Building and Environment 49 (2012) 304–309

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

A study on the effects of thermal, luminous, and acoustic environments on indoor environmental comfort in offices

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ARTICLE INFO

Article history:
Received 4 July 2011
Received in revised form
19 July 2011
Accepted 21 July 2011

Keywords:
Controlled field survey
Thermal environment
Luminous environment
Acoustic environment
Indoor environmental quality

ABSTRACT

In light of growing concerns about productivity, much more attention has focused on the indoor environment in offices in recent years. Standards typically address different environmental factors such as thermal comfort, indoor air quality, and aural and visual environments separately. In fact, these environmental factors have notable combined effects on occupants' acceptability and work performance. ASHRAE Guideline 10P emphasized the interactions among indoor environmental factors and recommended that more detailed research is conducted. In this study, a controlled field survey was carried out to investigate the acceptable range of every individual environmental factor as well as the cumulative effects of multiple factors on indoor environmental quality. In the survey, the parameters of thermal, luminous, and acoustic environments were measured and subjects' satisfaction levels with regard to the indoor environment were determined using questionnaires. The results show that the satisfaction levels of both temperature and noise have one-vote veto power over the satisfaction level of the indoor environment as a whole. In addition, the interactions among different factors were examined through chart analysis to classify indoor environmental quality.

1. Introduction

In recent years there has been an increase in public awareness about the effects of the indoor environment on people's comfort and health. In light of growing concerns about productivity, much more attention has focused on the indoor environment in offices. Besides the thermal environment, the indoor environment also includes indoor air quality, as well as acoustic and luminous environments [1,2]. The overall IEQ (Indoor Environmental Quality) acceptance can be used as a quantitative assessment criterion for an office environment and other similar environments where an occupant's evaluation is expected [3].

Related to temperature and humidity, the thermal environment affects occupants' sensation of "warm" or "cool" and "humid" or "dry", and is considered to be the environmental factor to which people pay the most attention. Extensive studies have been conducted on thermal comfort, resulting in many thermal comfort equations. The PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied) based on Fanger's comfort equation are widely used in design guides and standards [4,5].

Comparative risk studies performed by the United States Environmental Protection Agency (USEPA) ranked IAQ (Indoor Air Quality) as one of the top five environmental risks to public health [6]. In addition to health problems, poor indoor air quality will also cause a decline in productivity for occupants who spend most of their workday in offices. Therefore, indoor air should be of sufficient quality so that contaminants in the air are not at a harmful concentration level and the majority of people feel satisfied [7].

Any sound judged undesirable by an occupant can be considered as noise. Poor acoustic properties of offices will make occupants unable to concentrate on their work. The neutral sound pressure level for aural comfort in typical air-conditioned offices was found to be between 45 dB and 70 dB, with a mean of 57.5 dB [8]. Also, inadequate lighting will have a negative effect on occupants' attention and work performance because occupants will have to strain their eyes while in the office.

To establish an acceptable indoor environment, all these factors should be considered [9]. ASHRAE Standards 55 and 62 address different environmental factors. However, in the 1990s, it was acknowledged that complaints and health effects related to the indoor environment were not caused by one single parameter [10]. According to a chamber test on 99 young adults, the IEQ factors for thermal comfort, indoor air quality, and the aural and visual environment had several combined effects on the occupants'

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0360-1323/$ – see front matter
doi:10.1016/j.buildenv.2011.07.022

acceptance of the environment and their work performance [9]. More recently, the equivalence of the discomfort caused by different physical qualities was examined. An equivalence of acoustic sensation to thermal sensation for short-term exposure was established. Specifically, a change in temperature of 1 °C had the same effect as a change in noise of 2.6 dB [11]. Physical environmental parameters are all interrelated, and the feeling of comfort is a composite state involving an occupant's sensations of all these factors [12–15].

Mathematical expressions were proposed for the overall IEQ acceptance using a multivariate logistic regression model as well as other mathematical models based on recorded environmental parameters [16,17]. However, it is easier to consider the environmental factors separately with mathematical methods than to figure out the interactions among them.

ASHRAE Guideline 10P emphasized the interactions among the indoor environmental factors [18]. The guideline referred to the possible ways that different factors might affect each other, and recommended that more detailed research be conducted.

In accordance with these findings, the present study was carried out to investigate the acceptable range of every individual environmental factor as well as the cumulative effects of multiple factors on indoor environmental quality. In addition, the interactions among different factors were examined through chart analysis to classify indoor environmental quality. It is hoped that this study can provide useful information about how to manage all environmental factors collectively.

2. Methods

2.1. Controlled field survey

The results of previous field surveys in real offices showed that the environmental parameters often had a narrow range and generally were judged to be acceptable by occupants, leading to limitations in the analysis of the results. In order to extend the range of environmental parameters and also to ensure that subjects respond like they would in a real work environment, a controlled field survey was carried out in which the temperature, lighting, and noise level could be controlled. The survey was conducted in a real office at Tsinghua University in Beijing from July to August in 2009. The size of the office room was $3 \times 3 \times 3$ m^3 and a desk was centered in the room. Subjects and measurement points were located symmetrically as shown in Fig. 1. Thermal environment was measured at the height of 1 m. Luminous and acoustic environments were measured on the desk. During the survey, the temperature was controlled by air conditioning, the noise level was controlled by adjusting the volume of recorded fan noise, and the lighting was controlled using continuously adjustable lights and shutters. In the survey, the range of the concentration of CO_2, which was used as a representation of IAQ, was narrow and all subjects felt satisfied with the quality of the indoor air. Therefore, IAQ was not considered in this study.

2.2. Subjects

There were 120 subjects in total, and all of them were university students. Half of them were male and half were female. They were, on average, about 22 years old, weighed 59 kg, and were 1.67 m in height. Table 1 summarizes the subjects' profile details. Subjects were assessed during sedentary reading, and their mean metabolic rate was about 1.1 met. Their clothing insulation ranged from 0.36 clo to 0.61 clo, with an average value of 0.45 clo, as estimated from the clothing garment checklists in ASHRAE Standard 55.

2.3. Experimental procedures

The temperature was set at 18, 20, 22, 24, 26, 28, 30, and 32 °C; the noise level was set at 45, 50, 55, 60, and 65 dB; and the illumination was set at 100, 300, 500, 700, 900, 1100, and 1300 Lux. Using orthogonal design, each combination of parameters was tested.

Three subjects were tested at a time in the survey. Each survey lasted 105 min, following a 30 min adaptation period. The temperature and noise did not change throughout the survey, but the illumination level changed every 15 min so that in each survey, subjects experienced all 7 illumination levels with the same temperature and noise level. Subjects were required to fill out

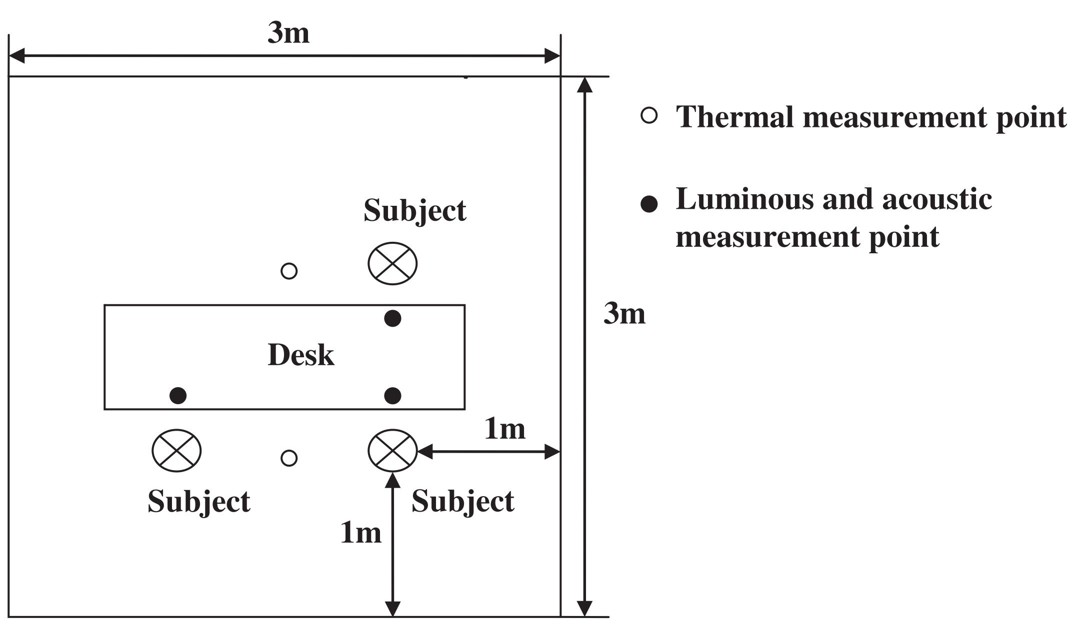

Fig. 1. The layout of the surveyed room.

Table 1
Subjects' profiles.

Gender		Male	Female
Sample size		60	60
Age (years)	Avg.	22.3	22.8
	Min.	19	20
	Max.	26	28
Height (m)	Avg.	1.72	1.63
	Min.	1.67	1.58
	Max.	1.85	1.72
Weight (kg)	Avg.	62.4	55.7
	Min.	56	47
	Max.	72	60

questionnaires every 15 min and the indoor environmental parameters were continuously recorded. There were 40 different surveys (8 different temperatures × 5 different noise levels = 40) and each subject only took part in one survey. In each survey 7 votes for 7 illumination levels were got for each subject. So there were totally 840(120 subjects × 7 votes = 840) votes we got.

2.4. Measurements and questionnaires

The survey included measuring the parameters of the indoor environment and inquiring about the participants' subjective sensations using questionnaires. These two aspects of the study were carried out at the same time.

In order to measure the environmental variables, different kinds of instruments were used. For the thermal environment, an AM-101 PMV and PPD indices meter was used, with which air temperature, mean radiant temperature (MRT), airflow velocity, and relative humidity could be measured. Illumination intensity was used as the parameter to evaluate the luminous environment, and it was measured with a portable TES-1330A digital illuminometer. The A-weighted sound pressure level (LA) was used as the parameter to evaluate the acoustic environment, and it was recorded using an AWA6270B noise spectrum meter.

Subjects' personal information, such as gender, age, and clothing condition, was determined using questionnaires. In addition, the satisfaction levels of the thermal, luminous, and acoustic environments, as well as the indoor environment as a whole, were investigated according to the scale shown in Fig. 2.

3. Results and discussion

3.1. Thermal environment

During the survey, mean daily outdoor temperatures ranged from 25.1 °C to 28.8 °C. Operative temperature was used as the indoor temperature index since it is comprised of both convection and radiation. The operative temperature in the survey ranged from 17.8 °C to 31.4 °C. The relative humidity ranged from 40% to 65%, with an average of 51%. The air velocity was 0.02 m/s–0.42 m/s; among all the samples, the average value was 0.16 m/s and most samples had an air velocity lower than 0.2 m/s.

Fig. 3 shows the relationship between the satisfaction level of the thermal environment and the operative temperature. Each dot represents the average value of the satisfaction level at the same

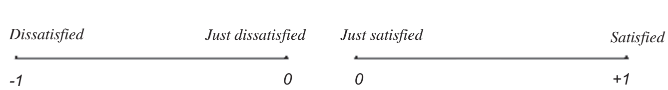

Fig. 2. The scale of satisfaction levels.

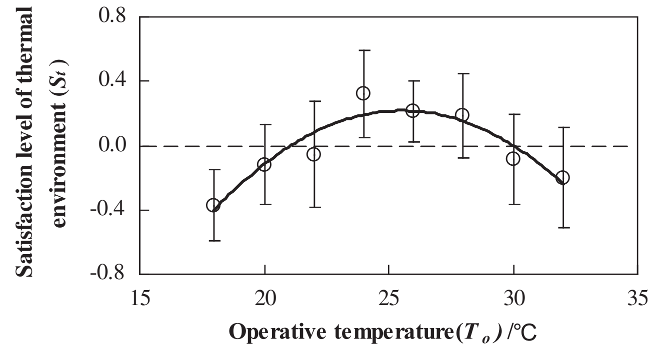

Fig. 3. Relationship between satisfaction level of the thermal environment and operative temperature.

operative temperature. The corresponding formula is written as follows:

$$S_t = -0.0108T_0^2 + 0.5541T_0 - 6.8587 \quad R^2 = 0.8796 \tag{1}$$

When the satisfaction level of the thermal environment was greater than 0, which indicated that subjects felt satisfied with the thermal environment, the operative temperature ranged from 20.9 °C to 30.4 °C. The highest level of satisfaction with the thermal environment occurred when the operative temperature was 25.7 °C. From these results, it can be seen that even in an air-conditioned environment, subjects had a wide range of acceptable temperatures. The upper limit of 30.4 °C was higher than the 28 °C which was set as the upper limit in the Chinese design code for air-conditioned rooms in summer.

3.2. Luminous environment

The illumination intensity in the survey ranged from 93 Lux to 1424 Lux. Fig. 4 shows the relationship between the satisfaction level of the luminous environment and the illumination intensity. The corresponding formula is written as follows:

$$S_i = -0.7844I^2 + 1.8886I - 0.497 \quad R^2 = 0.9914 \tag{2}$$

It can be seen that when the illumination intensity was above 300 Lux, subjects felt satisfied with the luminous environment. In the survey, most subjects felt satisfied with the illumination intensity overall. It is obvious that with low illumination intensity, occupants in offices will find reading more difficult, making it more challenging for them to concentrate on their work. Some previous field surveys showed that when occupants worked in an

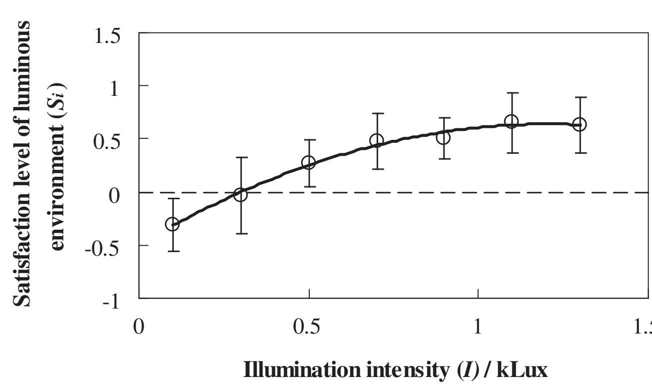

Fig. 4. Relationship between satisfaction level of the luminous environment and illumination intensity.

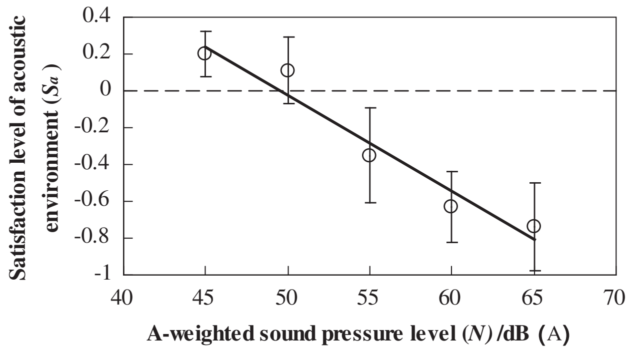

Fig. 5. Relationship between satisfaction level of the acoustic environment and A-weighted sound pressure level.

environment with very high illumination intensity, it would cause them discomfort. The results of one such study showed that the most comfortable illumination intensity range was 1500–3000 Lux in offices [6]. In the current study, when the illumination intensity was below the maximum of 1424 Lux, the higher the illumination intensity was, the higher the subjects' satisfaction level of the luminous environment was.

3.3. Acoustic environment

The noise level in the survey ranged from 44.3 dB to 65.4 dB. Fig. 5 shows the relationship between the satisfaction level of the acoustic environment and the A-weighted sound pressure level. The corresponding formula is written as follows:

$$S_a = -0.0524N + 2.6 \quad R^2 = 0.9514 \tag{3}$$

The Chinese code for the design of sound insulation of civil buildings suggests that the noise level in offices should not be higher than 55 dB. In this survey, however, when the noise level was below 49.6 dB, subjects felt satisfied with the acoustic environment. When the noise level increased above this threshold, subjects felt increasingly uncomfortable.

3.4. The effects of the three factors on the satisfaction level of the indoor environment

It is obvious that not all environmental factors have the same effect on indoor environmental quality. It will be beneficial to determine which factor affects the environment as a whole to the greatest extent. The thermal environment is often considered to be the most important factor with regard to the indoor environment, and the luminous and acoustic environments appear to be less important. An analysis was conducted to determine the different effects of the three factors.

When people evaluate indoor environmental quality, they often use grades instead of numeric values. In this study, satisfaction with the indoor environment is divided into four grades: "Quite satisfied," "Just satisfied," "Just dissatisfied," and "Quite dissatisfied." Each grade above represents the satisfaction level range of 0.5–1, 0–0.49, −0.49 to 0, and −1 to −0.5, respectively.

For simplicity, we considered the thermal, luminous, and acoustic environments in terms of two dimensions: all the data in Fig. 6 is divided into either "Satisfied with temperature" or "Dissatisfied with temperature." For both categories, the four grades of indoor environmental quality correspond to values of light and noise levels. "QS," "JS," "JD," and "QD" stand for "Quite satisfied," "Just satisfied," "Just dissatisfied," and "Quite dissatisfied," respectively. Each dot in the figure represents the average value of indoor environmental quality at the same light and noise level. In the following discussion, "light" is used to represent illumination intensity and "noise" is used to represent the A-weighted sound pressure level.

It can be seen that when the subjects felt satisfied with the temperature, they were most satisfied with the indoor environment with a higher level of light and a lower level of noise. The satisfaction level reached the "Quite satisfied" grade at a noise level of 45 dB and a level of light around 1000 Lux. However, when the subjects felt dissatisfied with the temperature, it was very difficult for them to feel satisfied with the indoor environment: even with a low level of noise and a high level of light, the indoor environment was still in the dissatisfied grade. It can be concluded that the satisfaction level of temperature has one-vote veto power over the satisfaction level of the indoor environment as a whole. In other words, once the temperature is outside the acceptable range, the entire indoor environment will be considered unacceptable.

Using the same method, the data can be divided according to the noise level, as shown in Fig. 7. When the subjects felt satisfied with the noise level, the satisfaction level of the indoor environment was highest at a higher level of light and a more moderate temperature. When the environment was around 25 °C and 800 Lux, there was a significant "Quite satisfied" zone. However, when the subjects felt dissatisfied with the noise level, it was very difficult for them to feel satisfied with the indoor environment. It appears that the satisfaction level of noise also has one-vote veto power over the satisfaction level of the indoor environment as a whole.

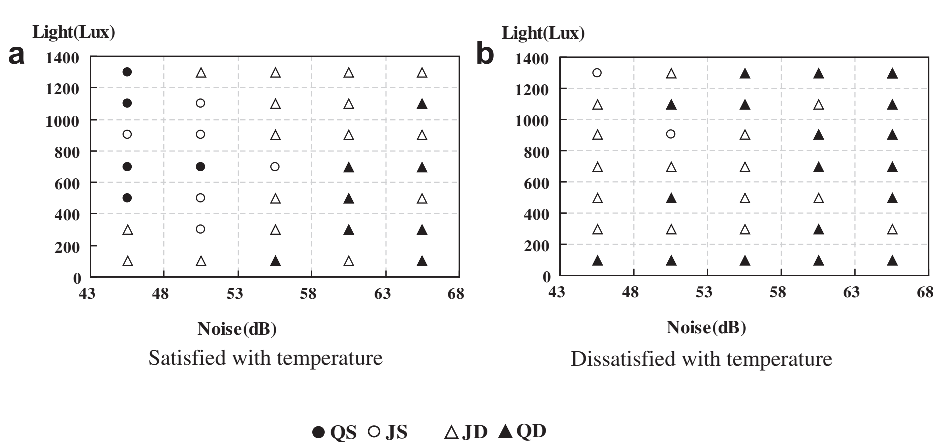

Fig. 6. The effect of temperature on the satisfaction level of the indoor environment.

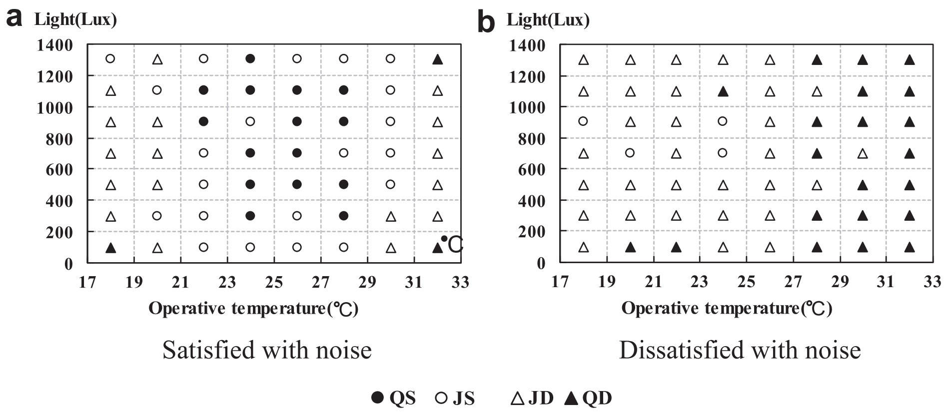

Fig. 7. The effect of noise on the satisfaction level of the indoor environment.

However, the situation was quite different for light. Whether or not the level of light was acceptable, subjects could find the indoor environment acceptable if there was a suitable level of noise and moderate temperature, as shown in Fig. 8. Thus, the satisfaction level of light does not have one-vote veto power over the satisfaction level of the indoor environment as a whole. In other words, even when the level of light is outside the acceptable range, it is still possible for the entire environment to be judged as acceptable. That's because the subjects are less sensitive to illuminance changes. Correlated study has been done to show that satisfaction with the lighting level is the least important contributor to overall comfort [19].

3.5. The classification of indoor environmental quality

Considering the different effects of three factors on the indoor environment and the interactions among them, it is difficult to calculate the satisfaction level of the indoor environment with a formula. Instead, based on the results of this survey, we can classify indoor environmental quality through chart analysis.

Figs. 9–11 show the satisfaction level of the indoor environment when one of the factors is at the satisfied level. In each figure, different zones are marked with broken lines according to the distribution of the dots in different grades. Zones I, II, III, and IV stand for “Quite satisfied zone,” “Just satisfied zone,” “Just dissatisfied zone,” and “Quite dissatisfied zone,” respectively. Thus, the classification can be achieved by checking the different zones in the figures. The shape of each zone also indicates the interaction between two factors. For example, in Fig. 11, when temperature was near 26 °C, at which the satisfaction level of the thermal environment was highest, subjects found a higher noise level acceptable. Also, when the noise level was lower, a wider range of temperatures could be accepted. In other words, with the same indoor environmental quality, different factors offset each other to a certain extent. These interactions can also be found in Figs. 9 and 10.

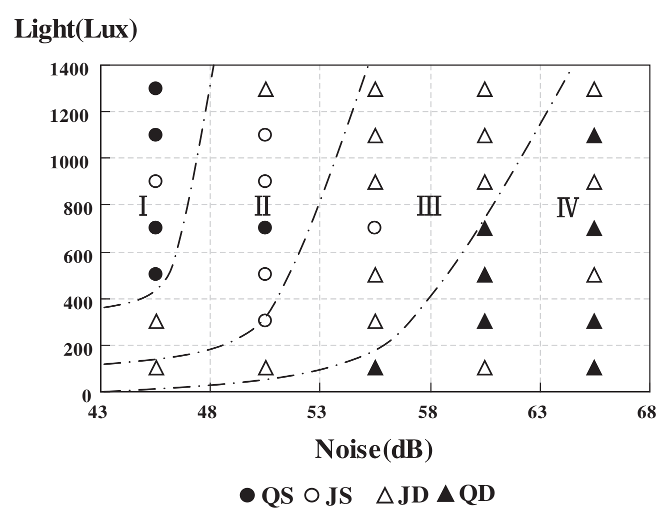

Fig. 9. The classification of indoor environmental quality with satisfied level temperature.

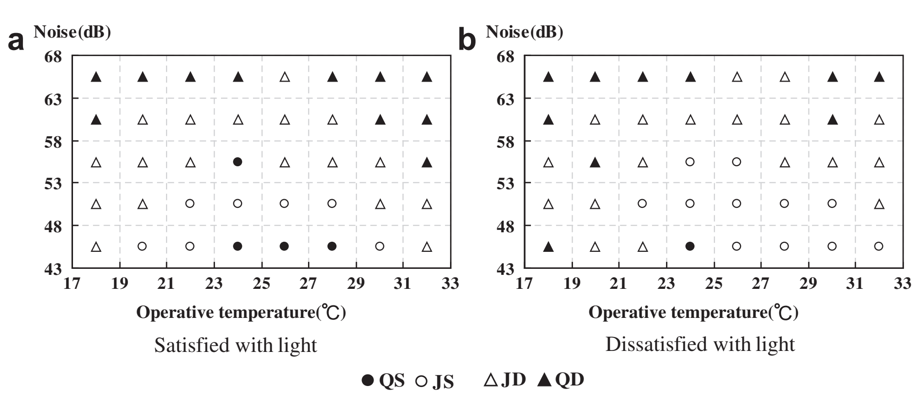

Fig. 8. The effect of light on the satisfaction level of the indoor environment.

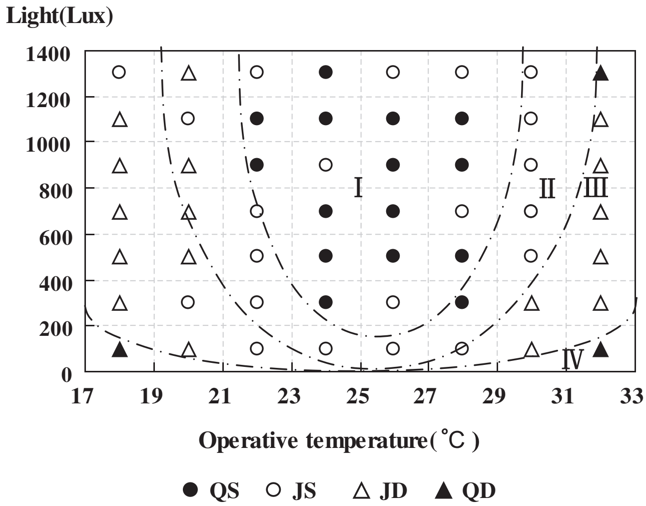

Fig. 10. The classification of indoor environmental quality with satisfied level noise.

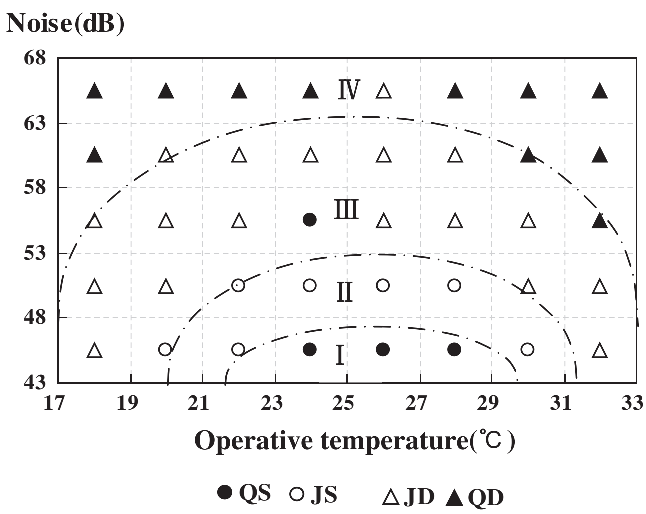

Fig. 11. The classification of indoor environmental quality with satisfied level light.

This method for classifying indoor environmental quality can be utilized as follows:

First, determine the parameter values and satisfaction levels of temperature, light, and noise from Figs. 3, 4, and 5, respectively. Second, if any of the factors are at the satisfied level, refer to Figs. 9 and 10, or Fig. 11 accordingly and determine the satisfaction level of the indoor environment. For example, if a given temperature is in the acceptable range found in Figs. 3 and 9 can be used to check which zone the environmental quality is in based on the light and noise levels, and the classification can be determined. If none of the factors are at the satisfied level, the indoor environment is obviously not acceptable.

4. Conclusions

In this study, a controlled field survey was carried out and the acceptable ranges of different environmental factors were determined. The acceptable range of temperature was between 20.9 °C and 30.4 °C, the acceptable level of illumination was above 300 Lux, and the acceptable level of noise was below 49.6 dB.

The three factors have different effects on the indoor environment as a whole. Based on two-dimensional chart analysis, it can be concluded that the satisfaction levels of both temperature and noise have one-vote veto power over the satisfaction level of the indoor environment as a whole. However, this is not true for light. That's because the subjects are less sensitive to illuminance changes.

Several figures displayed different satisfaction zones when one of the factors was at the satisfied level. The shape of each zone in the classification chart indicated the interaction between factors based on the results of this survey. With the same indoor environmental quality, different factors offset each other to a certain extent. The procedure for utilizing the classification method for indoor environmental quality was demonstrated.

Considering it is not a stringently controlled lab experiment, limitations of the controlled field survey should be acknowledged. To improve future research, higher illumination intensity should be included to determine the upper limit of the acceptable range, and IAQ should also be taken into account.

Acknowledgment

This research was supported by the NSFC (the Natural Science Foundation of China) No. 50838003. The authors also acknowledge the support of the Project Fund of National Eleven Five-Year Scientific and Technical Support Plans (No. 2006BAJ02A06).

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