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International High Performance Buildings Conference

School of Mechanical Engineering

July 2018

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Jialu Liu
Xi'an Jiaotong University, China, People's Republic of, liujialu@stu.xjtu.edu.cn

Xian Yang
Xi'an Jiaotong University, China, People's Republic of, xianer0604@stu.xjtu.edu.cn

Xiangzhao Meng
Xi'an Jiaotong University, China, People's Republic of, xzmeng@mail.xjtu.edu.cn

Yanhua Liu
Xi'an Jiaotong University, China, People's Republic of, yhliu@mail.xjtu.edu.cn

Effects of Indoor Temperature and Air Movement on Perceived Air Quality in the Natural Ventilated Classrooms

Jialu LIU[1], Xian YANG[2], Xiangzhao MENG[3], Yanhua LIU[4]*

[1]Xi'an Jiaotong University, School of Human Settlements and Civil Engineering,
Xi'an, Shaanxi, China,
liujialu@stu.xjtu.edu.cn

[2]Xi'an Jiaotong University, School of Human Settlements and Civil Engineering,
Xi'an, Shaanxi, China,
xianer0604@stu.xjtu.edu.cn

[3]Xi'an Jiaotong University, School of Human Settlements and Civil Engineering,
Xi'an, Shaanxi, China,
xzmeng@xjtu.edu.cn

[4]Xi'an Jiaotong University, School of Human Settlements and Civil Engineering,
Xi'an, Shaanxi, China,
yhliu@mail.xjtu.edu.cn

* Corresponding Author

ABSTRACT

Perceived air quality is an important aspect in current guidelines and standards for indoor environment. It represents occupants' real feeling about indoor air and affected by almost all environmental parameters, such as the temperature, the relative humidity, the air movement, and et al. Studies were conducted mainly in controlled climate chambers or air-conditioned spaces, rarely in natural ventilated spaces. In this paper, the effects of temperature and air movement on perceived air quality in natural ventilated classrooms are investigated. The indoor environmental parameters in 7 classrooms for 35 lessons are continuously measured and the students in class are asked to report their perception on the temperature, air movement, and the air quality of classrooms by filling questionnaires at once after a lesson. The number of received validated questionnaires is 992. The correlation analysis is used to investigate the effects of temperature and air movement on the perceived air quality. Results show that in natural ventilation classrooms, which are warm at temperature and moderate at humidity with an air speed lower than 0.1m/s, it is the thermal sensation rather than the temperature, enthalpy, thermal acceptability, CO_2 concentration or PM2.5 concentration that affects the perception of occupants for air quality. The perception for air movement influences the air quality acceptability. Increasing air movement increases the air quality acceptability. Besides, it is found that the preference of air movement is related to the air quality acceptability. When participants feel that the air movement is just suitable, the acceptability of air quality reaches the highest. When participants feel the air movement need to be adjusted, the air quality acceptability decreases.

1. INTRODUCTION

Occupant's subject feelings about indoor environment attracts the attention of researches all over the world because it is important for both human psychological health and working productivity. Perceived air quality is one of the most important subject feelings of acceptable indoor air environment. Occupants who are dissatisfied with the indoor air quality are assumed to be less productivity (WarGocki et,al., 1999, Kosonen and Tan, 2004). During the past 30 years, perceived air quality was studied in different sorts of indoor environment including mechanical ventilated spaces (Kinshella et al., 2001, Skwarczynski et al., 2010), natural ventilated spaces (Ruotsalainen et al., 1991), and spaces with different indoor pollutants (Wolkoff and Nielsen, 2001).

A number of studies have shown that perceived air quality is affected by almost all environmental parameters, such as the temperature, the relative humidity, the air movement and et al. The parameters that affect perceived air quality are complex and have been studied over years. Previous experiments showed that the temperature and humidity significantly influenced the perceived indoor air quality (Berglund and Chain, 1989). Subsequent investigations found that with increasing indoor air temperature and humidity, the air was perceived as less acceptable (Fang et al., 1998a), and the chamber experimental results showed that the acceptability decreased linearly with increasing indoor air enthalpy (Fang et al., 1998b). Besides, researchers also found that perceived air quality was related to the subjective thermal state (Humphreys et al. 2002), indoor air movement (Melikov and Kaczmarczyk, 2012), and other environmental parameters. Common conclusions were drawn that in the mechanically ventilated space, as the temperature became uncomfortably warm, people perceived the indoor air quality as less acceptable (ASHRAE 10-2016).

However, human's perception of air quality in real indoor environment in natural ventilated spaces may be different from the previous studies. So in this study, the effects of air temperature and movement in natural ventilated classrooms on the perceived air quality are studied by collecting data from students and measurements in class.

2. METHODS

2.1 Field Experiments and Subjects

The field experiments were carried out in selected classrooms of Xi'an Jiaotong University in Xi'an, China, from November 1st to 15th in 2017. The classrooms were naturally ventilated. The indoor environmental parameters were measured and the questionnaires were collected for 7 classrooms in class, and repeated 5 times, respectively, which summed up to 35 observations. When having classes, students in the classrooms were the main source of the indoor air pollutants. We used CO2 concentration to represent the concentration of human bioeffluents.

The parameters measured continuously included the indoor air temperature, relative humidity, air speed, and PM2.5 and CO_2 concentrations. Volatile organic compounds (VOCs) and ozone (O_3) were measured twice before and after class. After class (50 minutes) the students who attended class were asked to report their perception by filling questionnaires voluntarily. Based on the data above and the correlation analysis the effects of temperature and air movement on the perceived air quality was assessed.

242 female subjects and 750 male subjects with an average age of 19 years participated in experiments. The participants were university students, and they were not aware of the purpose of the investigation. They were asked to fill questionnaires just after their 50-minutes class in order to acquire the adaptive perception which is more important to the occupants.

2.2 Measurements

The temperature was measured by a Swema 05 black globe temperature sensor with the measuring range of 0-50^{o}C and accuracy of ±0.1^{o}C. Relative humidity was measured by a Hygroclip2-S relative humidity sensor, the range of which is in 0-100% and accuracy is 0.8% at 23^{o}C. Air velocity was measure by a Swema 03 draught sensor with the measuring range between 0.05 and 3m/s at 15-30 ^{o}C, the accuracy of ±0.03m/s at 0.05 to 1m/s. CO_2 concentration in indoor air was measured by TES-1370 sensor ranging from 0 to 6000ppm and the accuracy is in ±3%. The concentrations of PM2.5 were measured use a QD-W1 PM2.5 detector ranging from 0 to 500μg/m^3. All instruments were put at the height of 1.1m (breathing height) from the ground and were connected to a PC, continuously recording data. To acquire more accurate data, five measurement points were set. One point was set at the center and other four were set at the corners of the classrooms. VOCs and O_3 were also measured before and after class, used a PV605 handheld gas detector. For VOCs, the range of measurement is 0 to 6000ppm with a resolution of 0.1ppm; for O_3, the range of measurement is 0 to 5ppm with a resolution of 0.05ppm. Photos of the experimental fields from different angles was shown in Figure 1.

Figure 1: Photos of field experiment

2.3 Questionnaires

Students in test classrooms were asked to use their cellphones to fill questionnaires just after 50-minute class in order to acquire their adaptive perception of the indoor environment which is more important to the classroom occupants. Since in this paper the impact of temperature and air movement on the perceived air quality is mainly focused on, the questionnaires designed contains three categories. The thermal sensation, the thermal preference and the thermal acceptability are included in a category. The other one includes the air movement perception, air movement preference, and air movement acceptability and the third one is with the indoor air quality perception and indoor air quality acceptability. The voting scales used in questionnaires are shown in Figure 2.

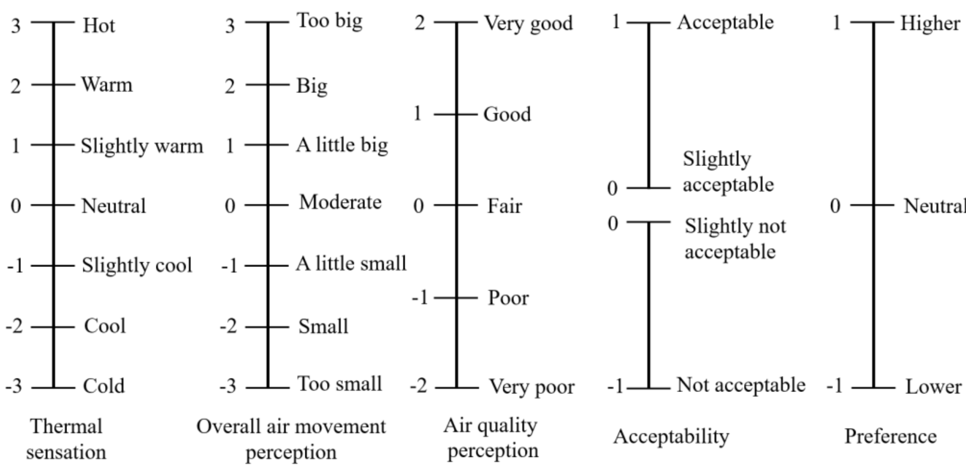


Figure 2: Scales used in the questionnaires

3. RESULTS

3.1 Indoor Environmental Parameters

Table 1 lists the indoor environmental parameters measured. It can be seen that the average temperature during the experiments ranges from 18.4ºC to 25.2ºC, the relative humidity is around 50% and the average air speed in the classrooms is lower than 0.1m/s. The concentration of CO_2 ranges from 450ppm to 2300ppm. The concentration of PM2.5 ranges from 31 to 174μg/m^3. These results show that during the pre-heating season in Xi'an of China, the indoor temperature and humidity of the classroom are moderate, while the ventilation rate is rather low because of the lack of mechanical ventilation. The CO_2 and PM2.5 concentrations vary in a relatively wide range. This indicates that students in the classrooms and outdoor pollutants are the main pollutant source of indoor air quality. The enthalpies of each cases are also calculated and listed in Table 1, which will be used in the discussion section.

Table 1: Indoor environmental parameters

Observations	Temperature (ºC)	Relative Humidity (%)	Enthalpy (kJ/kg)	Air Velocity (m/s)	CO_2 Concentration (ppm)	PM2.5 Concentration (μg/m³)
1	20.25	60.74	42.79	0.085	991.67	46
2	21.20	55.68	43.19	0.043	623.32	50
3	25.16	44.32	47.55	0.069	1054.26	56
4	24.75	48.18	49.10	0.077	1285.99	39
5	23.72	55.59	50.18	0.065	1320.71	42
6	23.48	54.11	47.70	0.047	1417.44	39
7	23.88	49.74	47.53	0.052	1467.60	41
8	23.63	39.02	42.15	0.058	828.20	39
9	24.21	40.33	43.36	0.051	1114.76	40
10	22.51	43.59	41.97	0.032	789.46	39
11	18.38	56.18	36.72	0.046	597.33	167
12	19.05	56.18	38.60	0.032	662.74	174
13	22.20	58.98	47.02	0.050	1919.44	165
14	22.75	58.11	48.76	0.027	1656.33	124
15	21.13	58.31	44.17	0.020	1000.26	94
16	21.84	48.98	42.41	0.067	1025.65	41
17	23.72	41.16	43.26	0.025	863.24	40
18	24.66	39.03	44.35	0.051	1296.64	34
19	24.02	41.87	43.90	0.059	1457.60	31
20	22.35	44.21	40.91	0.047	893.41	38
21	22.59	47.80	43.94	0.045	993.59	49
22	23.13	45.92	43.65	0.039	1205.79	66
23	23.83	43.62	44.55	0.054	782.72	95
24	22.52	42.88	41.66	0.068	450.79	103
25	22.23	42.88	40.23	0.056	962.65	106
26	21.83	53.92	44.49	0.076	2274.17	56
27	20.62	48.00	39.55	0.034	1191.36	74
28	20.60	48.13	39.58	0.060	1161.55	121
29	20.50	46.95	39.01	0.068	1049.65	107
30	21.30	53.85	42.57	0.056	1643.21	130
31	21.51	48.03	41.67	0.055	1264.54	131
32	23.34	42.40	42.28	0.060	1201.68	101
33	23.82	36.61	41.19	0.066	1230.07	56
34	23.54	37.06	41.12	0.059	1073.65	70
35	23.53	38.64	41.86	0.040	896.71	94
Average	22.51	47.74	43.23	0.053	1121.81	77

Besides, the results showed that VOCs and O_3 concentrations were in a very low level that the instrument even cannot detect, which means that VOCs and O_3 were not the main pollutants in the classrooms. This is because the teaching buildings in our experiments was built and put into use in 2005 with very simple decoration. There's little pollutant sources in the classrooms. And the classrooms are in a good maintenance. The cleaning crews used to clean the classrooms with clean water. Since the concentrations of VOCs and O_3 were very low, the impact of VOCs and O_3 on perceived indoor air quality were not discussed in this paper.

3.2 Perceptions for Thermal Environment

The perception of subjects for thermal environment include thermal sensation vote, thermal acceptability vote, and thermal preference vote. Figure 3 shows the percentages of the thermal sensation votes. We could find in figure 3 that 30.34% of the participants felt neutral about the thermal environment, 21.07% felt slightly warm, and 9.88% felt slightly cool. This means the thermal environment were in the thermal comfort zone of 61.29% participants. Besides, 26.41% of the participants felt warm, 9.07% felt hot, while 2.12% felt cool, and 1.11% felt cold. This indicate the thermal environment in pre-heating season in natural ventilated classrooms in Xi'an is under neutral to warm condition.

Figure 4 shows the percentages of thermal acceptability votes. 50.75% participants voted to acceptable, and 46.22% voted to clearly acceptable. The acceptability percentage for the thermal environment reaches 96.67%. Only 2.27% participants felt unacceptable, and only 0.76% participants felt clearly unacceptable. Compare to the data in figure 3, we can see that although 61.29% participants voted that they were in their the thermal comfort zone, 96.67% participants were acceptable with the thermal environment. This indicates that the students had a good tolerance for warm environment.

For thermal preference vote, 31.39% participants voted to cooler, 48.11% voted to remain the current thermal condition, and 8.74% voted to warmer. These results also suggest the thermal environment during the experiments was in a moderate to warm condition.

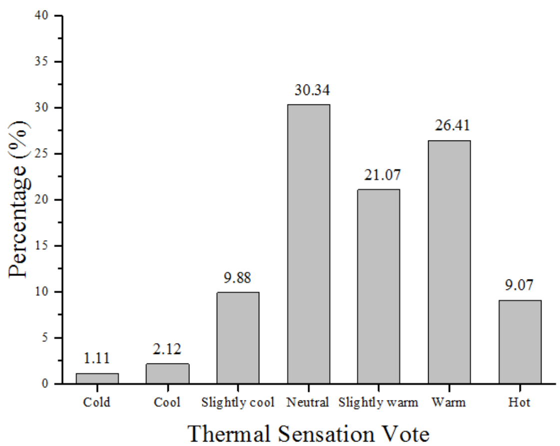


Figure 3: Percentage of thermal sensation votes

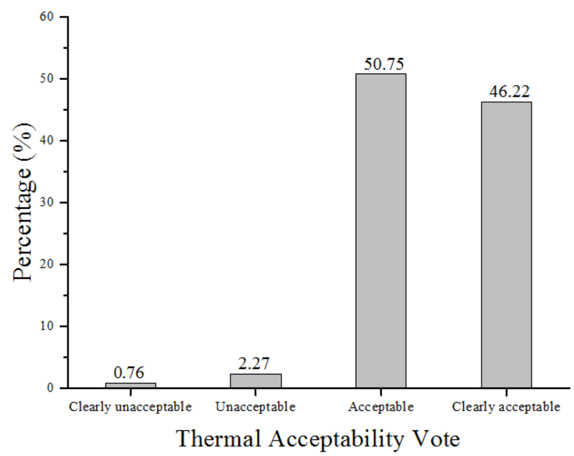


Figure 4: Percentage of thermal acceptability votes

3.3 Perceptions for Air Movement

The air movement perception of students was investigated by setting questions including overall air movement perception vote, air movement acceptability vote and air movement preference vote. Figure 5 shows the vote results of the perception for air movement. The air velocity in the classrooms was less than 0.1m/s as stated before, and the air movement perception vote is in accordance with the objective experimental data. 27.52% participants felt that the air movement in the classrooms is too small, 17.84% felt small, 14.32 felt a little small, and 35.08% of participant felt neutral. Only 5.24% of participants felt that the air movement is larger than neutral. These results indicate that the air movement during the experiments was not satisfied by nearly half of the participants.

Figure 6 shows the vote results of air movement acceptability. The percentage of the participants who felt acceptable to the indoor air movement is 85.65% with 4.1% clearly unacceptable votes. Although the air movement is not as satisfied as the thermal environment, but it is acceptable for the majority students.

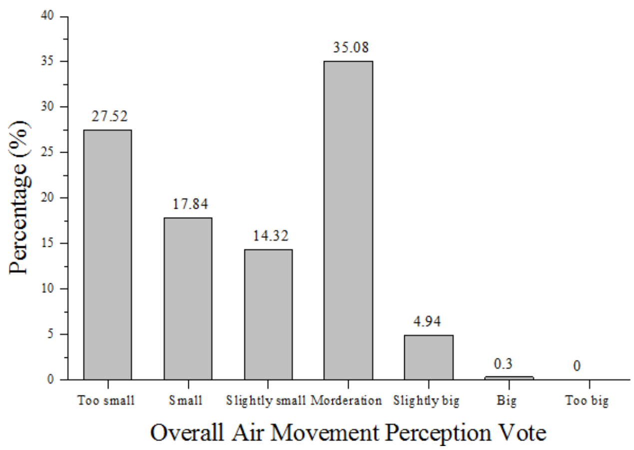


Figure 5: Percentage of air movement perception votes

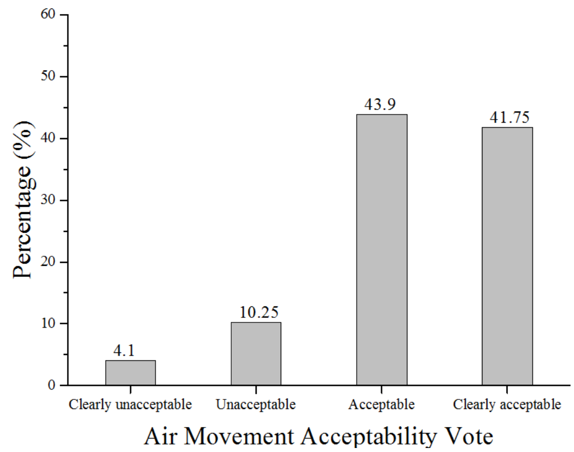


Figure 6: Percentage of Air movement acceptability votes

Another finding is that the air movement acceptability has a strong correlation with the thermal sensation. Figure 7 shows the air movement acceptability under different thermal sensations. It can be seen that the unacceptability for air movement is lowest under the neutral sensation of thermal environment. It increases from neutral to hot and cold sensations. And the unacceptability under hot sensation, which is 52.17% is higher than that under cold sensation which is 12.5%. The same trend between the overall air movement perception and thermal sensation is found. So the acceptability of air movement may strongly affected by thermal sensation and may not reflect the real acceptability for air movement.

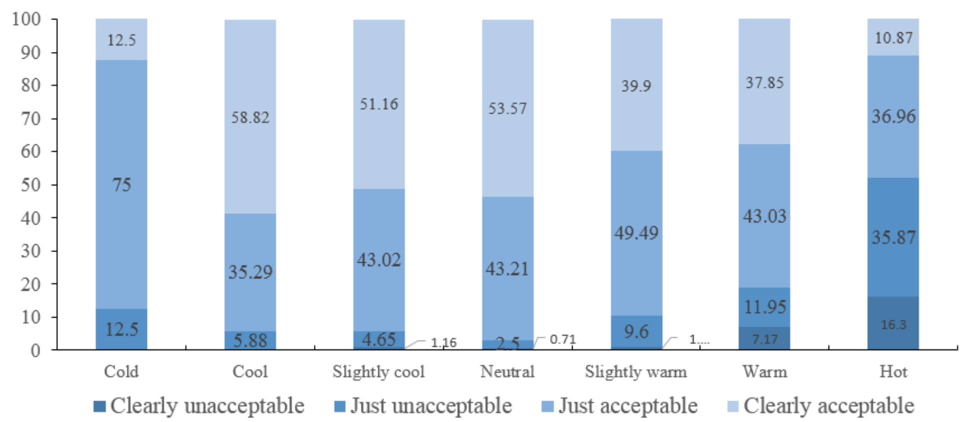


Figure 7: Air movement acceptability under different thermal sensations

3.4 Perceptions for Indoor Air Quality

The votes for overall indoor air quality perception and indoor air quality acceptability are shown in Figure 8 and Figure 9. The air quality of the classrooms is determined by the number of occupants, the outdoor pollutants, the ventilation rate, and the size of the classroom, et al. It can observed in the figures that about half of the participants, 52.47%, vote that the indoor air quality is fair or the votes is in fair scale. 19.68% of them is in poor scale and 21.39% in good, 3.94% in very poor scales. Only 2.52% of votes is in very good scale. For the air quality acceptability, about 87.49% participants felt the air is acceptable, 8.52% felt it is unacceptable and 3.99% felt it clearly unacceptable.

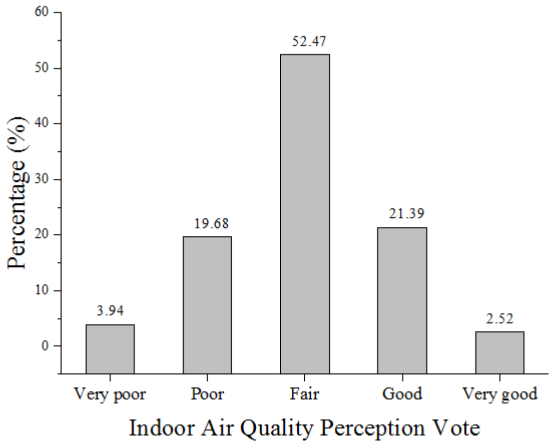


Figure 8: Percentage of air quality perception votes

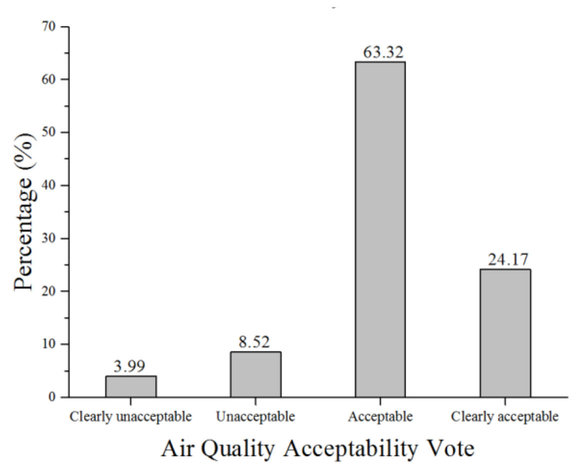


Figure 9: Percentage of indoor air quality acceptability votes

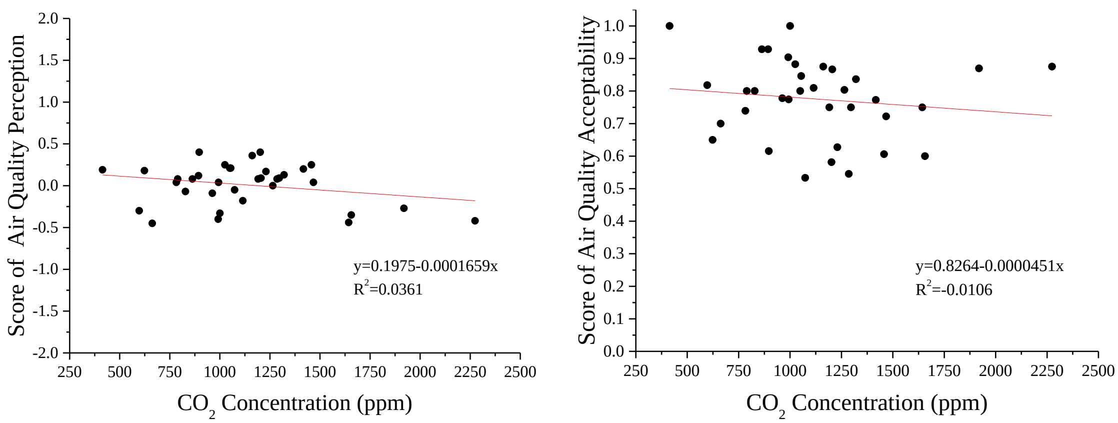
4. DISCUSSION

In this part, the mean scores of the votes were calculated for each case according to the vote scales listed before. Regression analysis were used to evaluate the correlations of different factors with indoor air perception.

3.1 Indoor Air Quality and Perceived Air Quality

The indoor air pollutants in the experiment classrooms during class time mainly came from two sources: human bioeffluent, and outdoor particulate matter. In this part, we discuss the correlation between CO_2 concentration and perceived air quality, and the correlation between PM2.5 concentration and perceived air quality.

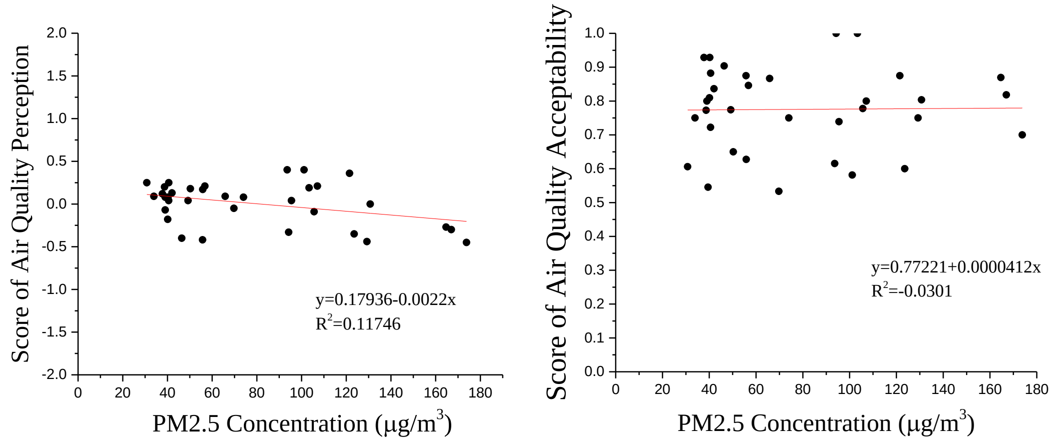
Figure 10 shows the average scores of perceived air quality and air quality acceptability related to CO_2 concentration, It can be seen that the perceived air quality or air quality acceptability are not strongly related to the CO_2 concentration. This result is consistent with Humphreys et al. (2012) who found that the perceived air quality was related to the subjective thermal state of the respondent rather than to the concentration of CO_2.



(a) Air quality perception (b) Air quality acceptability

Figure 10: Air quality perception (a) and air quality acceptability (b) related to CO_2 concentration

Figure 11 shows the average scores of perceived air quality and air quality acceptability related to PM2.5. From the figures we could see that the perceived air quality or air quality acceptability are not related to the PM2.5 concentration.



(a) Air quality perception (b) Air quality acceptability

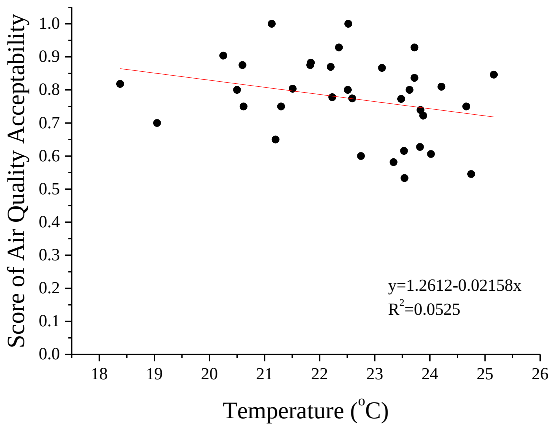
Figure 11: Air quality perception (a) and air quality acceptability (b) related to PM2.5 concentration

3.2 Effect of Temperature on Perceived Air Quality

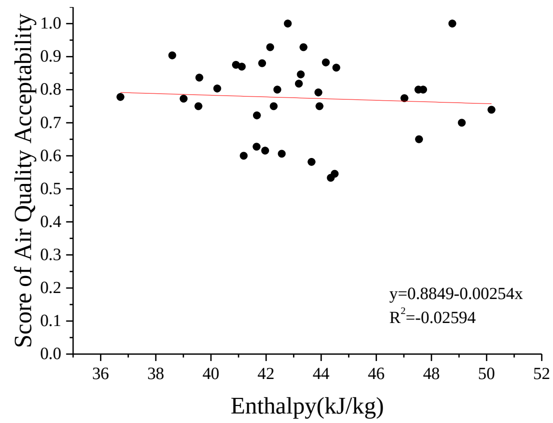
Fang *et al.* (1998a, 1998b) found that adapted perception of occupants for indoor air quality was strongly correlated with temperature. When temperature was decreased, the perceived air quality may significantly improve. And their study further found that acceptability of air linearly increased with decreasing enthalpy of the air. However, Humphreys *et al.* (2002) found that the subjective thermal state of the participants influence the perceived air quality rather than temperature. Those who successfully adapted thermally to warmer room temperatures did not report deterioration in perceived air quality, and the perceived air quality reached the best under neutral conditions. More recently, Yang Geng *et al.* (2017) found that when thermal environment was unsatisfactory, it weakened the "comfort expectation" of other indoor environment factors including the perception of indoor air quality, which accordingly resulted in the less dissatisfaction of indoor air quality. Meiling He *et al.* (2017) found that under moderate humidity condition, temperature did not significantly affect the perceived air quality.

In order to understand the effect of temperature on perceived air quality, the regression analysis was used to assess the correlation of air quality acceptability with the temperature, enthalpy, thermal sensation and thermal acceptability and shown in Figure 12. It was found that under the experiment conditions (neutral to warm temperature and moderate humidity), the correlation coefficient between indoor air temperature and air quality acceptability is 0.0525, the correlation coefficient between enthalpy and air quality acceptability is 0.0260 and the correlation coefficient between thermal acceptability and air quality acceptability is 0.0307. These indicates that temperature, enthalpy, and thermal acceptability have no correlation with air quality acceptability. The correlation coefficient between thermal sensation and air quality acceptability is 0.2995, which is relatively high. This indicates that the thermal sensation has a relatively strong correlation with air quality acceptability.

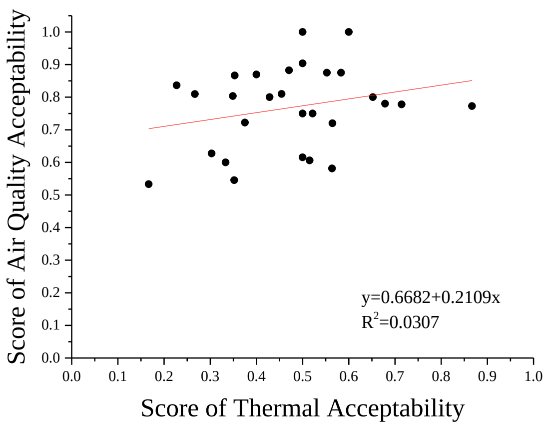
The results consistent with those of Humphreys and Meiling He. It is the thermal sensation that influences the acceptability of air quality. When the participants feel neutral about thermal environment, their perception for indoor air quality reached the best. For temperature, enthalpy and thermal acceptability are not obviously relative with the perceived indoor air quality.



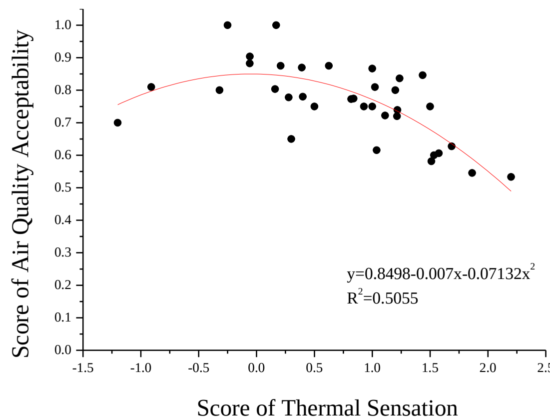
(a) Temperature



(b) Enthalpy



(c) Thermal acceptability



(d) Thermal sensation

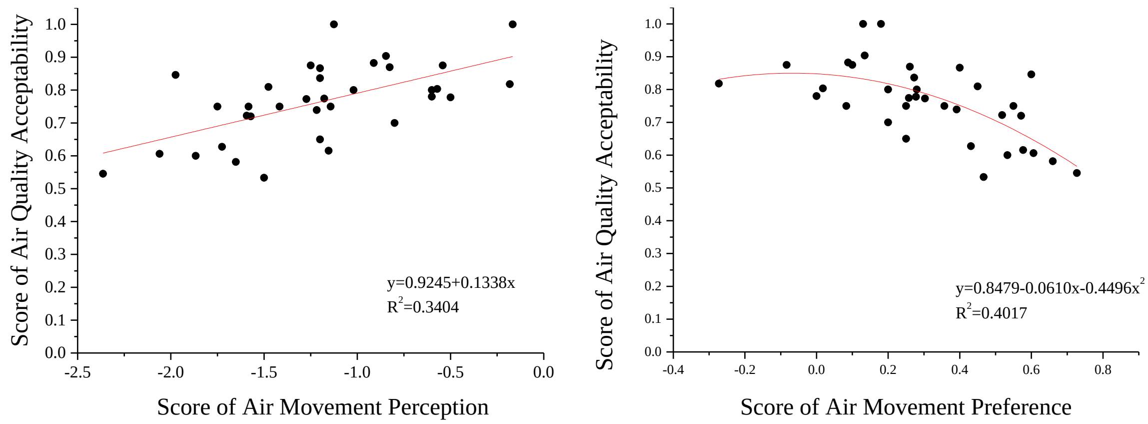
Figure 12: Air quality acceptability related to temperature (a), enthalpy (b), thermal acceptability (c), and thermal sensation (d)

3.3 The Effect of Air Movement on Perceived Air Quality

Arens E. *et al.* (2017) reported that perceived air quality was significant improved by air speed under neutral to warm temperatures. This is in accordance with Melikov and Kaczmarczyk (2012). They found that elevated the air velocity of the breathing zone could improve the perceived air quality. Our data support the previous findings.

Figure 13 shows the air quality acceptability with the air movement perception and the air movement preference. Figure 13(a) shows the correlation between air movement perception and air quality acceptability in natural ventilated classrooms. We can see from Figure 13(a) that in our experiment environment (moderate to warm temperature, moderate humidity, and small indoor air speed), when the score of air movement perception increases, the acceptability of indoor air has a rising tendency. The correlation coefficients between air movement perception and air quality acceptability is about 0.34. This indicates that increasing air movement perception will improve the acceptability of air quality.

Figure 13(b) shows the correlation between air movement preference and air quality acceptability. In Figure 13(b) it is found that the expectation for air movement influences the air quality acceptability. When participants feel that the air movement is just suitable, the acceptability of air quality reaches the best, and when participants feel that the air movement need to be adjusted, the air quality acceptability decreases.



(a) Air movement perception (b) Air movement preference

Figure 13: Air quality acceptability related to air movement perception (a) and air movement preference (b)

5. CONCLUSIONS

Based on the results and discussions, following conclusions can be drawn:

- Perceived air quality and air quality acceptability are not strongly related to indoor CO_2 concentrations and PM2.5 concentrations.
- Thermal sensation influences the acceptability of air quality. When the participants feel neutral about the thermal environment, their perception for indoor air quality reaches the best.
- There is no enough evidence to show that temperature, enthalpy and thermal acceptability are relative to the acceptability of indoor air quality.
- Air movement perception influences the air quality acceptability. With the increase of air movement perception, the acceptability of air quality is increased.
- The air movement preference influence the air quality acceptability. When participants feel the air movement is just suitable, the acceptability of air quality reaches the best, and when participants feel the air movement need to be adjusted, the air quality acceptability decreases.

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