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To cite this article: Shrestha Mishan and Rijal Hom Bahadur 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **294** 012062

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Study on Adaptive Thermal Comfort in Naturally Ventilated Secondary School Buildings in Nepal

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Abstract. Most of the Nepalese school buildings are naturally ventilated and poor in thermal insulation which causes thermal discomfort during cold and hot seasons. Thermally uncomfortable classroom causes a negative impact on the academic performance of students. So, there should be serious attention to improve and optimize the indoor thermal environment of the classroom. This study investigated the students' perceptions towards thermal comfort in naturally ventilated higher secondary school buildings during the autumn season of 2017 in a temperate climate (Dhading, Kathmandu and Nuwakot districts) of Nepal. 22 classrooms (33 students in average in each class) of 8 school buildings with a total of 818 students aged 12-18 years, 40% males and 60% females have participated. The thermal measurement and thermal comfort survey were conducted during the regular lesson period in each classroom. Students voted at the beginning, in the middle and at the end of the class in 15 minutes' interval of 45 minutes' lesson period. More than 76% responses of the students were found in the comfort zone with mean comfort temperature 27°C and the preferred temperature 26°C. The findings of this study may hopefully invoke the awareness for the school building designers, teachers and students to control the classroom environment without the use of air conditioning system.

1. Introduction

The students spend approximately 30% of their daily lives in school [1] for their study and other educational activities. The activities of the students are dependent on the indoor thermal environment of the classroom and thermal comfort. Thermal comfort is the state of mind that expresses the satisfaction with the thermal environment [2]. Extremely high or low indoor air temperature of classroom interrupts the learning ability of students and difficult to focus on their study. Thermally uncomfortable indoor environment causes health problems and less productivity of learning for no apparent reason [2]. In Nepal, most of the classrooms may not be able to meet the recommended thermal comfort condition. A satisfactory classroom is where more than 80% of the students perceive it thermally comfortable [2]. The acceptance of indoor thermal environment is directly connected with the building's performance [3]. The poor insulation and ventilation have a negative impact on the indoor thermal comfort of students. Most of the Nepalese school buildings are naturally ventilated and windows always remain open during school time. They are much more thermally dynamic compared to mechanically conditioned classrooms. The temperatures including other physical parameters like humidity, air velocity, carbon dioxide are easily varying in those building. In residential and office buildings, people use adaptive behavior to adjust thermal comfort. But it is not easy for the students inside the classroom as they are restricted to change their clothes, position, window open-close activities [4].

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Most of the countries have been conducting the thermal comfort survey in school buildings. But, in Nepal, such kind of study has not been conducted at all except in a few residential buildings [5]. International standards [2, 6, 7] are made for the indoor thermal comfort predictions of residential and office buildings. The frequently used standards are ASHRAE-55 [2], CEN 15251 [6] and ISO7730 [7]. ASHRAE-55 describes a method of compliance for designed spaces and adaptive method for naturally ventilated spaces. ISO7730 is based on Fangers' Predicted Mean Vote (PMV) that presents the method of calculation of mean thermal sensation of people and the Predicted Percentage of people Dissatisfied (PPD) with the thermal environments. CEN 15251 specifies indoor environmental parameters for design and performance of buildings addressing air quality, thermal environment, lighting, and acoustics. The particular thermal comfort standard for the school buildings has not been developed. This paper, therefore, investigates students' comfort level in naturally ventilated school buildings of Nepal.

The summary of thermal comfort studies conducted in different areas is presented below which investigated the comfort status of students in school buildings. These studies established their own comfort models and comfortable temperature. Kwok [8] conducted a long-term thermal comfort field study in an air-conditioned and non-air-conditioned school building over 3,544 students in Hawaii and found that 75% of the classrooms were not able to meet the comfort requirements prescribed by ASHRAE-55 [2]. This study estimated that the preferred temperature of the students is higher than the neutral temperature in naturally ventilated school buildings than in air-conditioned. The neutrality of the students is different than adults due to the activity in the classroom, clothing and environmental parameters. This was found in the study of Teli et al. [9,10] which concluded that the comfort temperature of students is 2K lower than adults. The similar kind of result is found in the study conducted in NV classrooms in Iran by Haddad et al. [11]. The comfort temperature found in this study was lower than the temperature prescribed in ASHRAE adaptive model [2] during the warm season. Studies conducted in Taiwan [12,13] for summer months found that the thermal sensitivity of the students is more in summer than winter. Further, Liang et al. [18] investigated the effects of buildings envelope energy regulations on thermal comfort level in NV classrooms in primary and secondary schools. They found the significant impact of building energy regulation on the level of thermal comfort. de Dear et al. [14] conducted a study in Australian primary classrooms. They found the same value of comfort temperature and preferred temperature of 22.5 °C which is lower than adults under the same thermal environments. A study conducted over 10 million US secondary school students over 13 years found the negative impact on exam result in hot weather [15]. They found 0.55°C increase in average temperature over the year, there was a 1% fall in learning.

Therefore, it is necessary to make an analysis for a better understanding of indoor thermal environmental necessities and the follow up thermal comfort requirements. Our study aims to find the thermal comfort level of the students under the naturally ventilated condition. The main objectives of this study are: 1) to find the thermal perception of the students under the naturally ventilated mode, 2) to find the comfort temperature and preferred temperature of the students, 3) to investigate the gender difference of comfort temperature, and 4) to compare data of this study with thermal comfort standards.

2. Methodology

2.1. Study areas and buildings

A field study was conducted in three districts (Dhading, Kathmandu, and Nuwakot) in the temperate climate of Nepal in September-October of 2017. The survey was conducted in 22 classrooms of 8 naturally ventilated school buildings. Most of the school buildings were two stories and walls are finishes with of bricks and stones mortar plaster. Their structure is the reinforced concrete. The general type of buildings and classrooms are shown in Figure 1. The walls are not insulated and the students have to accept varied indoor thermal conditions. The students from grade 8,9 and 10 in each school participated in the field study: altogether 818 students, 489 females (60%), 329 males (40%) with age group of 12-18 years. Each student voted three times in 45 minutes' lecture and we gathered 2454 responses. The average number of students in each classroom were 33 persons. The survey was conducted for a couple of times between 10:00 and 16:00

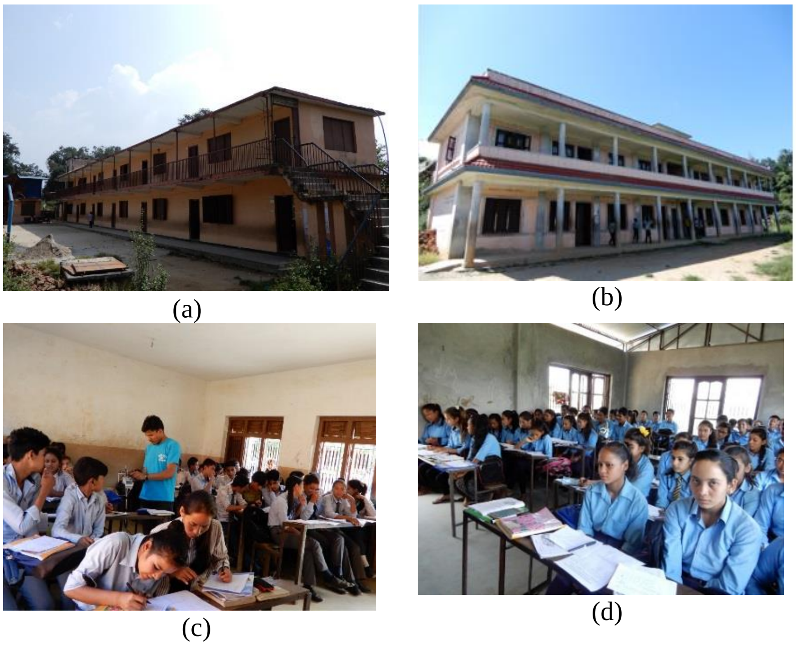

Figure 1: View of investigated school buildings (a, b) and classrooms (c, d)

2.2. Thermal measurements

The physical parameters such as air temperature, relative humidity, globe temperature, surface temperature, air movement, and lighting level were measured using digital instruments (Fig. 2). Table 1 presents the details of digital instruments used in the field study to measure the environmental conditions. The parameters were recorded at a height of around 1m above the floor level and measured three times at the interval of 15 minutes for a 45-minute lecture.

Figure 2: Digital instruments

2.3. Thermal comfort survey

Students voted for their perception of thermal sensation, thermal preference, thermal acceptance and overall comfort under sedentary conditions in regular lecture. The purpose of the survey was explained to students and guided to fill up the questionnaire. They responded three times: at the beginning, in the middle and at the end of the class based on sensation scale (Table 2). For easily understand and better response from students, scales were translated into Nepalese language [5].

Table 1: Description of survey instruments

Parameter measured	Sensors	Range	Accuracy	Name of instruments
Air temperature	Thermistor	0-55ºC	±0.5ºC	TR-74Ui
Relative humidity	Polymer membrane	10-95%	±5% RH	TR-74Ui
Globe temperature	Metalic globe, 75 mm-diameter globe	-60 to 155ºC	±0.3ºC	Tr-52i, SIBATA, 080340-75
Air velocity	Hot-wire anemometer	0 to 30m/s	±0.015 m/s	Trust Science Inovation (TSI) 9535
Carbondioxide	Nondispersive infrared analyzer	0 to 9,999 ppm	±50 ppm	TR-76Ui

Table 2: Scale for the thermal comfort survey

Scale	Thermal sensation	Thermal preference	Overall comfort	Thermal acceptance
0				Acceptable
1	Very cold	Much warmer	Very comfortable	Unacceptable
2	cold	A bit Warmer	Moderately Comfortable	
3	Slightly cold	No change	Slightly comfortable	
4	Neutral	A bit cooler	Slightly uncomfortable	
5	Slightly hot	Much cooler	Moderately uncomfortable	
6	Hot		Very uncomfortable	
7	Very hot			

3. Results and discussions

3.1. Indoor and outdoor temperatures

The detailed descriptions of mean indoor and outdoor environmental parameters of each naturally ventilated school buildings are shown in Table 3. In naturally ventilated school buildings, an indoor environment of the classroom is highly influenced by the outdoor environment. The season and region are the major factors that bring the change in air temperature. In this study, the mean indoor temperature ranged 23-32.6°C and mean outdoor temperature 22.3-34.9°C. The mean indoor temperature was 30.6°C which is highest in school S2 and lowest 23.5°C in school S4. Due to natural ventilation, the indoor and outdoor relative humidity was found to be similar (53%). The structure and the performance of the school buildings or classroom and the materials used are also other types of factors that effect in air temperature which could be confirmed by our measured data. Fig. 3 shows the box plot of indoor and outdoor temperature of each school buildings. The mean globe and outdoor air temperatures are different for each school buildings.

Table 3: Mean indoor and outdoor parameters

School	Temperature [˚C]						Relative humidity [%]				Air velocity [m/s]		CO2 [ppm]	
	Indoor globe		Indoor		Outdoor		Indoor		Outdoor					
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
S1	28	0.6	28.3	0.7	27.7	0.7	60.8	2.8	63.3	2.8	0.06	0.05	391	36.7
S2	30.6	0.4	30.6	0.5	33.9	0.7	48.9	3.3	41.7	3.6	0.12	0.02	450	18.9
S3	29.9	1.3	30.1	1.5	29.8	1.3	58.1	8.9	59.3	3.6	0.09	0.07	522	162.7
S4	23.5	0.2	23.5	0.2	25.5	0.7	56.8	1	53.0	2.8	0.09	0.03	410	25.5
S5	27.6	0.8	27.5	0.7	27.6	0.9	50.3	1.6	51.9	2.1	0.11	0.05	483	60.3
S6	26.4	0.5	26.4	0.5	25.4	0.6	49.2	2.8	53.9	3.1	0.10	0.04	415	28.2
S7	25.5	0.6	25.6	0.9	27.2	2.4	36.3	2.0	35.0	6.3	0.13	0.04	485	58.8
S8	24.4	1	25	1	25	2.6	69.1	6	72.1	10.6	0.12	0.07	370	17.7
Mean	27.4	2.6	27.6	2.6	28.3	3.2	53.1	10.5	52.8	12.2	0.10	0.05	454	98

S1: Kewalpur Harihar Bhajkumari School (Dhading)
S2: Bhuwaneshwori Secondary School (Dhading)
S3: Mahankaleshwori Secondary School (Dhading)
S4: Jyoti Secondary School (Dhading)
S5: Gramsewa Secondary School (Kathmandu)
S6: Pragya Commerce College (Kathmandu)
S7: Greenland Int'l Secondary School (Kathmandu)
S8: Belkot Bhanjyang Secondary school(Nuwakot)

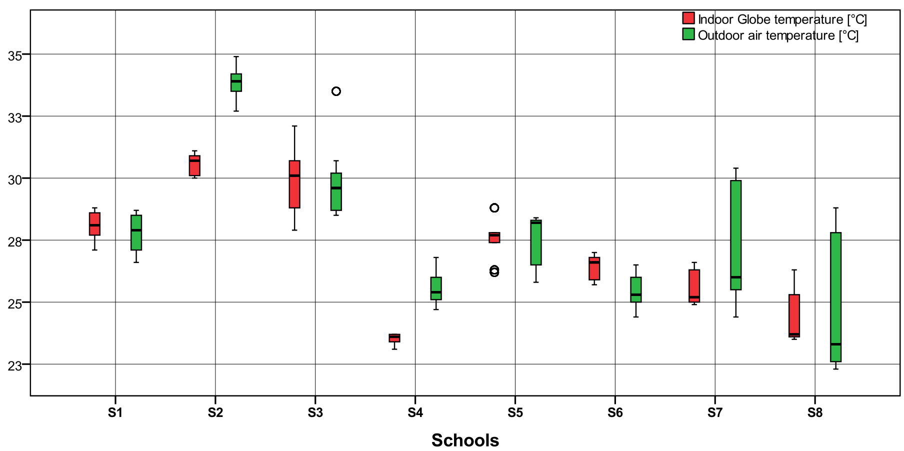

Figure 3: Box plot of the outdoor air temperature and indoor globe temperature

3.2. Thermal sensation and preference

The thermal perception of the students was collected using the modified 7-point ASHRAE scale [2]. Figure 4 shows the distribution of students' response in thermal sensation indicating 95% confidence interval error bars. In Fanger's thermal comfort model [25], the central three categories of the 7-point thermal sensation vote (TSV) are said to be satisfied in their indoor thermal environment. In our study, about 76%, 77% and 77% responses of the students were found in comfort zone in the classrooms of Dhading, Kathmandu and Nuwakot districts. The responses on "very cold", "cold", "hot" and "very hot" can be expressed in thermal dissatisfaction: 24% (Dhading), 22% (Kathmandu) and 24% (Nuwakot) where a student experienced thermal discomfort. According to the ASHRAE standard [2], the classroom needs to satisfy 80% acceptability level which is closed to this research. Nuwakot has fewer responses on neutral It might be the reason that students of Nuwakot were settled in the temporary shelter made by zinc after massive earthquake 2015. However, the mean thermal sensation of all areas was found to be neutral. The votes on very hot and very cold sides are expected from those students who were seated on window side who were directly affected by the solar radiation and the high or very low air movement.

Thermal preference (TP) of the students was collected using a 5-point thermal preference scale. Figure 5 shows the distribution of students' thermal preference. Students who responded on "No change": Dhading (34%), Kathmandu (41%) and Nuwakot (34%) were able to accept the indoor environment. It means that they do not want to change their current indoor thermal environment. However, the mean thermal preference for all areas was found to be slightly cooler.

Overall, about 76% of the students responded comfortable on thermal sensation preferring a slightly cooler temperature.

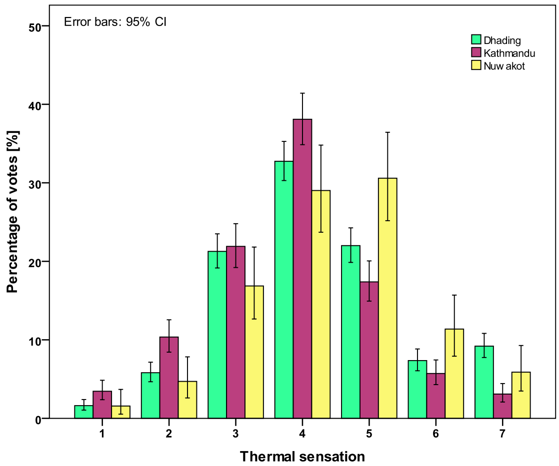

Figure 4: Distribution of thermal sensation

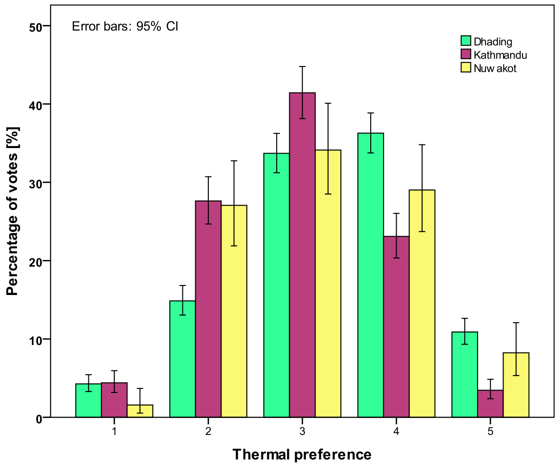

Figure 5: Distribution of thermal preference

3.3. Thermal acceptance

A direct binary question were asked to students to obtain responses on thermal acceptance. The distribution of thermal acceptance is shown in Figure 6. More than 85% of the responses were acceptable for their immediate classroom environment: Dhading (85%), Kathmandu (94%) and Nuwakot (92%). This result shows the satisfaction of students with their current environments. The psychological adaption of the students is the reason to have a higher percentage of acceptability in the naturally ventilated classroom. The restriction of binary response on the question to response might be another reason to have a higher percentage of thermal acceptability.

3.4. Overall comfort

We obtained responses on current classroom thermal environment using a 6-point scale. The distribution of responses on the overall thermal comfort level of students is presented in Figure 7. Most of the responses in all three districts were found to be quite high for moderately comfortable: Dhading (31%),

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Kathmandu (41%) and Nuwakot (44%). Less percentage of responses was obtained for "very comfortable" and "very uncomfortable".

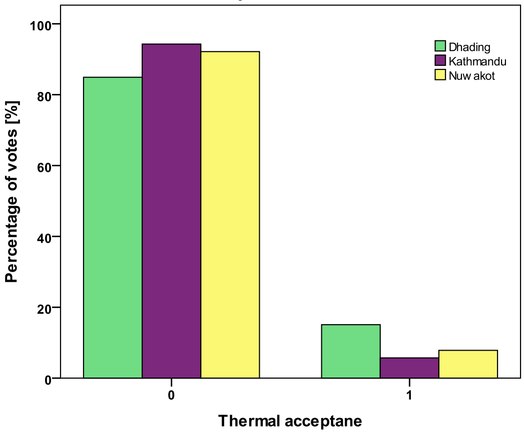

Figure 6: Distribution of thermal acceptance

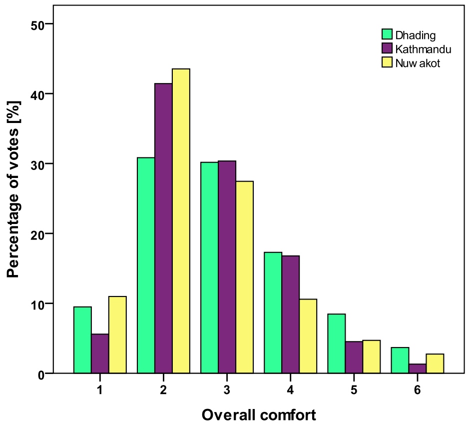

Figure 7: Distribution of overall comfort

3.5. *Acceptable temperature range*

The relationship between the thermal sensation and indoor globe temperature (T_g) helps to determine the acceptable range of comfort temperature. The comfort temperature is the indoor globe temperature at which most of the students will response for neutral on TSV scale. The quadratic regression relationship between the thermal sensation and indoor globe temperature for three districts in combine is shown in Figure 8. This is to clarify the acceptable range of temperature for the classrooms of investigated areas. We classified the responses of students into two binary groups. Very cold, cold, hot and very hot responses are grouped as "uncomfortable". The rest (slightly cold, neutral and slightly warm) are grouped as "comfortable". The ASHRAE -55 [2] suggested the central zone as comfortable if 80% of responses fall within this zone. The combined quadratic regression equation between the proportion of comfortable and indoor globe temperature for the classrooms of three districts using quadratic regression method are presented below:

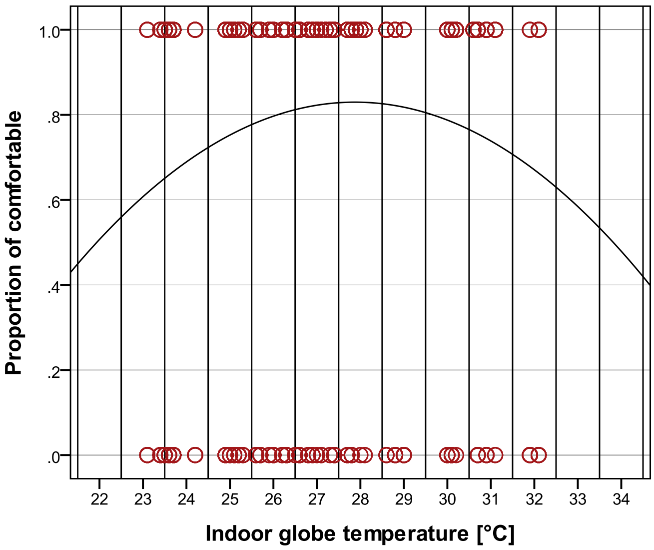

Figure 8: Relationship between the proportion of comfortable and indoor globe temperature

$$P_{comfortable} = -0.009T_g^2+0.521T_g-6.436 \quad (1)$$

(N=2454, R^2= 0.02, S.E.$_1$ = 0.001, S.E.$_2$ = 0.077, p<0.001)

Where N: Number of responses, R^2: Coefficient of determination, S.E.$_1$, and S.E.$_2$: Standard errors of the regression coefficient of T_g^2 and T_g respectively, p: Significance level of the regression coefficient. The optimum comfort temperature found at the maximum value of $P_{comfortable}$ is equal to 28.9°C. The quadratic regression graph (Figure 8) yields an acceptable temperature range of 26.0-29.5°C at 80% acceptability for all the visited schools of three districts. It is also cleared that the students in the naturally ventilated classroom are comfortable and adapted at a higher temperature up to 29°C. The high air movement in the naturally ventilated classroom may be one of the reasons to be comfortable at higher air temperature. Comfortable is sharply decreased below or above this comfort range.

3.6. *Comfort temperature*

We also estimated the comfort temperature (T_c) using linear regression (Fig. 9). The linear regression equations of thermal sensation and indoor globe temperature for all districts are shown in Table 4. From combined linear regression we found a regression coefficient (sensitivity) of 0.17 thermal sensation per °C. It shows a unit change in thermal sensation for 6°C change in indoor globe temperature. The estimated mean comfort temperature is 27.1°C. The facts reason might be that the students are adapted and acclimatized in the classroom thermal environment.

We again estimated the comfort temperature using the Griffiths method [5, 26-28] which includes no adaptive effects. The following Griffiths equation is used to calculate the comfort temperature.

$$T_c=T_g + (4-TSV)/a \qquad (2)$$

Where T_c: Comfort temperature (°C), *TSV*: Thermal sensation vote and a: Griffiths constant (0.05).

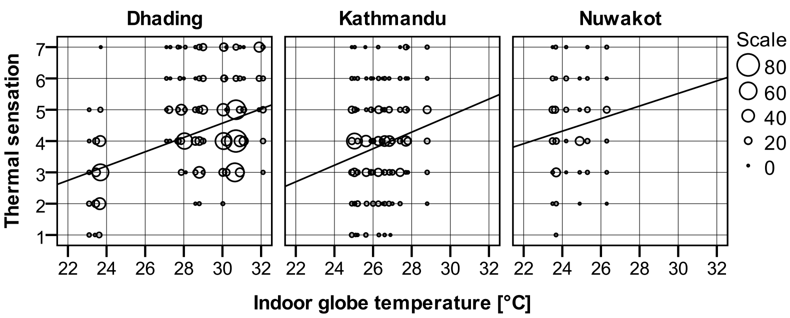

Figure 9: Relationship between the thermal sensation and indoor globe temperature

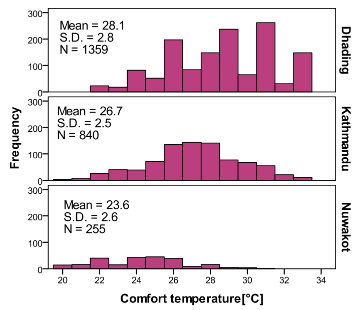

Figure 10: Distribution of comfort temperature

Figure 10 shows the distribution of Griffiths comfort temperature.

The comfort temperatures of the students for the three districts are 28.1°C, 26.7°C and 23. 6°C. The mean comfort temperature for all districts is found to be 27.2°C. We further analyse the comfort temperature by gender (Fig. 11). The present study found the following regressions equations for individual comfort temperature of students:

$$TSV_{male} = 0.15T_{op}+0.20 \text{ (N=987, } R^2\text{=0.079, S.E. =0.016, } p< 0.001) \qquad (3)$$

$$TSV_{female}=0.19T_{op}-1.21 \text{(N=1467, } R^2\text{=0.0142, S.E. =0.012, } p< 0.001) \qquad (4)$$

The estimated comfort temperature is 25.3°C for male and 27.4°C for female students. It seems that females are more sensitive to coldness than male students.

These results are similar to a study conducted by Tanabe et al. [29] with respect to college-age students.

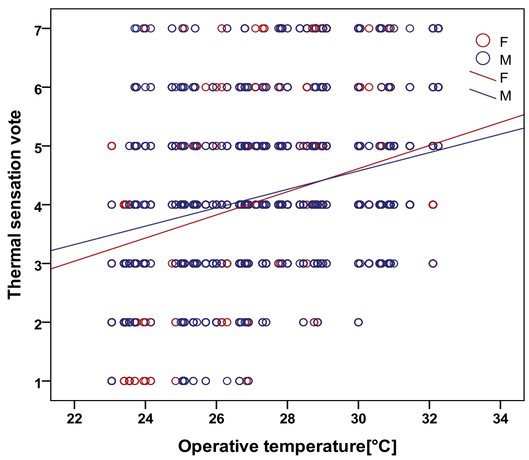

Figure 11: Relationship between the thermal sensation and indoor operative temperature

Table 4: Linear regression equation of the thermal responses and indoor globe temperature

Study areas	Responses (N)	Equations	R^2	Equations	R^2	T_c [°C]	T_p [°C]	Δt [°C]
Dhading	1359	$TSV = 0.23T_g - 2.3$	0.2	$TP = 0.19T_g - 2.1$	0.26	27.4	26.8	0.6
Kathmandu	840	$TSV = 0.26T_g - 3.1$	0.05	$TP = 0.18T_g - 1.7$	0.05	27.3	26.1	1.2
Nuwakot	255	$TSV = 0.26T_g - 3.1$	0.05	$TP = 0.27T_g - 3.5$	0.08	22.5	24.1	-1.6
All	2454	$TSV = 0.17T_g - 0.6$	0.11	$TP = 0.16T_g - 1.2$	0.18	27.1	26.2	0.9

3.7. Preferred temperature

Students preferred the temperature slightly lower or higher for a hot or cold classroom. The neutral thermal sensation vote does not necessarily mean the students are neutral to the indoor classroom environment. There is the possibility of wanting cooler or wanting warmer even experiencing neutral thermal sensation. Figure 12 shows the relationship between the thermal preference and indoor globe temperature. The regression equations and preferred temperature (T_p) are presented in Table 4. The mean preferred temperature is 26.2°C. The difference (Δt) between the comfort temperature and preferred temperature is found to be small.

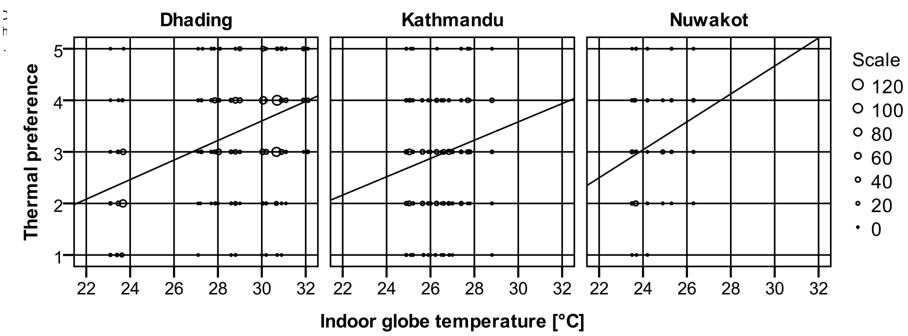

Figure 12: Relationship between the thermal preference and indoor globe temperature

3.8. Comparison with the ASHRAE adaptive model

The adaptive model is described using the relationship between the comfort temperature and the outdoor air temperature. In NV classrooms, students adapt themselves to indoor air temperature for given outdoor air temperature *(T_o)*. Therefore, the comfort temperature of the students varies corresponding to season and region [30]. We compare the comfort temperature of students with ASHRAE adaptive model. The ASHRAE-55 [2] adaptive model defines the acceptable zone of comfort temperature: 80% (±3.5K)

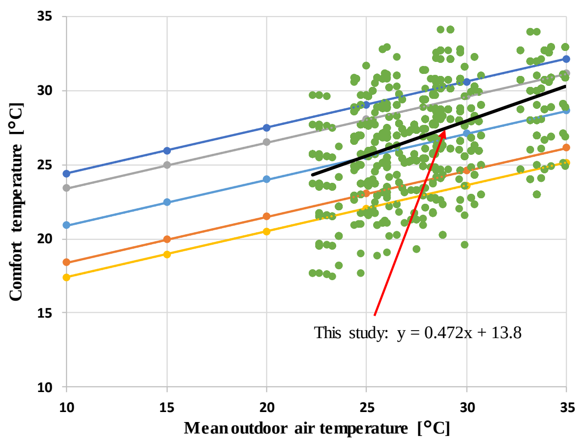

Figure 13: Comparison of comfort temperature with ASHRAE standard

and 90% (± 2.5K). The acceptable comfort temperature range corresponding to 80% and 90% thermal acceptability were calculated using the following equations [2, 31]:

$T_c = 0.31 T_o + 17.8$ (5)

Figure 13 shows the comfort temperature versus outdoor air temperature ASHRAE-55 adaptive model. The middle baseline with upper and lower limits of the comfort zone is shown in Figure 13. The diagram illustrates that the comfort temperature of students in naturally ventilated classrooms falls beyond the adaptive limits. It also showed that the students in NV classrooms are adapting to higher indoor temperature. Originally, ASHRAE model is developed for the office buildings collecting the huge amount of data from the different parts of the world. The design of the buildings and the behavior of the people in these buildings are different than the school buildings. The adaptive behaviors of the students in the classroom are limited. The results are in agreement with the recent studies [22-24] that describes the students accommodated in the naturally ventilated classroom have a wide range of comfort temperature.

4. Conclusions

This paper presents a thermal comfort study conducted for the first time in naturally ventilated school buildings in Nepal for the autumn season of 2017. The two simultaneous surveys: measurement survey and thermal comfort survey are conducted. Altogether 2454 responses were obtained form 818 students. The measurements and responses are obtained three times in 45 minutes of lecture. Based on the analysis of collected data, we have found the following results:

1. The indoor environment of the school buildings was found to be slightly warmer. About 76% responses of the students were found in the comfort zone.
2. The higher comfort temperature and the wider range of acceptable indoor comfort temperature show that the students might have a higher thermal tolerance level and a wider range of adjustment temperature in the naturally ventilated school buildings. The comfort temperature and preferred temperature was found to be around 27°C and 26°C respectively.
3. The comfort temperature for female students is slightly higher than male and female students are slightly sensitive to indoor temperature.
4. The comfort temperature of the students in naturally ventilated school buildings was found beyond the upper and lower limits of the ASHRAE standard, and thus the students are adapted to higher indoor air temperature.

Our analysis found that students in NV classroom preferred to be cooler and so they want more air movement inside the classroom. This study only does not cover all the information on the thermal comfort level of students in Nepalese school buildings. So, we need further field studies in other seasons and their results to expand the understanding of thermal comfort level of students in naturally ventilated school buildings and classrooms.

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