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Thermal comfort assessment and characteristics of occupant's behaviour in naturally ventilated buildings in composite climate of India

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ABSTRACT

Energy consumption in Indian building sector is increasing at high rate. The National Building Code of India specifies a narrow comfort temperature range between 21 °C and 26 °C for all types of buildings and for all seasons. A thermal comfort field study was conducted in 32 naturally ventilated buildings, collecting a total of 2610 samples spread over a total period of four years, covering multiple seasons, age groups, clothing types and building types. Questionnaires were administered to building occupants to record sensations and preferences for air temperature, relative humidity and air velocity on ASHRAE seven point and five point scales. The objective of the study was to evaluate thermal comfort of occupants and study the methods of thermal adaptation such as adjusting clothing, window opening, and use of air circulation fans. Griffith's method was used to determine thermal neutrality. The comfort temperature for summer and winter season was found to be 30.6 °C and 25.2 °C, respectively. Preferred clothing level for summer was found to be 0.30 clo, whereas in winter it was 0.80 clo. Preferred air velocity was observed as 0.62 m/s in summer season and 0.27 m/s in winter. Controlling air velocity has been found to be preferred method of thermal adaptation over adjusting clothing and window opening.

Introduction

The internationally accepted standard for defining thermal comfort conditions (American Society of Heating, Refrigerating and Air-conditioning Engineers Inc., 2013; ISO 7730, 2005), is based on Fanger's heat balance model of the human body. This heat balance model, also called PMV (Predicted Mean Vote) / PPD (Percentage People Dissatisfied) model, is among the most widely accepted models for building thermal design and determination of thermal comfort conditions especially in air conditioned spaces. The evidence of critical role played by psychological, physiological and socio-cultural aspects of adaptation in defining comfort standards has led researchers to question the universal applicability of uniform comfort conditions suggested by these standards (Brager and de Dear, 1998; Humphreys and Nicol, 1998; Yao et al., 2009; Nicol, 2004).

An alternative to the PMV/PDD model is the adaptive model, which is based on the results of field studies conducted since 1960s (Auliciems, 1981; Nicol et al., 2012). According to the adaptive hypothesis, contextual factors and past thermal history modify the occupant's thermal expectations and preferences. Currently, the adaptive model is widely accepted as efficient tool in predicting indoor comfort conditions for naturally ventilated buildings (American Society of Heating, Refrigerating and Air-conditioning Engineers Inc., 2013; Brager and de Dear, 1998; Cândido et al., 2011).

The National Building Code of India of 2005 (Bureau of Indian Standards (BIS), 2007) defines two indoor temperature ranges, for summer 23 °C–26 °C and winter 21 °C–23 °C. These are supposed to be applicable for conditioned as well as naturally ventilated buildings.

Sharma and Ali (Sharaf\at and Sharma, 1986) carried out thermal comfort study in tropical climate of India and reported high comfort temperature range (25 °C–30 °C).

Indraganti (2010a) carried out thermal comfort field study in naturally ventilated apartment and found a neutral temperature of 29.2 °C for studied subjects in summer season.

Singh et al. (2010) carried out a field study for vernacular architecture of North-Eastern India for three climatic zones and demonstrated seasonal and regional differences in neutral temperature.

Dhaka et al. (2015) carried out a thermal comfort study for naturally ventilated buildings in composite climate of Jaipur and found a neutral temperature of 27.2 °C for all seasons. This study was conducted mainly with young subjects. Differences in age were not considered. Moreover this study did not include analysis of occupant behaviour and adaptation.

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It has been found that most of the studies conducted in India so far had carried out data collection from one particular building type, including study conducted by Sharma and Ali (Sharafat and Sharma, 1986), Indraganti (2010a) and Singh et al. (2010). Even the recent work for project IMAC (Indian model for adaptive thermal comfort) (Manu et al., 2016), only included office buildings, and is carried out with very limited surveys from four months of the year.

Research on adaptive comfort, specifically in warm to hot climates, has revealed that occupants in naturally ventilated buildings are more tolerant towards high fluctuations encountered in indoor environmental conditions (Sharafat and Sharma, 1986; Nicol, 1974; Wong and Feriadi, 2004).

In a naturally ventilated building, occupants use several adaptive opportunities and controls such as operable windows, doors, blinds, curtains, fans & fan regulator for adjustment of air velocity to make themselves comfortable in the changing thermal environment. Uses of these adaptive controls are also affected by seasonal and climatic variations in indoor conditions (Brager et al., 2004; Indraganti, 2010b; Rijal et al., 2007, 2008).

Most of the current research in other countries is aiming at the prediction of occupant behaviour and use of various controls; simultaneously developing algorithms of occupant's controls. Algorithms developed through such studies can be utilized for simulation of buildings (Nicol and Humphreys, 2004). However, a very few studies have been reported for the use of various behavioural controls in residential and educational environments from Indian building sector in recent years (Dhaka et al., 2013; Indraganti, 2010c).

The present study was conducted to find out the range of neutral temperature specific to naturally ventilated buildings in composite climate and occupants' behaviour in the context of control strategies. This paper summarizes a thermal comfort field study conducted in 32 naturally ventilated buildings in composite climate zone of India.

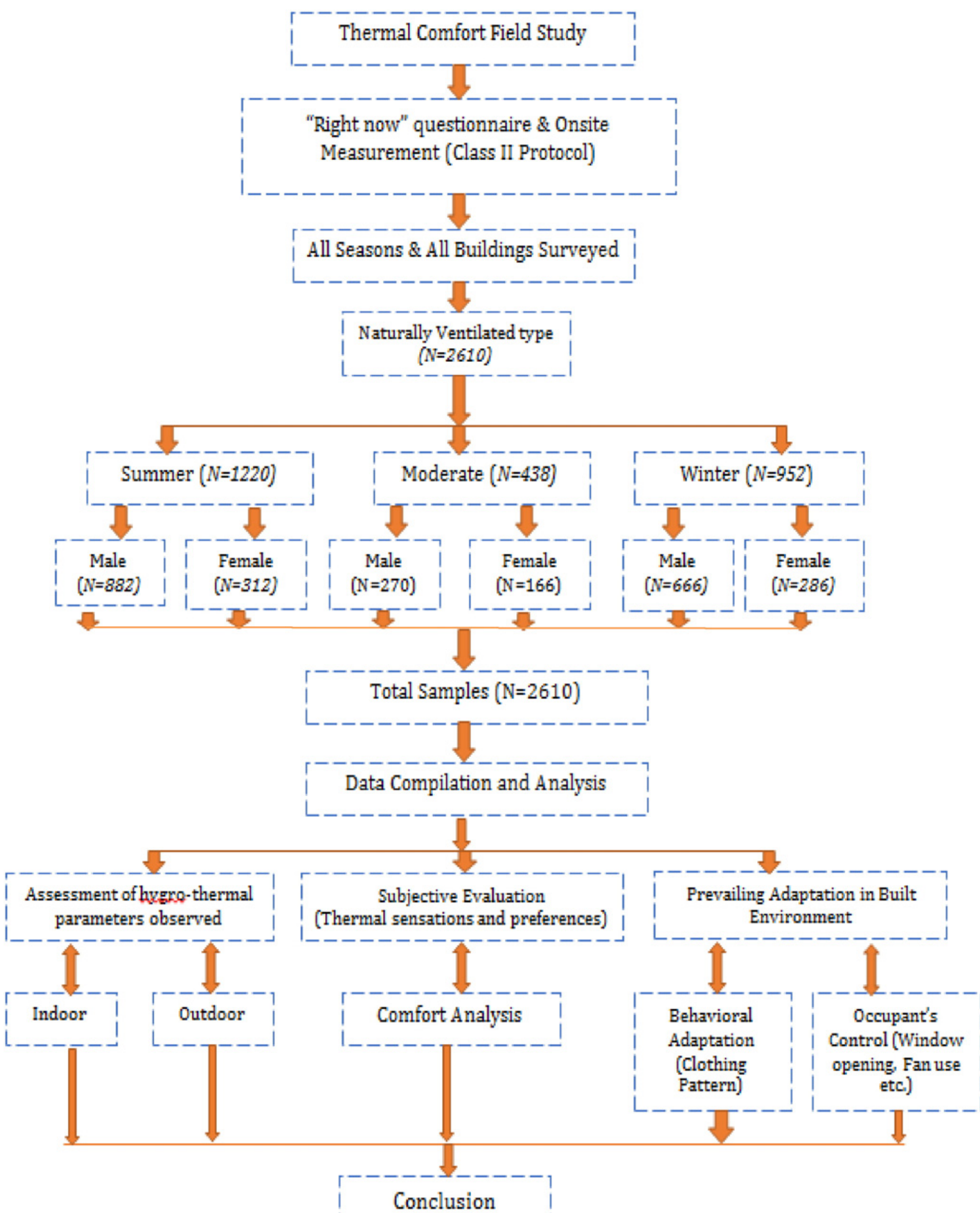


Fig. 1. Methodology of the study.

Methodology

Description of field study

The field study of thermal comfort was performed in the composite climate of Jaipur (26.82°N, 75.80°E and 390 m mean sea level) for 14 offices and 18 residential buildings for a period of four years (April, 2011–July, 2015). Fig. 1 shows the overview of the methodology of this study. Meteorological conditions under this climate vary from extremely hot during summer to chilling cold during winter. Summer peak temperature soars above 45 °C, and then falls to about 4 °C in winter. Due to this large variation, months across the year are segregated into three categories, namely, summer, moderate, and winter. In the present study, a particular month is considered winter if the daily mean outdoor temperature varied between 4 °C–25 °C for minimum 20 equivalent days (480 h). Likewise, a particular month is considered summer if daily mean outdoor temperature was more than 27 °C for more than or equal to 20 equivalent days. If any month, is neither winter nor summer as per above criteria, it is considered as moderate (Dhaka et al., 2015; Bansal and Milne, 1995). This approach was adopted for categorization of climatic zones of India that are presented in the National Building Code of India and Energy Conservation Building Code (Bureau of Indian Standards (BIS), 2005; Bureau of Energy Efficiency, 2007).

Following this approach, in Jaipur, the summer season is of six months (April–September), winter of four months (November–February), separated by the moderate season of two months (March and October). The present thermal comfort surveys were conducted covering multiple seasons.

Building selection and data collection

In this study, the buildings were named as O1–O14 for office stock and R15–R32 for residential stock. These buildings lie within a radius of 10 km in Jaipur city. Table 1 presents the details of the buildings, mode of operation, ownership and subjects who participated in the study. In these buildings walls were constructed of brick/stone walls of 0.20–0.23 m and roofs of Reinforced Cement Concrete (RCC) were used. Window assemblies were largely, single clear glass panes of 4–8 mm thickness, except a few newer buildings that have doubled glazed windows. The surveyed buildings were naturally ventilated and provide opportunities for use of adaptive controls to the occupants such as opening or closing of windows and doors, control of ventilators, and operation of fan and fan speed regulators.

The transverse type questionnaire was used as per the study conducted by Dhaka et al. (2013). Section-A of the questionnaire consists of thermal sensation and preference votes for environment conditions such as air temperature, relative humidity, air velocity and lighting on ASHRAE seven-point sensation and five-point preference scales. Section-B of the survey form was used to measure the environmental parameters and the environmental conditions surrounding the study subjects.

A brief introduction was given to subjects before they started filling the questionnaire to minimize the chances of human error in understanding the purpose of survey. While subjects were responding to the questionnaire, environmental parameters, personal parameters and environmental controls in subject's surroundings were recorded. During the survey, care was taken that the functioning conditions of the building and occupants' settings are not modified.

Table 1
Buildings and subjects surveyed details.

Building details				Subject's details		
Building title	Type (office/residential)	Age of buildings (years)	Ownership	Sample size	Male sample	Female samples
O1	Office	40	Govt.	175	140	35
O2	Office	8	Govt.	95	57	38
O3	Office	25	Govt.	12	7	5
O4	Office	40	Private	25	20	5
O5	Office	10	Govt.	98	85	13
O6	Office	15	Private	5	2	3
O7	Office	15	Private	12	9	3
O8	Office	10	Private	8	7	1
O9	Office	10	Private	12	10	2
O10	Office	40	Govt.	24	24	0
O11	Office	10	Private	7	3	4
O12	Office	30	Govt.	38	33	5
O13	Office	10	Private	36	24	12
O14	Office	30	Govt.	64	54	10
R16	Residential	40	Govt.	248	248	–
R17	Residential	40	Govt.	33	33	–
R18	Residential	40	Govt.	55	–	55
R19	Residential	30	Govt.	5	5	–
R20	Residential	30	Govt.	228	228	–
R21	Residential	40	Govt.	228	228	–
R22	Residential	40	Govt.	108	108	–
R23	Residential	40	Govt.	206	206	–
R24	Residential	25	Govt.	18	12	6
R25	Residential	10	Govt.	335		335
R26	Residential	40	Govt.	38	38	–
R27	Residential	40	Govt.	70	60	–
R28	Residential	30	Govt.	249	240	9
R29	Residential	40	Govt.	32	32	–
R30	Residential	10	Private	38	30	8
R31	Residential	10	Private	73	50	23
R32	Residential	10	Private	35	10	25
All	32			2610	2013	597

R: residential; O: office.

Table 2
Details of instruments used in the field study for environmental measurements.

S. No.	Parameter	Instrument	Make	Range	Accuracy
1	Outdoor temperature	Weather station (MNIT, Jaipur)	Virtual instrumentation	−40–123.8 °C	±0.5 °C(5–40 °C)
2	Indoor air temperature	480 VAC	Testo	−20–70 °C	±0.5 °C
3	Globe temperature	480 VAC	Testo	0–120 °C	±0.5 °C
4	Relative humidity	480 VAC	Testo	0–100% RH	±(1.0% RH + 0.7% reading)
5	Air velocity	480 VAC	Testo	0–5 m/s	±(0.03 m/s + 4 reading)
6	CO_2	435-2	Testo	0–10,000 ppm	±(50 ppm CO_2 + 2% of reading)
7	Lighting level	LX-103	Lutron	0–50,000 lx	±4% of 10 digit

Table 3
Summary of subject's details.

Variable	Seasons															
	Summer				Moderate				Winter				All seasons			
	Male		Female		Male		Female		Male		Female		Male		Female	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Sample size	882		312		270		166		270		166		2013		597	
Age	27	10.4	22	6.8	22	6.2	21	3.6	24	5.1	20	2.1	25	7.8	21	4.8
Weight (kg)	65.9	11.30	52.1	7.16	64.4	10.02	51.9	7.09	64.0	11.63	50.7	7.18	63.8	9.83	51.4	7.12
BSA	1.75	0.16	1.53	0.13	1.73	0.18	1.51	0.11	1.76	0.18	1.49	0.14	1.75	0.17	1.50	0.13
$I_{cl,tot}$(clo)	0.31	0.08	0.42	0.09	0.34	0.07	0.43	0.08	0.67	0.22	0.65	0.20	0.41	0.19	0.46	0.19
Activity (Met)	1.08	0.15	1.1	0.11	1.07	0.17	1.03	0.11	1.04	0.10	1.01	0.07	1.06	0.14	1.06	0.11

M: mean of sample; SD: standard deviation of sample size; BSA: body surface area.

Measurement of indoor and outdoor environments

Physical measurements of environment variables were recorded surrounding the subject using high accuracy instruments. The measurements were taken at a height of 1.1 m above the ground level following the Class-II protocol (American Society of Heating, Refrigerating and Air-conditioning Engineers Inc., 2013; ISO 7730, 2005). The measurement of environmental parameters such as air temperature, globe temperature, air velocity, and personal variables such as clothing level and metabolic activity (T_a, T_g, V_a, RH, clo, met) were recorded at the same time and place when the questionnaire was administered to the subjects. Table 2 demonstrates the details of instruments used in this study to measure the indoor conditions. Outdoor environmental data consisting of temperature and relative humidity for entire period of study was recorded from a weather station located at MNIT, Jaipur, India.

Sample size and description

The subjects were all Indian nationals well acclimatized to the composite climate of Jaipur for more than one year and were in the age group of 18–70 years. Each subject participated in the survey after he/she had settled in the environment for more than 20 min. The sample size varied across the seasons and a total of 2610 fully completed survey forms were obtained including responses from 2013 males and 597 females.

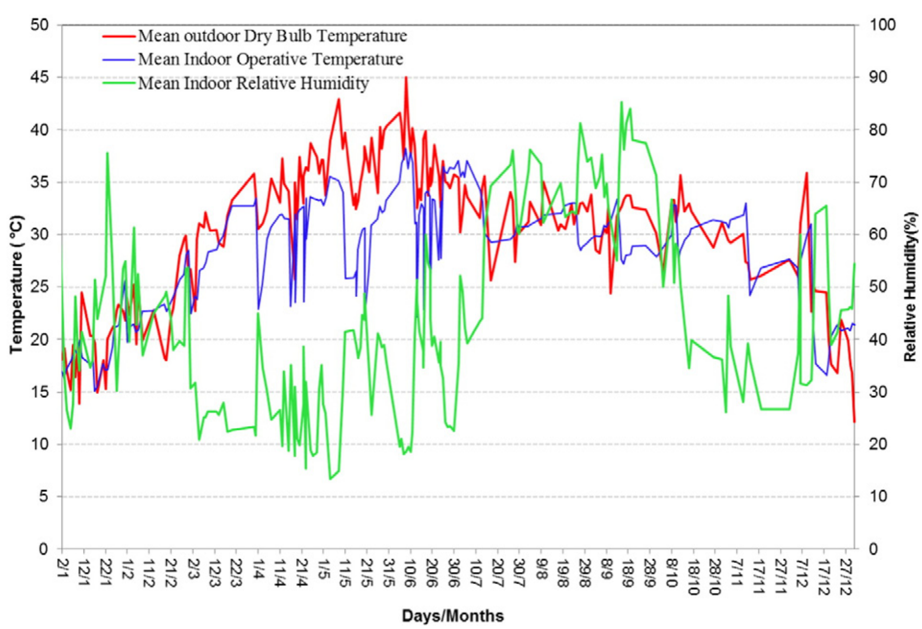


Fig. 2. Details of daily mean outdoor and indoor environmental parameters observed during field study.

Table 4
Descriptive indoor and outdoor environmental parameters observed.

Parameters	Seasons							
	Summer		Moderate		Winter		All seasons	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Sample size	1220		438		952		2610	
T_{mm} (°C)	30.2	3.44	25.6	3.02	17.5	2.87	25.0	6.66
T_o (°C)	34.0	3.39	31.3	2.77	22.8	4.38	29.4	6.56
T_a (°C)	31.7	2.87	29.1	2.97	21.9	3.62	27.7	5.49
T_{op} (°C)	31.8	2.86	29.2	2.89	22.1	3.60	27.8	5.42
T_g (°C)	31.9	2.87	29.3	2.84	22.4	3.60	28.0	5.37
RH (%)	46	20.1	32	12.2	43	13.8	43	17.8
Va (m/s)	0.62	0.39	0.57	0.37	0.27	0.19	0.60	0.43
CO_2	545	242	537	129	582	137	582	305
$I_{cl,tot}$ (clo)	0.34	0.15	0.34	0.06	0.67	0.14	0.42	0.15
Activity (Met)	1.08	0.13	1.06	0.14	1.04	0.10	1.06	0.12

T_{mm}: Outdoor monthly mean temperature (°C); T_o: Outdoor temperature (°C); T_a: Indoor air temperature (°C); T_{op}: Indoor operative temperature; T_g: Indoor globe temperature (°C); RH: Indoor relative humidity; V_a: Indoor air velocity (m/s); CO_2: Indoor CO_2 concentration (ppm); $I_{cl,tot}$: Total clothing insulation (clo); Met: Metabolic activities.

For clothing insulation and metabolic rates, we used the standard checklists provided in ASHRAE 55 (American Society of Heating, Refrigerating and Air-conditioning Engineers Inc., 2013). Clo-values for Indian women clothing including the cotton salwar—kameej, saari, etc. which are not available in ASHRAE 55 and ISO 7730, were taken from other India specific studies (Indraganti, 2010a; Mishra and Ramgopal, 2014). The mean activity of the subjects was observed to be nearly sedentary activity, i.e. 1.06 met (1 met = 58.2 W/m^2) and it shows that the subjects were mostly seated or doing light office work. A detailed description of sample size; each subject's physical characteristics such as age, weight, body surface area, clothing insulation and activity level has been recorded for all seasons and is presented in Table 3.

Results & discussion

Assessment of indoor and outdoor thermal environments

During the field study period, minimum and maximum outdoor dry bulb temperatures were 12 °C and 45 °C. Room air temperature varied

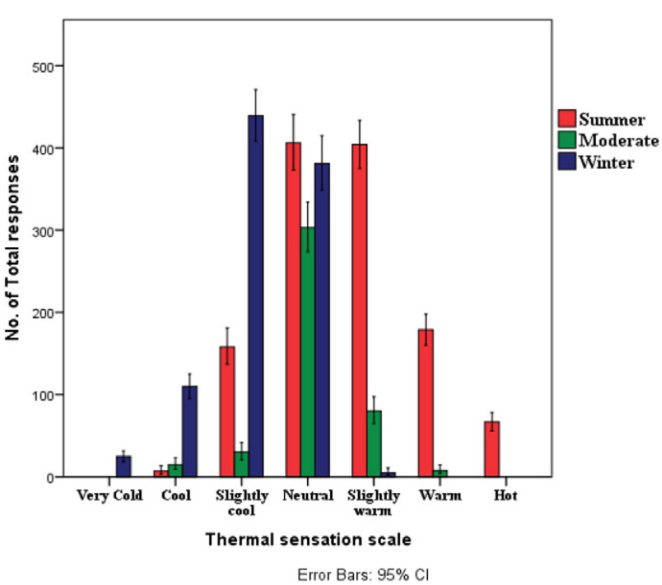


Fig. 3. Distribution of thermal sensation responses in different seasons for field study.

Table 5
Descriptive statistics of subjective thermal sensation and preference variables.

Variables	Seasons							
	Summer		Moderate		Winter		All seasons	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Sample size	1220		438		952		2610	
TSV	0.67	0.92	0.56	0.92	−0.75	0.76	0.16	1.24
TPV	−0.84	0.66	−0.51	0.78	0.37	0.80	−0.22	0.92
HSV	+0.21	1.26	−0.23	0.87	−0.35	0.82	0.13	1.09
HPV	−0.17	1.01	0.00	0.68	+0.10	0.66	0.00	0.85
AVS	−0.35	1.09	−0.25	1.01	−0.10	0.62	−0.10	0.97
APV	0.67	0.72	0.61	0.71	0.20	0.65	0.49	0.72
PMV	1.73	1.48	0.22	1.40	−1.90	1.18	0.14	2.15
PPD (%)	56.03	35.48	35.65	30.40	66.48	33.98	56.07	35.59

TSV: Thermal sensation vote; TPV: Thermal preference vote; HSV: Humidity sensation vote; HPV: Humidity preference vote; AVS: Air velocity sensation vote; AVP: Air velocity preference vote; PMV: Predicted Mean Vote; PPD: Predicted Percentage Dissatisfied.

between 14.4 °C and 39.1 °C and relative humidity was recorded between 8% and 96%. Fig. 2 shows the details of environmental parameters observed, viz. mean daily outdoor temperature, mean daily indoor operative temperature and mean daily indoor relative humidity for the whole study period.

The naturally ventilated buildings experience a higher fluctuation in mean indoor temperature, from winter (mean T_{op} = 22.1 °C, SD = 3.60) to moderate (mean T_{op} = 29.2 °C, SD = 2.89) to summer (mean T_{op} = 31.8 °C, SD = 2.86) during the study period. Subjects in naturally ventilated buildings are more responsive to various adaptive actions, viz. changing clothing level, the opening of window and doors, using fans to maintain comfort, and this phenomenon is more pronounced at the higher temperatures and relative humidity in the summer season. Correspondingly, the mean air velocity was observed to be higher during the summer (mean V_a = 0.62 m/s, SD = 0.39) than during the moderate season (mean V_a = 0.57 m/s, SD = 0.37) and winter (mean V_a = 0.27 m/s, SD = 0.19), respectively. Table 4 shows the statistical analysis of seasonal variation in outdoor and indoor variables observed during the field study.

Subjective thermal variables: evaluation of sensation and preferences

Sensation and preference for temperature (TSV & TPV)

Through the comfort survey questionnaire, thermal sensation of the building occupants was accessed using the question "How do you feel the temperature right now?" Fig. 3 shows the distribution of subject responses collected during summer, moderate and winter seasons, respectively. About 79%, 92%, and 70% of the subjects' responses were found in comfort band (±1 sensations) in summer, moderate and winter seasons, respectively. A total of 82% of the subjects felt comfortable (including ±1 sensations) at prevailing indoor temperature conditions.

Table 5 presents the statistical analysis of sensation and preference votes of the building occupants on a seasonal basis. The following observations can be made from Table 5:

- Over an annual cycle, average thermal sensation varied between slightly warm and slightly cool.
- Mean value of sensation votes on an annual basis, combined for all seasons, was found slightly higher than neutral in naturally ventilated buildings (mean thermal sensation vote, TSV = +0.16, SD = 1.24).
- During the summer season, the mean thermal sensation was higher than neutral but less than slightly warm (mean TSV = 0.67, SD = 0.92)
- During winter, it was lower than neutral but less than slightly cool (mean TSV = −0.75, SD = 0.76).

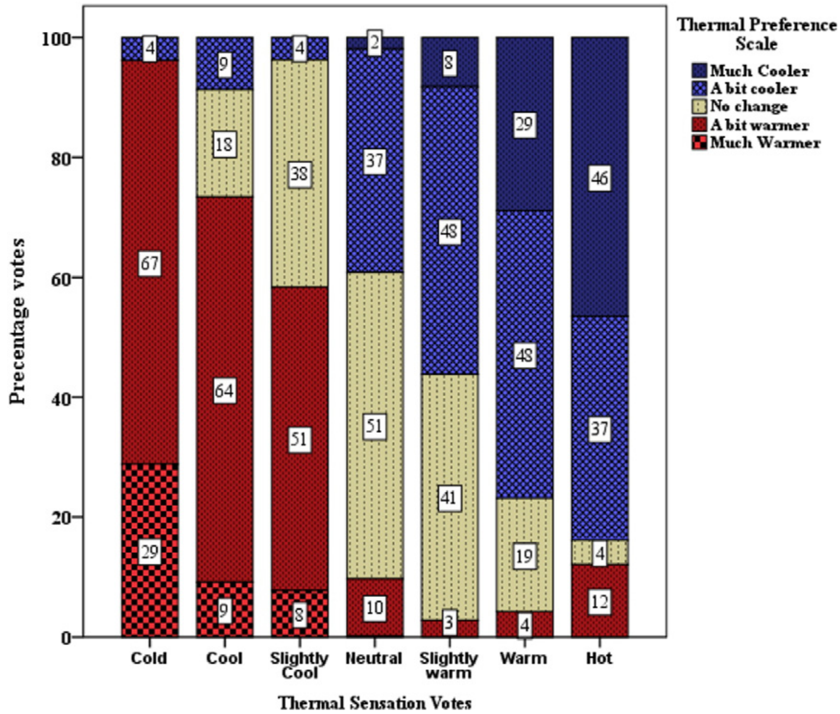


Fig. 4. Cross-tabulated summary of thermal preference votes and thermal sensation votes.

In response to thermal sensations recorded, the corresponding thermal preferences were captured with the question "How would you prefer to feel?" Fig. 4 shows a cross-tabulated summary of thermal preference votes and thermal sensation votes. Fig. 4 also shows that about 51% subjects reported the temperature neutral at the time of voting and want no change in temperature. It can be observed from Table 5 that the preference for a cooler environment dominates across the seasons, with a mean value of −0.22 (SD = 0.92). Using the scale described above, the mean preference for temperature change was −0.84(SD = 0.66) in summer, −0.51 (SD = 0.78) in moderate seasons and +0.37 (SD = 0.80) in winter. This pattern corroborates with the findings of Fountain et al. (Fountain et al., 1996).

Sensation and preference for humidity (HSV & HPV)

Relative humidity during the study was found varying between 8% and 96%. Sensation for humidity and preferences were asked on seven

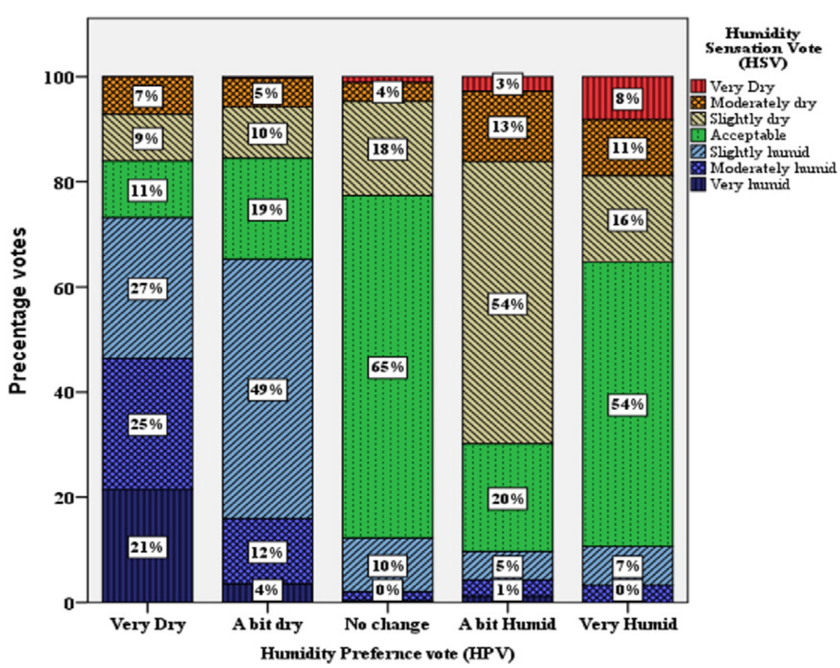


Fig. 5. Cross-tabulated summary of humidity preference votes and humidity sensation votes.

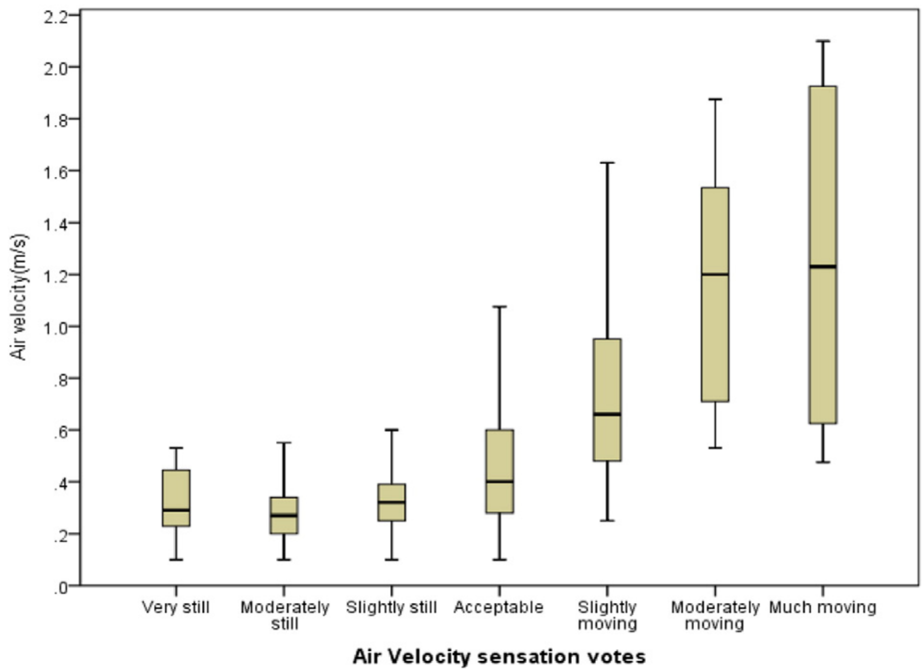


Fig. 6. Distribution of air velocity sensation votes over air velocity through boxplots.

point and five point scales respectively, as suggested by ASHRAE 55. The following observations can be made:

- 52% of subjects found humidity between 32%–38% acceptable at prevailing indoor humidity conditions.
- Mean humidity sensation (HSV) for all data sets in all naturally ventilated buildings was $+0.13$ (SD $= 1.09$) at a mean relative humidity of 43%.
- Mean humidity sensation for summer, moderate, and winter seasons was found to be $+0.21$(SD $= 1.26$), -0.23(SD $= 0.87$), and -0.35(0.82), respectively.
- Mean humidity of 47%, 33%, and 43% was observed for summer, moderate, and winter seasons, respectively (Table 5).

Fig. 5 shows the cross-tabulated summary for humidity sensation votes and humidity preference votes. A maximum of 65% subjects accept the prevailing humidity conditions during the study and prefer no change in humidity. 18% of the subjects did not prefer any change while having ‘slightly dry’ sensation for humidity. Similarly, 10% did not prefer any change while having ‘slightly humid’ humidity sensation. The reason for such preferences could be expectancy and acceptance of such conditions that prevail in this climatic region.

Sensation and preference for air velocity (AVS & AVP)

In the surveys, mean air velocity was found higher as the season got warmer. It was observed as 0.27 m/s during winter, 0.57 m/s during moderate and 0.62 m/s during the summer season. The corresponding

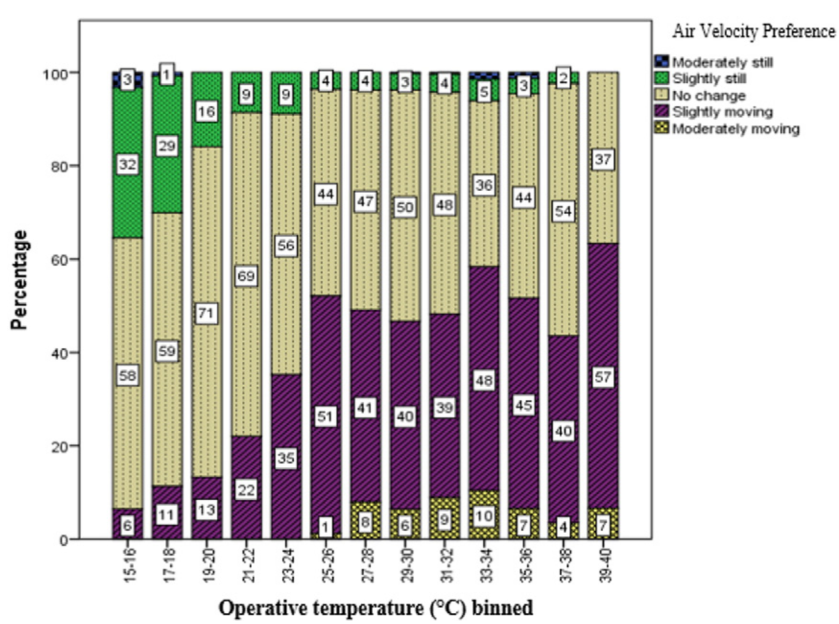


Fig. 7. Distribution of the preference votes across air velocity over operative temperature (binned to 2 °C).

Table 6
Linear regression models, Griffiths' comfort temperature (GC = 0.5 °C^{-1}), globe temperature when voting neutral (T_{gn}).

Case	N	Regression models[a]	R^2	T_n (°C)	Mean T_{gn}	N_n	Mean T_c (°C) (GC = 0.5 °C^{-1})
All season data	**2610**	TS = 0.149 T_g − 4.06	0.55	**27.2**	**28.1**	**1040**	**27.9**
		TS = 0.148T_a − 3.98	0.56	26.9	28.1		
		TS = 0.149T_{op}-4.05	0.56	27.2	28.4		
Summer season	**1220**	TS = 0.182T_g − 4.99	0.31	**27.4**	**30.5**	**504**	**30.6**
		TS = 0.181T_a − 4.98	0.31	27.5	30.4		
		TS = 0.180T_{op} − 5.04	0.31	28.0	30.5		
Moderate season	**438**	TS = 0.177T_g − 5.04	0.42	**28.5**	**29.5**	**202**	**29.5**
		TS = 0.184T_a − 5.19	0.43	28.2	29.1		
		TS = 0.186T_{op} − 5.28	0.44	28.4	29.3		
Winter season	**952**	TS = 0.101T_g − 2.99	0.28	**29.6**	**24.6**	**334**	**25.2**
		TS = 0.113T_a − 3.18	0.29	28.1	24.2		
		TS = 0.109T_{op} − 3.14	0.29	28.8	24.9		

N = Sample size; TS = Thermal sensation vote; T_g = Indoor globe temperature; T_a = Indoor air temperature; T_{op} = Indoor operative temperature; T_n = Regression neutral temperature; T_{gn} = Indoor globe temperature when voting neutral; N_n = Sample size (voting 'neutral' on the sensation scale); T_c = Griffiths' comfort temperature (°C) with 0.50 as coefficient.
[a] The regression models are all significant at ($p < 0.001$).

occupant mean sensation of air velocity for the different seasons was −0.35 (SD = 1.09) in summer, −0.25 (SD = 1.01) in moderate seasons and −0.10 (SD = 0.62) in winter.

Fig. 6 represents the distribution of air velocity sensation votes compared to measured air velocities prevailing inside the surveyed buildings. The study shows a large variation in air velocity measurements across the sensation votes. Fig. 7 reveals that as temperatures rise from winter to summer, the preference for more air velocity increases. This corroborates with other studies conducted in hot and humid countries, reporting that inhabitants in hot and warm countries prefer higher air velocity to make themselves comfortable at higher temperatures (Sharafat and Sharma, 1986; Givoni, 1992; Nicol, 2004; Zhang et al., 2007). It can be clearly seen from Fig. 7 that most of the subjects preferred to have higher air velocity than prevailing indoor air velocity. This trend can also be visualized in a mean air velocity preference vote shown in Table 5. The mean air velocity preference votes were 0.67 in summer, 0.61 in moderate seasons and 0.20 in winter, respectively. A total of 64% subjects preferred to stay at the prevailing air velocity conditions.

Comfort temperature

Linear regression method

The comfort temperature is known to be varying across the seasons (Brager and de Dear, 1998). Linear regression between subject's thermal sensation votes and corresponding room temperatures was performed in two ways: first, collectively for all the data sets over the year, and then separately for each of the three seasons, as shown in Table 6.

For combined year round analysis, a neutral temperature of 27.2 °C has been found as shown in Fig. 8. A comfort band of 21.0 °C–33.1 °C (i.e. corresponding to the TSV of −1 to +1) is obtained through the results of regression analysis. The slope of Eq. (1) is 0.15 °C^{-1} indicating that for every 6.7 °C change in indoor temperature, thermal sensation

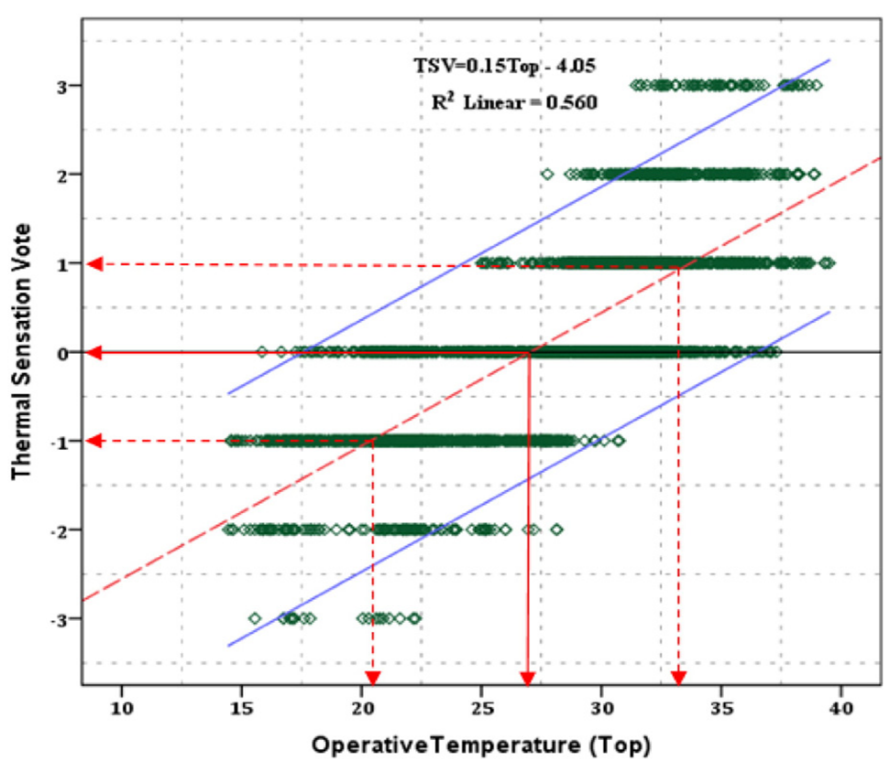


Fig. 8. Linear regression of thermal sensation with indoor operative temperature (with 95% CI).

Table 7
Comfort temperature predicted by Griffith method.

Mode	GC (°C^{-1})	T_C (°C) (indoor air temperature)			T_C (°C) (globe temperature)		
		N	Mean	S.D.	N	Mean	S.D.
Naturally ventilated mode	0.25	2610	27.2	3.8	2610	27.6	3.6
	0.33	2610	27.3	3.5	2610	27.7	3.4
	0.50	***2610***	***27.4***	***3.2***	***2610***	***27.9***	***3.1***
	Voting neutral	1040	28.1	1.6	1040	28.1	1.5

N = Sample size; GC = Griffith constant (°C^{-1}); Tc = Griffith comfort temperature (°C); S.D. = Standard deviation.

vote would have a unit change. Lower slope is also indicative of higher adaptation of the subjects to the indoor conditions encountered. A similar slope of 0.19 °C $^{-1}$ and a comfort band of 13 °C, were obtained by Nicol and Roaf (1996) for a study conducted in Pakistan, which has quite similar climatic and cultural background. Karyono (2000) noted a slope of 0.32 °C $^{-1}$ in Thai offices; Indraganti (2010a) recorded 0.31 °C $^{-1}$ in the residential environments in Hyderabad for their comfort studies. Zhang et al. (2010) observed a slope of 0.25 °C $^{-1}$ during a thermal comfort study for naturally ventilated and air-conditioned buildings in humid subtropical climate zone in China.

$$TSV = 0.15T_{op} - 4.05 \qquad \left(R^2 = 0.56, S.E. = 0.001, p < 0.001\right) \quad (1)$$

where TSV is thermal sensation vote, T_{op} is indoor operative temperature, S.E.is standard error, and p is significance level for linear regression method.

Griffith's comfort temperature

Some researchers have pointed out issues with applying the regression method in the presence of adaptive behaviour. It has been stated that the presence of behavioural adaptation in the data tends to artificially lower the regression coefficients and therefore the estimates of the comfort temperature (Humphreys and Nicol, 2007; Rijal et al., 2010, 2013). Also, the mean comfort vote which is much different from the neutrality (Table 6), may also adversely affect the predictive power of the resultant regression equation. Hence, survey results of this study have again been used to re-estimate the comfort temperature using Griffith method as given below through Eq. (2).

$$T_C = T_g + (0 - TSV)/G \quad (2)$$

where T_c is the comfort temperature (°C), T_g is the indoor globe temperature (°C), TSV is the thermal sensation vote and G is the Griffith constant (0.50 °C $^{-1}$).

In applying the Griffith's method, Nicol and Humphreys et al. (Nicol et al., 2012; Rijal et al., 2013) used the constants 0.25, 0.33 and 0.50 for a seven-7 point thermal sensation scale. Upon applying each of the three coefficients, it has been observed that there is hardly any change in the mean comfort temperature with each coefficient (Table 7). Analysis of mean indoor globe temperature for neutral votes on the sensation scale has shown close agreement with comfort temperature while using the Griffith method with 0.50 °C $^{-1}$ as Griffith's coefficient. Therefore, Griffiths' comfort temperature, T_c, obtained using 0.50 °C $^{-1}$ (with least standard deviation as shown in Table 7) is used in the subsequent analysis. The comfort temperature calculated using a coefficient of 0.50 is indicative of a 2 °C rise for unit perturbation in sensation vote, which is smaller as compared to linear regression approach applied in this study as well as other similar studies.

The mean indoor globe comfort temperature by Griffith's method is 27.9 °C in naturally ventilated buildings. The finding is in close agreement with the neutral operative temperature observed in Singapore: 28.5 °C (de Dear and Leow, 1991), and Hyderabad: 28.0 °C (Indraganti, 2010a) in natural ventilated buildings.

Comfort temperature: seasonal variation

Seasonal variation in comfort temperature was also noticed from summer to winter season. The comfort temperature variations were observed across season as well as within one season (Fig. 9). The results

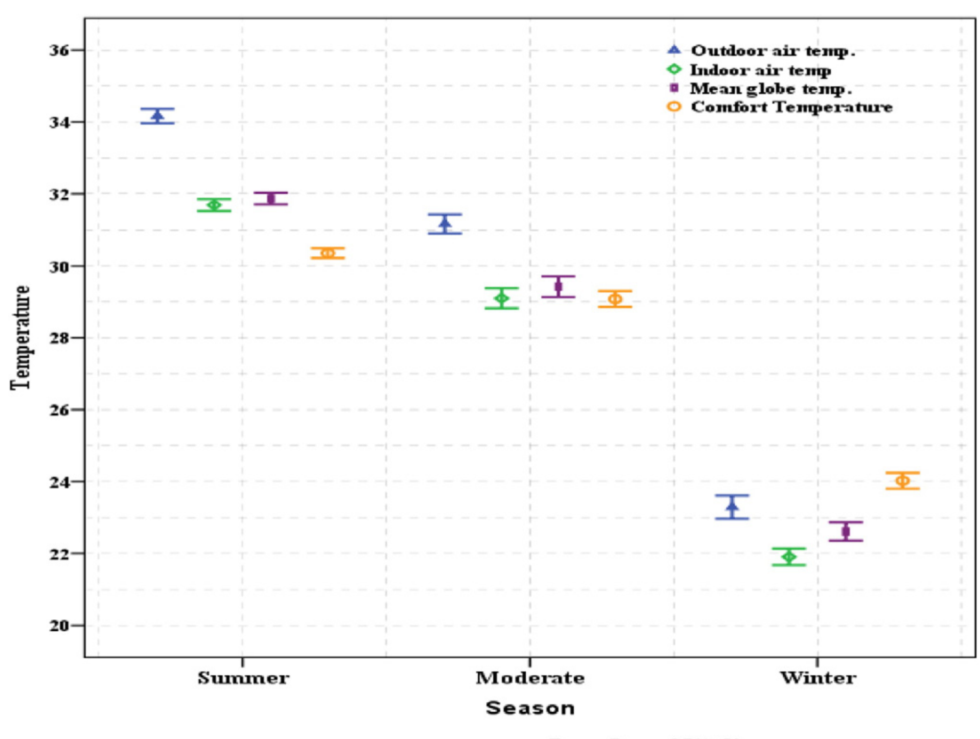


Fig. 9. Seasonal variation of comfort temperature (Griffith constant 0.5 °C$^{-1)}$ for naturally ventilated buildings (at 95% CI).

show that comfort temperature is related to the change in outdoor air temperature, which in composite climate of Jaipur is very high (~45 °C) during summer to appreciably low in winter (~4 °C). Singh et al. (2015) for their field study of vernacular residential buildings in North-East region of India has also reported similar results.

The mean comfort temperature calculated using Griffith's method is 30.6 °C in summer, 29.5 °C in moderate and 25.2 °C in winter, respectively in naturally ventilated buildings. Thus, the seasonal variation of mean comfort temperature is about 5.4 °C.

Analysis of occupant behavioural adaptation

Adaptive thermal comfort is based on the fundamental assumption that "if a change produces discomfort; people react in ways which tend to restore their comfort" (Auliciems, 1981). Behavioural use of controls is interconnected with the physiology/psychology of the body and physics of the buildings (Brager et al., 2004; Rijal et al., 2008). In this study, behavioural adaptations at personal level have been analysed, viz. changing clothing levels, use of personal environmental controls like the opening of window/door (for the natural flow of air) and use of a fan(for forced airflow); to make the surrounding environment comfortable.

Adaptation through clothing

The mean values of clothing were found a bit higher for female occupants than male occupants across all seasons. Clothing values continuously increased from the summer (mean clo = 0.34, SD = 0.15) to winter season (mean clo = 0.67, SD = 0.14), revealing continuous

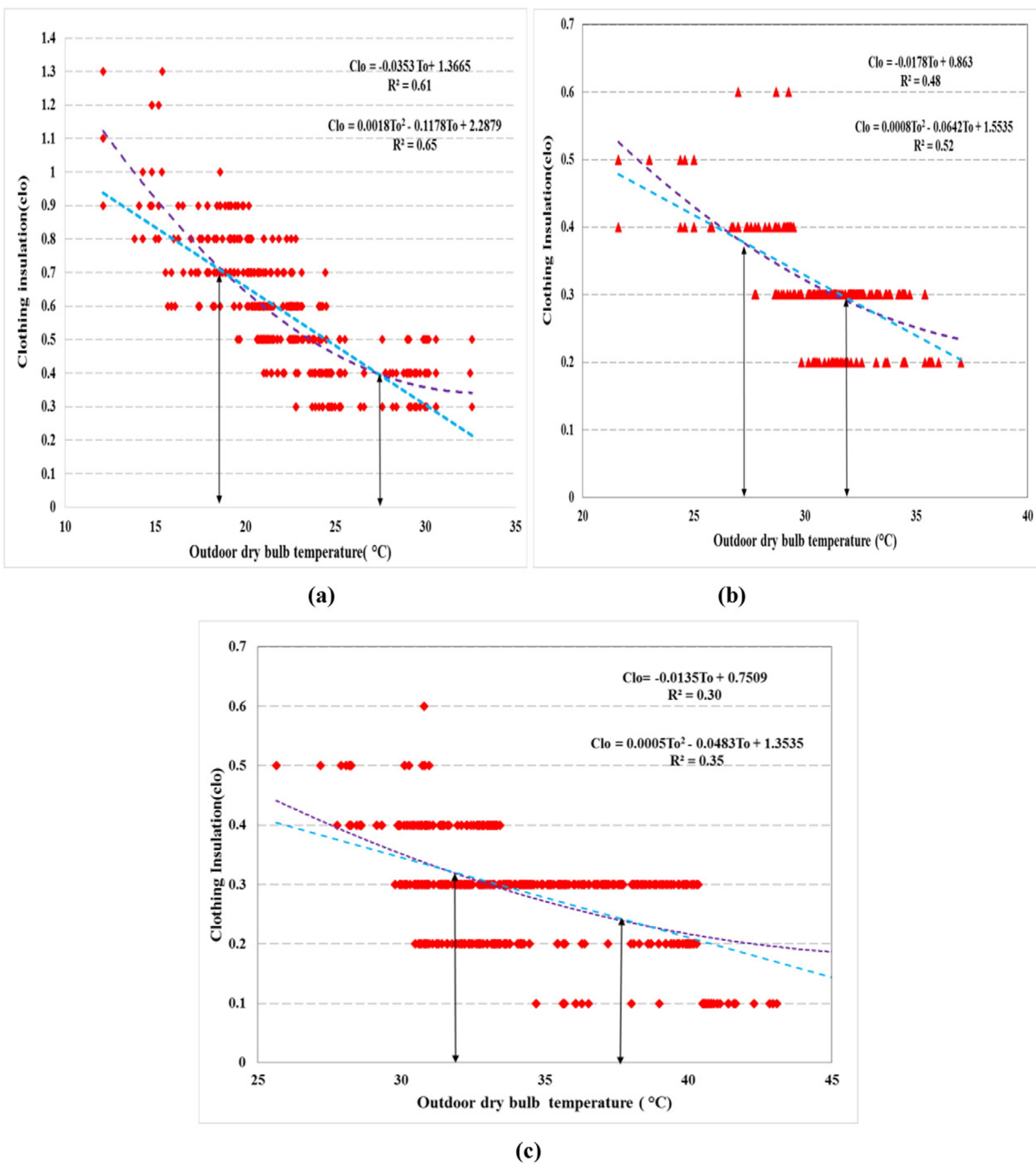


Fig. 10. Variation of clothing with instantaneous outdoor temperature for (a) winter season, (b) moderate season, and (c) summer season.

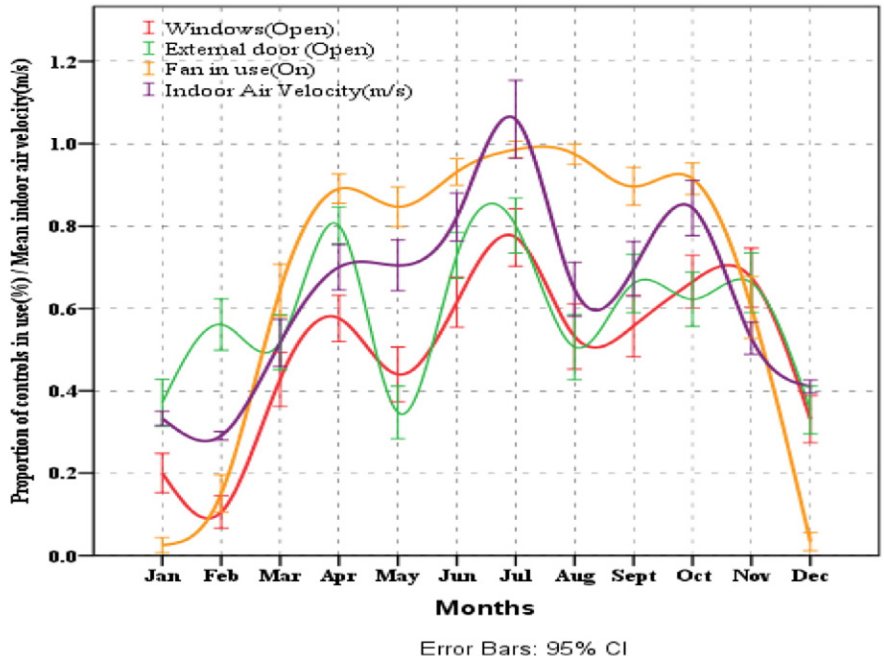


Fig. 11. Proportion of controls in use and prevailing indoor mean air velocity for all seasons in naturally ventilated buildings.

adaptation by occupants through adjusting clothing patterns. Clothing level variations were recorded for each season across the multiple years of study. Clothing levels have been plotted against instantaneous outdoor temperature for winter, moderate and summer seasons in Figs. 10 (a, b, and c), respectively. This data presents an important characterization of continuous adaptation by building occupants that is taking place season by season. The temperatures corresponding to inflexion points (maximum and minimum temperatures) have been noticed as being common between two adjoining seasons, i.e. summer to moderate and moderate to winter. This shows that clothing is the principal adaptive opportunity available to occupants to overcome seasonal discomfort. The most preferred clothing level for summer was found to be 0.30 clo, for moderate 0.40 clo and 0.80 clo for winter season of composite climate in India.

To study the dependence of clothing level on outdoor temperature, linear and polynomial regression analysis was carried out for different seasons. Eqs. (3) to (5) represent the polynomial regression for summer, moderate and winter seasons, respectively.

$$\mathrm{clo} = 0.0005 \times T_o{}^2 - 0.049 \times T_o + 1.35 \left(R^2 = 0.35\right) \quad (3)$$

$$\mathrm{clo} = 0.0008 \times T_o{}^2 - 0.064 \times T_o + 1.55 \left(R^2 = 0.50\right) \quad (4)$$

$$\mathrm{clo} = 0.0018 \times T_o{}^2 - 0.118 \times T_o + 2.28 \left(R^2 = 0.65\right) \quad (5)$$

A similar analysis for correlation of clothing insulation and outdoor temperature was carried out by de Dear and Leow (1991), Singh et al. (2011) and Mui and Chan (2003). This study revealed higher coefficient of correlation for clothing insulation with outdoor temperature than what Mui and de Dear had observed in their field study. As evident from Figs. 10 (a, b, c), the polynomial regression was found to be more appropriate as compared to the linear regression for capturing variation in region specific clothing.

Use of controls: window, external door and fan

In Section-B of the questionnaire, adaptive behaviour for use of controls such as adjusting opening of windows, curtains and other electrical controls such as adjusting operation of fans was noted as binary data (0: not in use/closed; 1: in use/open). The mean proportion of windows and doors open to external environment were found to be 0.56 and 0.64 during summer season and relatively low in winter season 0.27 and

Table 8
Deciles of mean globe temperature, outdoor air temperature and the proportion of windows open in naturally ventilated buildings.

Deciles	T_g (°C)							T_{out} (°C)						
	N	Max.	Min.	Mean	SD	Mean[a]	SD[a]	N	Max.	Min.	Mean	SD	Mean[a]	SD[a]
1	**266**	20.5	14.5	18.1	1.54	**0.26**	0.44	**255**	19.9	11.0	17.12	2.10	**0.24**	0.43
2	**271**	22.4	20.6	21.6	0.55	**0.23**	0.42	**270**	24.0	20.0	21.80	1.29	**0.20**	0.40
3	**255**	25.3	22.5	23.7	0.92	**0.25**	0.43	**260**	26.8	24.0	25.24	0.78	**0.32**	0.47
4	**261**	27.8	25.4	26.7	0.79	**0.39**	0.49	**260**	29.9	26.8	28.47	0.89	**0.54**	0.50
5	**265**	29.2	27.9	28.5	0.41	**0.51**	0.50	**260**	31.0	29.9	30.41	0.35	**0.56**	0.50
6	**250**	30.4	29.2	29.9	0.33	**0.45**	0.50	**265**	32.3	31.0	31.75	0.39	**0.54**	0.50
7	**260**	31.5	30.4	30.9	0.31	**0.64**	0.48	**255**	33.5	32.3	32.88	0.34	**0.56**	0.50
8	**260**	32.7	31.5	32.2	0.38	**0.69**	0.46	**260**	35.1	33.5	34.18	0.45	**0.60**	0.49
9	**260**	34.6	32.7	33.5	0.53	**0.75**	0.43	**262**	37.2	35.1	36.05	0.61	**0.63**	0.48
10	**260**	39.6	34.6	36.3	1.28	**0.51**	0.50	**262**	45.1	37.2	39.21	1.34	**0.50**	0.50

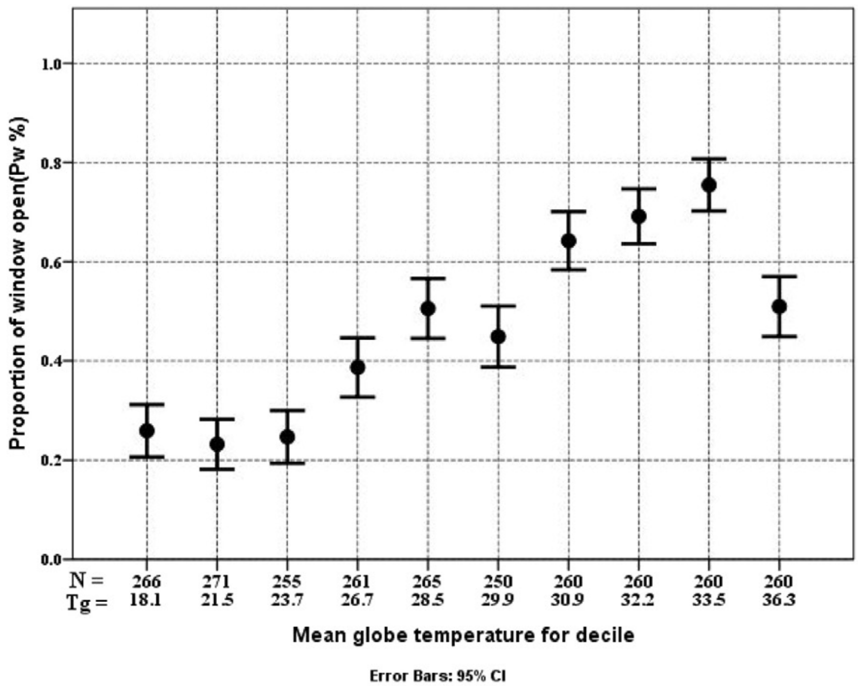
T_g = Globe temperature; T_{out} = Outdoor air temperature.
[a] Proportion of windows open.

0.40, respectively. Least open windows and doors were found during peak summer months (April–June) as outdoor conditions are very harsh, and entry of very hot outdoor air adds to occupant discomfort. Also, during rainy season (July & August), despite relatively low air temperature, to prevent entry of mosquitoes and insects breeding, only a limited use of windows is observed. Significant fraction of windows closed during summer season suggests that there might be other more influencing reasons for opening/closing of windows such as noise, pollution, safety.

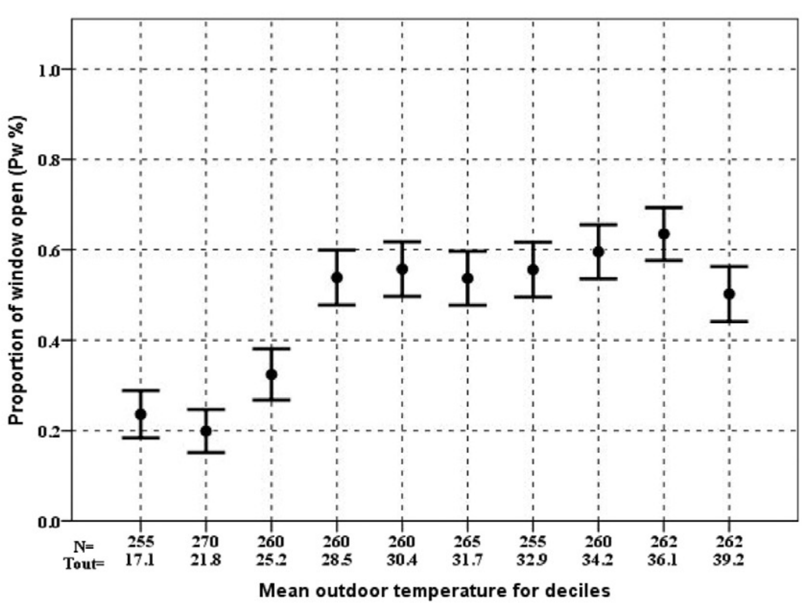
The window opening trend, use of fan, and mean air velocity (at 95% confidence interval) observed in naturally ventilated spaces across all season and months is shown in Fig. 11.

Window opening behaviour in respect to outdoor temperature and indoor temperature. To analyse the window opening behaviour in built environment; the data were divided into ten groups called deciles (ranked and aggregated group of data), in an ascending order of temperature as shown in Table 8. In the present study 40% of total observation, windows were found open (mean $P_w = 0.40$, $N = 2610$). The proportion of the window opening rises as the indoor globe or outdoor air temperature rises as shown in Fig. 12.

When mean indoor globe temperature and outdoor air temperature are 28.5 °C and 28.7 °C, the proportion of open windows were 0.50 and 0.57 respectively. The findings for window openings are similar to Nicol and Rijal (Rijal et al., 2008) in their Pakistan study, but lower than that of



(a)



(b)

Fig. 12. Deciles of mean globe temperature (a) and mean outdoor temperature (b) with the proportion of 'windows open' in naturally ventilated buildings.

Table 9
Correlation matrix for proportion of window open with outdoor & indoor environmental parameters.

	Pearson correlation Sig. (2-tailed)	Windows open (P_w %)	Thermal sensation vote(TSV)	Outdoor air temperature (T_o)	Indoor air temperature (T_i)	Indoor globe temperature (T_g)	Indoor air velocity (V_a)
Windows open (P_w %)	r =	1.00	0.16a	0.24a	0.30a	0.29a	0.08a
Thermal sensation vote (TSV)	r =	0.16a	1.00	0.56a	0.60a	0.60a	0.10a
Outdoor air temperature(T_o)	r =	0.24a	0.56a	1.00	0.88a	0.87a	0.12a
Indoor air temperature(T_i)	r =	0.30a	0.60a	0.88a	1.00	0.98a	0.15a
Indoor globe temperature(T_g)	r =	0.29a	0.60a	0.87a	0.98a	1.00	0.16a
Indoor air velocity(V_a)	r =	0.08a	0.10a	0.12a	0.15a	0.16a	1.00

[a] Correlation is significant at the 0.01 level (2-tailed).

European subjects in office buildings (Rijal et al., 2007). Also, a study for residential buildings in summer and monsoon season of Hyderabad, about 40% of windows were found open at same prevailing conditions (Indraganti, 2010b, 2010c). People opened the windows in response to the increase in the indoor and outdoor temperatures and reaches to a maximum of 75% when mean indoor globe temperature peaks at 33.5 °C. Explaining this phenomenon, Rijal et al. (2007) and Indraganti et al. (2014) observed that the indoor climate, the outdoor climate and a mixture of both might drive the use of controls. Results also reveal that proportion of window open (P_w %) correlate significantly ($p < 0.01$) with both indoor globe and outdoor air temperature (Table 9).

Use of ceiling fans. Nicol (Nicol, 1974) for a study conducted for buildings of Roorkee (India) and Bagdad (Iraq), that air velocities up to 1.5 m/s were acceptable for subjects in hot and warm countries. Fig. 13 shows the use of fan with decile of indoor globe temperature. The use of fans significantly increased with the rise in indoor temperature (Pearson's correlation $r = 0.76$, $N = 2628$, $p < 0.01$). Also, Pearson correlation (r) for the fan use is higher than window, indicating fans come into use over a narrow range of indoor air temperature. This indicates that controlling air velocity is found to be the preferred method of thermal adaptation over adjusting clothing and window opening in composite climate of Jaipur.

The proportion of fans in use (Pf %) reached a maximum of 81% when the mean indoor temperatures peaked at 28.5 °C. Similarly, Rijal et al. (2008) noted around 81% 'fans on' at an indoor temperature of 30 °C, in Pakistan. Subjects in the present study are found to have 3 °C higher comfort temperature (T_c) under 'fan on' use than when 'fan was off' (29.6 °C as against 26.6 °C).

Conclusion

This paper summarizes the findings of a thermal comfort field study conducted in 32 naturally ventilated buildings in the composite climate of Jaipur. A total of 2610 data sets were collected spread over a total period of four years, covering multiple seasons, age groups, clothing types and building types. The questionnaires were used to collect the sensations and preferences of subjects related to room temperature, relative humidity, air velocity and overall comfort. Simultaneously, the environmental conditions surrounding the subjects were recorded considering Class-II protocol of field measurement. The results from this adaptive comfort study reveal range of thermal parameters for comfort, occupant expectations, seasonal clothing adaptations and use of various controls.

Key conclusions of the study are as follows:

1 A total of 82% of the subjects felt thermally comfortable (±1 sensations) at prevailing indoor conditions. The mean value of sensation votes for all seasons was found slightly higher than neutral in naturally ventilated buildings.
2 Mean air velocity increases as the season gets warmer. It has been observed as 0.27 m/s in winter, and 0.62 m/s in summer. The corresponding occupant mean sensation of air velocity for the different seasons was −0.35 in summer and −0.10 in winter. This reflects typical high air velocity preference of Indian subjects living in composite climatic conditions.
3 On annual basis, the mean comfort temperature, as predicted by Griffith's method, was found to be 27.9 °C.
4 Seasonal analysis reveals, the mean comfort temperature is 30.6 °C in summer and 25.2 °C in winter, respectively. Thus, the seasonal

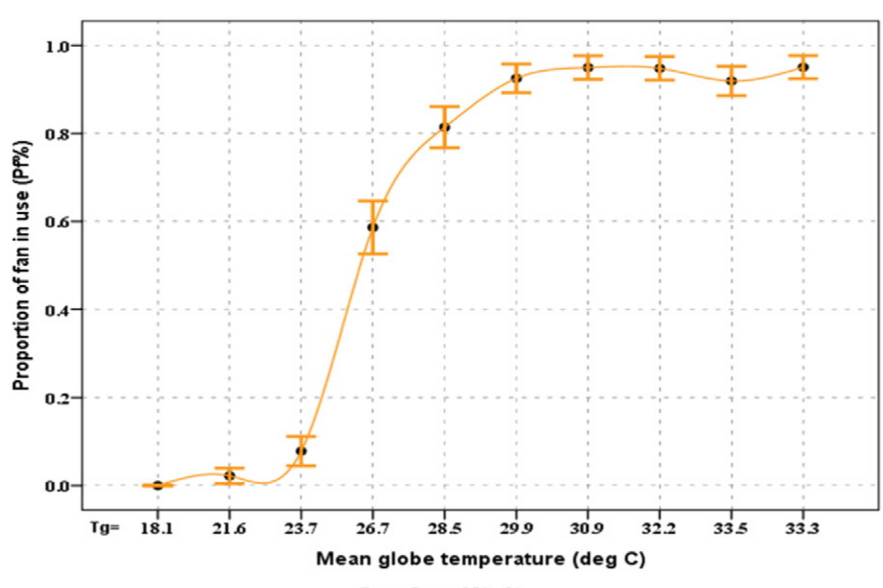


Fig. 13. Deciles of mean globe temperature and the proportion of 'fans on' in naturally ventilated buildings.

variation of mean comfort temperature is about 5.4 °C as obtained through Griffith's method.

5 In naturally ventilated buildings of this climate, there is a continuous adaptation in clothing pattern throughout the year, affecting occupant sensations and preferences. The most preferred clothing level for summer is 0.30 clo and 0.80 clo for winter in composite climate of Jaipur.

6 The proportion of window opening reaches to a maximum of 75% when mean indoor globe temperature peaks at 33.5 °C.

7 The proportion of fans in use (P_f %) increased as the temperature increased, and it reached a maximum of 81% when the mean indoor temperatures peaked at 28.5 °C. Use of fans elevated the comfort temperature by about 3 °C in naturally ventilated buildings.

The results from this study indicate that subjects in naturally ventilated buildings are more comfortable at temperature higher than recommended in Indian codes. This study can help architects, building designer and building owners to create comfortable indoor thermal environment.

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