expected that when the IEQ index reached maximum score (100), the researcher's research performance should also reach the best. There were slight differences with the actual situation, which was caused by the regression accuracy. When the IEQ index fell below 55.0, the derivative value is negative. Within this range, the researcher's research performance decreased with the increase of IEQ index, and the minimum value was 62.46. Because the IEQ index was already in the uncomfortable range at this time, the reason why performance index decreased with the increase of IEQ needed to be explored in future experiments.

$$Derivative\ Function\ PI' = -5.769 \times 10^{-4} \times IEQ_{Index}^{2} + 0.0892 \times IEQ_{Index} - 3.161 \quad (Eq.7-5)$$

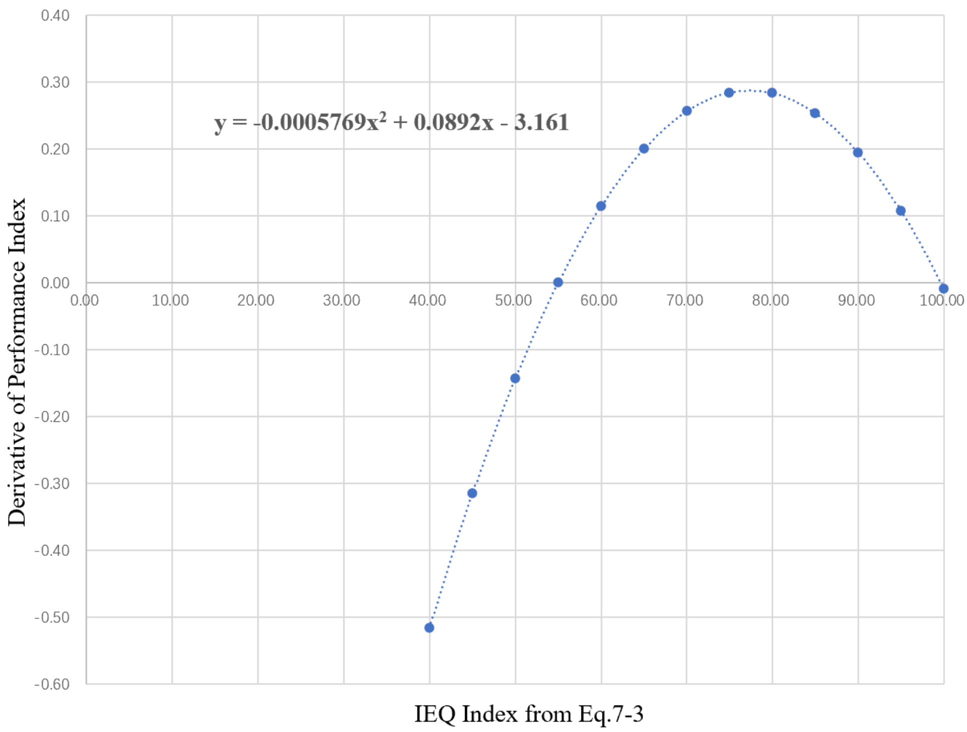


Fig.7-5. Derivative of performance prediction equation

Chapter VIII

Conclusion and Future Work

8.1 Conclusion

8.1.1 Answer for main objective

In order to solve the main objective, this experiment developed a mathematical model between indoor environment physical parameters and researchers' research performance. The model is summarized as the following:

$$Thermal\ Comfort\ Index: T_{index-ori} = 100 - PPD$$

$$Acoustic\ Comfort\ Index: A_{index-ori} = 100 - PD_{ACc}$$

$$where\ PD_{ACc} = 2 \times (Actual_{SoundPressureLevel} - Design_{SoundPressureLevel})$$

$$Visual\ Comfort\ Index: \quad V_{index-ori} = 0.33E_{av}$$

Improved Thermal Comfort Index:

$$T_{index-improved} = 1.143 \times T_{index-ori} + 0.129 \times V_{index-ori} + 0.134 \times A_{index-ori} - 31.209$$

Improved Acoustic Comfort Index:

$$A_{index-improved} = 1.063 \times A_{index-ori} + 0.233 \times T_{index-ori} + 0.085 \times V_{index-ori} - 28.914$$

Improved Visual Comfort Index:

$$V_{index-improved} = 0.793 \times V_{index-ori} + 0.124 \times A_{index-ori} + 0.253 \times T_{index-ori} - 14.266$$

Indoor Environment Quality Index:

$$IEQ_{index} = 0.363 \times T_{index-improved} + 0.339 \times V_{index-improved} + 0.297 \times A_{index-improved}$$

Performance Index:

$$PI = -1.923 \times 10^{-4} \times IEQ_{Index}^3 + 0.0446 \times IEQ_{Index}^2 - 3.161 \times IEQ_{Index} + 133.290$$

In the model, the relevant parameters are explained as follows:

1. PPD is calculated using indoor air temperature(°C) and relative humidity(%) according to Fanger's thermal comfort prediction model.

2. $Actual_{SoundPressureLevel}$ is the measured average background noise intensity(dB(A)) and $Design_{SoundPressureLevel}$ is set to 40dB(A) for research institution.

3. E_{av} is the average illuminance level (lux) of the measured point.

8.1.2 Answer to Sub objective 1

From Chapter 3 to Chapter 5, this experiment discussed the influence mechanism of thermal environment, acoustic environment and visual environment on environmental perceptions and satisfactions, respectively.

For thermal environment, with the increase of temperature from 21℃ to 24℃, the thermal perception changes from slightly cool to slightly warm, and the thermal satisfaction also improves. When the temperature continues to increase from 24℃ to 27℃, the participants start to feel hot, and the thermal satisfaction start to deteriorate. The tendency of actual comfort is a parabolic curve, where the optimal point is within the range between 22℃ and 23℃.

As for the influence of thermal environment on environmental perception and satisfaction other than thermal aspects, the result can be concluded that the thermal environment has no significant effect on acoustic perception and satisfaction. Thermal environment also has no effect on visual satisfaction, but for bright and noisy condition, when the temperature increases from 24℃ to 27℃, participants feel brighter about visual environment of the office.

For visual environment, with the increase of illuminance level from 200lux to 500lux, the participants' visual perception changes from dark level to bright level, and the satisfaction about visual environment improves about two level. Under the temperature condition of 24℃, with the increase of illuminance level, the participants feel warmer and the thermal satisfaction score of subjects increased significantly. As for the influence of visual environment on acoustic satisfaction, only for the 27℃ condition, the satisfaction about acoustic environment improves with the improvement of visual environment.

For acoustic environment, when the average background noise intensity changes from 45dB(A) to 70dB(A), the participants' feeling about acoustic environment decreases from quiet level to noisy level. And the satisfaction about acoustic environment also decreases about two levels from slightly satisfied to dissatisfied. As for the influence of acoustic environment on thermal perception, only for 21℃ dark and 24℃ dark condition, the participants feel hotter when the acoustic environment changes from 45dB(A) to 70dB(A).

8.1.3 Answer to Sub objective 2

From Chapter 3 to Chapter 5, this experiment discussed the influence mechanism of thermal environment, acoustic environment and visual environment on researchers' research performance, respectively.

For all three environment aspects, there is no significant influence of environment on the answering accuracy of performance test. However, with the deterioration of the environment, the response time has increased significantly. Because the research performance is calculated using equation where answering accuracy and reciprocal of response time of performance test share the same weight, and according to the influence tendency of indoor environment on answering accuracy and response time, the research performance has decreased significantly with the deterioration of the environment.

8.1.4 Answer to Sub objective 3

According to the results from Chapter 6, there exists positive and weak correlation among thermal, visual and acoustic comfort. Even though the correlation level is weak, when establishing the prediction equation of a single environmental comfort index, it was necessary to consider not only the corresponding environment physical parameters, but also the influence of other environment physical parameters.

8.1.5 Answer to Sub objective 4

Chapter 7.1 discussed the weight of the thermal comfort, visual comfort and acoustic comfort in predicting the indoor environment quality for research institution. Through normalization and standardization, thermal comfort contributes the most impact to the indoor environment quality

(0.363), followed by the visual comfort (0.329), while the weight of the influence caused by acoustic comfort on indoor environment quality is the smallest (0.297).

8.2 Limitation and Future Work

8.2.1 Amount of environment conditions

In this experiment, three different temperature, two different illuminance levels and two different background noise levels were tested. In total, 12 different environment combinations were considered. However, the value range of each environment variable is not enough to quantitatively analyze the impact trend of each environmental variable on the research performance. At the same time, extreme indoor environment conditions are not considered. Although the possibility of appearance of extreme indoor environment is very small, the probability is not zero.

Therefore, in the subsequent research, it is necessary to increase the value range and reduce the value interval of each environmental variable, so as to quantitatively analyze the impact trend of each environmental variable on the research performance, as well as the impact of extreme environment conditions on research performance.

Recommended value range and interval for different environmental variables:

(1) Temperature: 20℃, 22℃, 24℃, 26℃, 28℃, 30℃

(2) Illuminance level: 50lux, 200lux, 500lux, 1000lux

(3) Background noise intensity: 45dB(A), 60dB(A), 70dB(A)

8.2.2 Short-term stimulation

In this experiment, each environmental condition was carried out for 90 minutes. However, several researches reported that the effects of occupants' performance could be highly motivated during short-term test and it was difficult to reflect the actual occupants' performance [102].

Therefore, in the subsequent research, it is necessary to increase the duration of each environment condition. The recommended duration of each environment condition is 4 hours or 8 hours.

8.2.3 Performance test type

In this experiment, calculation performance test was used to evaluate researchers' scientific research performance. But for research activities, it needs not only computational ability, but also logical thinking, creative ability and language ability. Therefore, it is not enough to evaluate scientific research performance only by the calculation performance test.

Therefore, in future experiments, other performance tests need to be designed to evaluate logical thinking, creativity and language ability. In this way, the scientific research level can be evaluated more accurately together with the calculation performance test

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Appendix 6-1

This appendix demonstrated the calculation steps for Fanger's PPD. The predicted percentage dissatisfied (PPD) in Fanger's model is calculated as follows:

$$PPD = 100 - 95 \times \exp(-0.03553 \times PMV^4 + 0.2179 \times PMV^2) \quad -2 \le PMV \le 2$$

Predicted Mean Votes (PMV) is:

$$\begin{aligned} PMV = {} & \left[0.303 \times \exp\left(-0.036 \times \frac{M}{A_{Du}} + 0.028\right)\right] \\ & \times \left\{\left(\frac{M}{A_{Du}} - E_W\right) - 3.05 \times 10^{-3} \times \left[5733 - 6.99 \times \left(\frac{M}{A_{Du}} - E_W\right) - p_a\right]\right. \\ & - 0.42 \times \left[\left(\frac{M}{A_{Du}} - E_W\right) - 58.15\right] - 1.7 \times 10^{-5} \times \frac{M}{A_{Du}} \times (5867 - p_a) \\ & - 0.0014 \times \frac{M}{A_{Du}} \times (34 - T_a) \\ & \left. - 3.96 \times 10^{-8} \times f_{cl} \times [(T_{cl} + 273)^4 - (T_{mrt} + 273)^4] - f_{cl} \times h_{conv} \times (T_{cl} - T_a)\right\} \end{aligned}$$

The surface temperature of clothing T_{cl} (°C) is:

$$\begin{aligned} T_{cl} = {} & 35.7 - 0.028 \times \left(\frac{M}{A_{Du}} - E_W\right) \\ & - I_{cr}\{3.96 \times 10^{-8} \times f_{cl} \times [(T_{cl} + 273)^4 - (T_{mrt} + 273)^4] + f_{cl} \times h_{conv} \times (T_{cl} \\ & - T_a)\} \end{aligned}$$

The convective heat transfer coefficient h_{conv} $(W \times m^{-2} \times °C)$ is:

$$h_{conv} = max\begin{Bmatrix} 2.38 \times (T_{cl} - T_a)^{0.25} \\ 12.1 \times \sqrt{U_{ar}} \end{Bmatrix}$$

The ratio of clothed surface area to nude surface area of occupant f_{cl} is:

$$f_{cl} = f(x) = \begin{cases} 1.00 + \dfrac{1.290}{I_{cr}}, & I_{cr} \le 0.078 \\ 1.05 + 0.645 \times I_{cr}, & I_{cr} > 0.078 \end{cases}$$

$A_{Du}(m^2)$ is the surface area of occupant

E_W $(W \times m^{-2})$ is the external work by activity of occupant

$I_{cr}(W^{-1} \times m^2 \times °C)$ is the thermal resistance of cloting

M (W) is the metabolic rate

p_a (Pa) is the water vapor pressure

T_a (°C) is the indoor air temperature

T_{mrt} (°C) is the mean radian temperature

U_{ar} $({}^{m}/_{s})$ is the indoor air velocity

Appendix 6-2

This appendix recorded the outdoor temperature during the experiment

DATE	MIN	MAX
2021/1/13	-20	-11
2021/1/14	-19	-12
2021/1/15	-24	-14
2021/1/18	-27	-18
2021/1/19	-22	-6
2021/1/20	-7	0
2021/1/21	-16	-1
2021/1/22	-16	-6
2021/1/25	-9	2
2021/1/26	-18	-5
2021/1/27	-18	-8
2021/1/28	-25	-14
2021/1/29	-23	-15
2021/2/1	-26	-15
2021/2/2	-25	-16
2021/2/3	-21	-12
2021/2/4	-22	-8
2021/2/5	-14	0
2021/2/22	-17	-8
2021/2/23	-16	-7
2021/2/24	-13	1
2021/2/25	-11	-1
2021/2/26	-5	4
2021/3/1	-15	-7
MEAN	-17.9	-7.4
SD	6.0	6.4

Appendix 6-3

This appendix demonstrates the calculation step for L_{pi} in Iordache's IEQ model.

Indoor sound pressure level L_{pi} is

$$L_{pi} = L_{po} - D_b$$

The sound attenuation D_b is calculated as:

$$D_b = R_f + 10 \times \log\left(\frac{0.161 \times V}{T_r \times \sum A_i}\right)$$

The sound attenuation of the façade R_f is calculated as:

$$R_f = 10 \times log \times \frac{A_{wall} + A_{window}}{10^{-\frac{R_{wall}}{10}} \times A_{wall} + 10^{-\frac{R_{window}}{10}} \times A_{window}}$$

The sound attenuation of the opaque structure R_{wall} is calculated as:

$$R_{wall} = 13.5 \times \log(\rho_{wall}) + 13.5 \log(f) - 22.5$$

L_{po} is outdoor sound pressure level

$\sum A_i$ is sum of all surface area

T_r is the reverberation time of the room

V is the room volume of the room

ρ_{wall} is the wall density

Appendix A: Informed consent

(English Translation of Chinese Original Version)

You are invited to participate in a research survey. This informed consent provides you with some information to help you decide whether to participate in this study. Please read carefully. If you have any questions, please ask the researcher.

1. This survey is to study the impact of indoor environment on environmental perception, satisfaction and research efficiency
2. This questionnaire is used to collect the participants' perception, satisfaction and subjective performance evaluation of the indoor environment
3. If you agree to participate in this study, you will be asked to answer the questionnaire, which consists of 3 parts and 16 questions. During the research, the researcher will adjust the temperature, illumination and background noise intensity of the office. Please answer the questionnaire according to your subjective feelings. Your questionnaire is only used for this study.
4. Risk and discomfort: This study will not have any adverse effects on your health.
5. Benefit: Scientific analysis of your questionnaire results will help to improve the indoor office environment.
6. As a research subject, please truly express your subjective feelings and fill in the questionnaire. If you have any discomfort, please inform the researcher in time.
7. Privacy: If you decide to participate in this study, all the personal information is confidential.

You can learn about the information related to this study at any time. If you have any questions related to this study, please contact with the researcher, LI ZHIHENG at (+86) 13039009427.

☐ I have read this informed consent form.

☐ I have the opportunity to ask questions and all the questions have been answered.

☐ I understand that participation in this study is voluntary.

☐ I can choose not to participate in this study or discontinue this study at any time under any circumstances.

Signature:

Date:

Appendix B: Subjective Questionnaire

(English Translation of Chinese Original Version)

This appendix demonstrates the sample of subjective questionnaire in the experiment (English Translation of Chinese Original Version)

Indoor Environment Assessment

The questionnaire is used to collect the perception and satisfaction of the participants

Part 1: General Information

Name		Gender		Age
Clothing	Sweater	Thick	Medium	Thin
	Trousers	Thick	Medium	Thin
		Long	Medium	Short
	Socks	Thick	Medium	Thin
	Shoes	Thick	Medium	Thin
	Thermal Underwear	Yes	No	

Part 2: Preference Information

1. Do you prefer cool or warm thermal condition?	Cool	Warm
2. Do you prefer listening to music when you study?	Yes	No
3. Do you prefer slightly dark or slightly bright condition when you study?	Slightly Dark	Slightly Bright

Indoor Environment Assessment

The questionnaire is used to collect the perception and satisfaction of the participants

Environment Condition A: 21 centigrade, 200lux, 45dBA

Part 3: Indoor Environment Assessment

Q1: What is your feeling about the current thermal condition?

-3	-2	-1	0	1	2	3
Very Cold	Cold	Cool	Neutral	Warm	Hot	Very Hot

Q2: Do you satisfy with the current thermal condition?

-3	-2	-1	0	1	2	3
Strongly Dissatisfied	Dissatisfied	Slightly Dissatisfied	Neutral	Slightly Satisfied	Satisfied	Strongly Satisfied

Q3: What is your feeling about the current visual condition?

-3	-2	-1	0	1	2	3
Very Dark	Dark	Slightly Dark	Neutral	Slightly Bright	Bright	Very Bright

Q4: Do you satisfy with the current visual condition?

-3	-2	-1	0	1	2	3
Strongly Dissatisfied	Dissatisfied	Slightly Dissatisfied	Neutral	Slightly Satisfied	Satisfied	Strongly Satisfied

Q5: What is your feeling about the current acoustic condition?

-3	-2	-1	0	1	2	3
Very Noisy	Noisy	Slightly Noisy	Neutral	Slightly Quiet	Quiet	Very Quiet

Q6: Do you satisfy with the current acoustic condition?

-3	-2	-1	0	1	2	3
Strongly Dissatisfied	Dissatisfied	Slightly Dissatisfied	Neutral	Slightly Satisfied	Satisfied	Strongly Satisfied

Q7: What is your feeling about the current indoor air quality condition?

-3	-2	-1	0	1	2	3
Very Bad	Bad	Slightly Bad	Neutral	Slightly Good	Good	Very Good

Q8: Do you satisfy with the current Indoor air quality condition?

-3	-2	-1	0	1	2	3
Strongly Dissatisfied	Dissatisfied	Slightly Dissatisfied	Neutral	Slightly Satisfied	Satisfied	Strongly Satisfied

Q9: Do you think you completed the work efficiently during the last session?

-3	-2	-1	0	1	2	3
Very Insufficient	Insufficient	Slightly Insufficient	Neutral	Slightly Efficient	Efficient	Very Efficient

Appendix C: Performance Test

(English Translation of Chinese Original Version)

This appendix demonstrates the sample of the performance test in the experiment (English Translation of Chinese Original Version).

Performance Test

Environment Condition A: 21 centigrade, 200lux, 45dBA

Please calculate the difference between the left and right numbers of each line

1. If the number on the left is less than the number on the right, please fill in "-" value "in the space
2. If the number on the left is equal to the number on the right, please fill in "0" in the space
3. If the number on the left is greater than that on the right, please fill in "+ value" in the space

3		1		8		3		7		10		9		6		5		10		5
4		2		1		9		2		4		1		5		0		7		8
1		1		7		4		8		0		1		5		6		2		5
4		1		5		9		10		8		3		8		9		4		7
8		9		9		1		3		9		0		4		10		9		10
6		9		8		8		4		2		6		3		9		3		6
0		4		5		6		6		0		10		6		9		3		5
6		9		4		9		2		0		7		3		9		2		10
7		3		4		0		6		1		6		2		6		10		8
7		10		5		4		2		4		5		6		5		3		7

Duration