Thermal comfort perception in naturally ventilated affordable housing of India

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Abstract

Indoor thermal comfort is critical to building sustainability besides improving occupants' health, well-being and productivity. However, the applicability of existing comfort standards within different climatic conditions and contextual settings is often in question. This study presents the findings from a longitudinal thermal comfort study conducted in low-income affordable housing in Mumbai, India. Surveys were conducted in three distinct seasons within a warm-humid climate. The linear regression method yielded a mean neutral temperature of 28.3oC and a wide comfort band ranging from 24.6oC to 32.2oC indicating high thermal adaptation among the occupants. The preferred temperature was found to be 26.3oC. Adaptive comfort standards, ASHRAE and the National Building Code of India prescribed a narrow range of comfort and were ineffective in predicting comfort conditions within affordable housing units. The role of income in shaping comfort expectations was established, lending support to the economic dimension of comfort. The results would be helpful in providing design recommendations for the future affordable housing stock and the development of an adaptive comfort model for vulnerable low-income communities.**Keywords:** affordable housing; low-income; thermal comfort; India; comfort standards; perception.

1. Introduction

1.1. Overview

Thermal comfort is defined as "*that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation*"(American Society of Heating Refrigerating and Air Conditioning Engineers, 2017). There are two widely adopted approaches to thermal comfort- heat balance approach and adaptive approach. The heat balance approach, based on laboratory studies, considers occupants as passive recipients of thermal stimuli, thus miscalculating comfort conditions for naturally ventilated buildings. On the other hand, the field study based adaptive approach considers the influence of thermal adaptation and is deemed effective in predicting the often-wider comfort range observed in naturally ventilated buildings. However, the adaptive practice is context dependent (J. F. Nicol & Humphreys, 2002) and is influenced by psychological, physiological and behavioural factors (de Dear, Brager, & Cooper, 1997). Thus, it could be said that the perception of comfort may vary among people living in dissimilar building typologies, climate, culture or contextual settings (de Dear et al., 1997). This complexity of thermal comfort perception further increases within low-income population where another degree of freedom exists in form of socioeconomic level (Pérez-Fargallo et al., 2018). However, till date, the issue of adaptive comfort in these vulnerable and resource-constrained communities has not been adequately addressed in scientific literature.

India’s urban housing shortage, estimated at 18.78 million, is primarily driven by economically weaker sections and low-income group population. Multiple efforts have been carried out by the Government of India to meet the burgeoning housing demand through affordable housing schemes and policy initiatives such as National Housing Policy, 1994; Jawaharlal Nehru National Urban Renewal Mission, 2005; Rajiv Awas Yojana 2013 (Reserve Bank of India, 2018). Pradhan Mantri Awas Yojana (PMAY), launched in 2015 is one of the significant governmental initiatives which integrates all the previous urban housing schemes(KPMG, 2012; Ministry of Housing & Urban Poverty Alleviation Government of India, 2015). PMAY aims at providing affordable ‘Housing for All’ by the year 2022 through the construction of 20 million urban housing units (Ministry of Housing & Urban Poverty Alleviation Government of India, 2015). Additionally, affordable housing demand is projected to rise to 38 million units by 2030 which would further surge the upcoming housing stock(India Brand Equity Foundation, 2010). Indian affordable housing sector plays a catalytic role in fulfilling the UN Sustainable Development Goals for 2030, SDG 3 (Good health and well-being), SDG 11 (Sustainable and clean cities) and SDG 13 (Climate action), besides accomplishing the climate change mitigation goals of Paris Pact and Montreal Protocol [1]. Given the centrality of affordable housing in creation of sustainable built environment, investigating their environmental performance towards human comfort is imperative. Thermal comfort becomes a critical environmental parameter due to the magnitude of the health effects that are related to it.

1.2. Literature Review

Significant research has been carried out in context of thermal comfort improvement (Bhikhoo, Hashemi, & Cruickshank, 2017; Hashemi, 2017; Hong, Gilbertson, Oreszczyn, Green, & Ridley, 2009; Oluwafeyikemi & Julie, 2015) , thermal performance (Ibrahim, Baharun, Mohd Nawi, & Junaidi, 2014; Pignatta, Chatzinikola, Artopoulos, Papanicolas, & Serghides, 2017; Santamouris et al., 2014; Tinker, Ibrahim, & Ghisi, 2004) and adaptive comfort behaviour (Barkenbus, 2013; Chen, Xu, & Day, 2017; Moore, Ridley, Strengers, Maller, & Horne, 2017) in low-income housing context, but studies exploring acceptable comfort conditions and thermal perceptions are scarce. To the authors' knowledge, only two field studies were found in this regard. The first study, conducted by Soebarto & Bennetts (Soebarto & Bennetts, 2014), investigated comfort conditions within Australian affordable homes and observed wide range of comfort temperature due to greater reliance on low-cost adaptive actions. The research concluded that affordable home owners delayed the use of air-conditioners despite experiencing warmer sensations due to implications on energy bills. In another study performed within Chilean social housing (Pérez-Fargallo et al., 2018), a new adaptive model was developed reflecting the inhabitants' needs and socio-economic culture. The research suggested that low-income dwellers show more tolerance to extreme temperatures and despite being out of the comfort standards' limits, they are considered to be in thermal comfort. However, such studies have not been performed yet in Indian or the Global South, where socio-cultural complexities are critical factors in shaping comfort perception (Malik & Bardhan, 2020a).

Representative studies in the Global South that have tested the validity of the standards like EN 16798 (formerly 15251) and ASHRAE 55–2017 in regulating the occupant's thermal comfort in social housing suggests that users have high tolerance to extreme temperatures (Pérez-Fargallo et al., 2018). The Indian thermal comfort research is predominantly focused on naturally ventilated offices and classrooms and a few studies related to the residential building typology (Malik, Bardhan, & Banerji, 2020). Some earlier studies in vernacular residential architecture demonstrated that design elements like high celling height, height of the building and nearly 40% of fenestration are critical to maintain thermally comfortable natural ventilation. Residences, especially in warm and humid climates, that emphasise on humidity removal are potentially more thermally comfortable than other buildings. Singh et al (2011) carried out a comfort survey in three different climatic zones of North-East India in four different seasons of a year concluded that the predicted mean vote (PMV) deviates from actual mean votes by a factor of adaptive co-efficient which depict the range of the adaptive actions residents undertake in different seasons to restore thermal comfort. Nguyen et al (2012) emphasizes that the derived adaptive coefficient reflects the variability of the thermal comfort controls residents use and that it can be used for thermal comfort assessment of the buildings. Recent studies demonstrated that comfort temperature for summer and winter season were within 30.6 °C and 25.2 °C and that the preferred level of clothing for summer and winter are 0.30 clo and 0.80 clo respectively (Kumar, Singh, Loftness, Mathur, & Mathur, 2016). Most studies conducted in residential buildings in India emphasized that controlling air velocity was the most preferred method of thermal adaptation over adjusting clothing and window opening(Földváry Ličina et al., 2018). While these studies are more concentrated in the over all residential sector. Specific studies on residential thermal comfort in the affordable housing segment remains understudied and need concentrated attention. Moreover, the applicability of existing international and national thermal comfort standards to Indian affordable housing is also subject worthy of investigation.

1.3. Objectives

In view of the above, this study aims at exploring thermal comfort conditions within affordable housing occupied by low-income population, henceforth referred as affordable housing. The research would rely on the field study data for apprising the comfort preferences of the occupants. The findings from this work could aid the architects and policymakers in providing comfortable environment for the future housing stock. The broader goal is to enhance occupant's health, wellbeing and productivity by improving upon comfort conditions of the vulnerable population. As per the authors' knowledge, this is the first-of-its-kind study to comprehend comfort requirements and perceptions within the affordable housing of India. The major objectives of this study are:

- To determine preferred temperature, thermal neutral temperature and thermal acceptability within affordable housing.

- To examine the influence of psychological factors on comfort perception of low-income population.
- To test the applicability of existing comfort standards in Indian affordable housing context.

This paper is an extended version of work published in Malik & Bardhan, 2020b where we discussed occupants' thermal sensation and comfort temperature . In the present study, we have extended our previous work to occupants' subjective comfort votes comprising of humidity, air movement and overall acceptability; analysis of preferred temperature and explored the psychological aspect of comfort to understand thermal perception of occupants. The paper is organized as follows: Section 2 introduces the study area, field study method and data analysis approach. The subsequent section presents the field study results and analyses the subjective comfort votes and comfort acceptability. Comfort conditions and neutral temperature ranges are estimated thereafter in this section. Section 3 further examines the effect of psychological factors on comfort perception and investigates the performance of existing comfort standards in affordable housing context. Section 4 offers a discussion on the policy implications through this study and identifies the need for a novel adaptive model suitable for the low-income population. Key conclusions, limitation and future works are presented in the closing section of this paper.

2. Materials and Methods

2.1. Study Area

The coastal city of Mumbai spread across 603 square kilometers is located in the southwestern part of India. The city falls within tropical savanna climate as per Koppen classification and warm humid climate according to National Building Code of India. Mumbai has three distinct seasons: monsoon, winter and summer and experiences an average annual temperature of 27.2 °C and average annual precipitation of 245.7 centimeters (M.C.G.M., 2011). Two, government provided affordable housing - a slum rehabilitation housing and an institutional staff housing, situated in administrative Ward M and Ward S respectively were selected as the field study locations. More than half of the population of selected wards-M and S consist of low-income people and thus these wards are representative of the city’s low-income population(Mehrotra, Bardhan, & Ramamritham, 2018). The housing units comprise of conventional concrete frame structure with brick in-fill walls and the floor area ranges from 22 square meters to 26 square meters. The details related to the construction materials are listed in Table 1. The spatial configuration of the surveyed housing units are attached in Appendix A. The selected buildings were operated in free-running (fan-assisted natural ventilation) mode during the investigation. In the free-running mode, no energy is supplied for heating or cooling and the thermal environment can be controlled to an extent by opening windows or doors, using ceiling fans or curtains(M. Humphreys, Nicol, & Raja, 2007).

Table 1. Construction details of the case study buildings.

Parameter	Location 1 (Ward M) 	Location 2 (Ward S) 
No. of floors	G+7	G+2
Unit area	22 sq. m	26 sq. m
External Walls	Brick-kiln fired (U-value = 1.8 (W/m^2-K)	Brick-kiln fired (U-value = 1.6 (W/m^2-K)
Roof	Uninsulated reinforced concrete	Uninsulated reinforced concrete
Floor	Uninsulated reinforced concrete	Uninsulated reinforced concrete
Windows	UPVC frame with single glazed clear glass panel	Wooden frame with clear glass panel and mild steel grill

2.2. Field Study

Longitudinal field study, conforming to ASHRAE Class II protocol, wasconducted in three different seasons of Mumbai to understand thermal comfort conditions and preferences of the occupants. Longitudinal sampling technique has been adopted in several classical thermal comfort studies over cross-sectional method (de Dear et al., 1997; M. Humphreys et al., 2007; Sharma & Ali, 1986) because of its advantage of providing responses over an extended period, such as months or seasons, thereby ensuring diverse thermal environments. The data collection method included a thermal comfort questionnaire survey and concurrent monitoring and measurement of environmental parameters such as air temperature, relative humidity and air velocity. Ethical approval was sought and obtained from the Institute ethics committee (Proposal no: IITB-IEC/2020/016). All the participants provided a verbal consent at the beginning of the study in which they were assured that their responses would be treated confidentially and they could withdraw from the research at any stage. Longitudinal surveys require dedication on the part of the subjects, since the survey is conducted multiple times a day and across seasons. It is common that some of the subjects may lose interest leading to unequal number of surveys across the day and seasons. To minimize the loss of samples, participants were informed before the start of surveys about the timeframe and dedication required. The questionnaire was prepared in English and then translated into Hindi. Each respondent was enquired thrice a day- during morning (9:00 a.m.- 12:00 noon), afternoon (12:00 noon -5:00 p.m.) and evening (5:00 p.m.- 9:00 p.m.) in each season. These times were chosen based on the average temperature peaks of the city. The survey screening criteria included a minimum residency of 6 months and a minimum age of 16 years.

2.2.1. Subjective measurements

The questionnaire comprised of four segments: Socio-demographic profiles, subjective thermal comfort votes, personal variables and adaptation controls. Socio-demographic characteristics of respondents: age, gender, height, weight, years of residency, housing unit location and appliance ownership were enquired. Subjective thermal comfort segment contained questions about thermal, humidity and air movement sensation and preference votes. A close-ended question enquiring about the overall comfort acceptability was included. ASHRAE's seven-point scale of thermal sensation and Nicol's five-point scale of preference were used (See Table 2).

Table 2. Sensation scales used**.**

Scale Value	Thermal sensation	Humidity sensation	Air movement sensation	Thermal preference	Humidity preference	Air movement preference	Overall comfort acceptability
-3	cold	very dry	very still				
-2	cool	moderately dry	moderately still	much warm	much humid	much moving	
-1	slightly cool	slightly dry	slightly still	a bit warmer	a bit humid	a bit moving	
0	neutral	neutral	neutral	no change	no change	no change	acceptable
1	slightly warm	slightly humid	slightly moving	a bit cooler	a bit drier	a bit less moving	not acceptable
2	warm	moderately humid	moderately moving	much cooler	much drier	much less moving	
3	hot	very humid	much moving				

Personal thermal comfort variables like clothing insulation and metabolic rates were enquired. Clothing insulation checklist was adopted from ASHRAE Standard 55-2010 [23] and typical Indian ensembles and garments such as saree, salwar kameez, dupatta, and dhoti were added from relevant literature. Suitable chair insulation was also recorded and added to insulation values. Metabolic activity of respondents performed in the past 15 minutes was enquired and corresponding metabolic rates were identified from ISO 8996 “Ergonomics of the thermal environment—Determination of metabolic rate” (International Organization for Standardization, 2004). Adaptation controls are not within the scope of this study and have been discussed in a supplementary study (Malik, Bardhan, Hong, Piette, & Ann, 2020).

2.2.2. Field measurements

Outdoor environmental data comprising of temperature and air relative humidity were monitored from the nearest weather stations (“Weather Underground,” 2019). Indoor environmental data were measured using research grade monitoring Testo 480 (Testo AG & Germany, 2018) multi-function measuring instrument comprising of digital temperature, humidity and air flow meter; indoor air quality probe; globe thermometer; vane probe and lux meter (Table 3). The measuring instruments were placed close to the participant at a height equal to their working plane. Figure 1 depicts the glimpses from field study comprising of instrumental setup, clothing ensemble of participants and general characteristics of the housing units.

Table 3. Indoor environment measurement instruments and specifications.

Parameter measured	Instrument	Details
Air temperature	IAQ probe	Range: 0 to +50 °C
Relative humidity		Range: 0 to 100 %RH
Carbon dioxide concentration		Range: 0 to +10000 ppm
Globe temperature	Globe thermometer	Diameter: 150 mm Range: 0 to + 120 °C
Air velocity	Vane probe	Diameter: 100 mm Range: +0.1 to +15 m/s
Illuminance	Lux probe	Range: 0 to +100000 Lux

Figure 1. Glimpses from field study

2.3. Data Assembly

The analysis began with compiling, coding and computing raw data obtained from different sources such as meteorological website, questionnaires and field measurements. This material was sorted and summarized into a Microsoft Excel dataset and then transferred to statistical package for social sciences (SPSS) software version 24. Monitored data from Testo 480 meter, which measured the indoor thermal conditions, was downloaded through Easy climate Software into an excel spreadsheet. Data from questionnaire forms which included personal identifiers, subjective comfort votes, personal variables and behavioural adaptation was coded into excel spreadsheet at the end of each survey day. Outdoor environment data was then matched with the data obtained from the questionnaires using date and time noted in the filled questionnaire forms. After eliminating data errors such as duplicate or missing values, the computed Excel data was converted into SPSS file for analysis.

3. Results

3.1 Sample size description

705 set of responses were collected through the field study administered in three seasons of Mumbai. During the first phase, conducted in the monsoon months of August-September, 103 occupants participated and 277 set of responses were yielded. The second phase was administered in January, the coolest month of the year and 253 set of responses were obtained. Last phase of survey carried out in the hottest month of May returned 175 set of responses. The sample size varied in each season depending on the participants' availability and willingness to participate. A detailed summary of the sample size distribution is presented in Table 4.

Table 4. Sample size distribution with respect to season, gender and time of the day.

		Total N=705		**Phase 1: Monsoon n=277**		**Phase 2: Winter n=253**		**Phase 3: Summer n=175**	
Description		**Sample size**	**Percent**	**Sample size**	**Percent**	**Sample size**	**Percent**	**Sample size**	**Percent**
Gender	Female	537	76%	215	78%	196	77%	126	72%
	Male	168	23%	62	22%	57	23%	49	28%
Time slots	Morning	120	17%	37	13%	45	18%	38	22%
	Afternoon	288	41%	105	38%	97	38%	86	49%
	Evening	297	42%	135	49%	111	44%	51	29%

Gender distribution of thermal comfort responses informs that around three-fourth of the responses were collected from the female participants. Female members of the low-income households spend more time indoors than the male members and thus they have a larger representation. Seasonal distribution of survey responses comprises of 40% in monsoon season followed by 35% and 25% in winter and summer seasons respectively. The temporal distribution of responses consists of 17% in morning, 41% in afternoon and the rest 42% in evening hours. Measurements were not conducted during the night time (9:00 p.m. to 9:00 a.m.) because of limited access to the residential units.

3.2 Personal Variables: Clothing insulation and metabolic rates

Mean clothing insulation was 0.53 with a minimum value of 0.15 clo and the maximum being 1.52 clo. Male participants adopted a wider range of clothing insulation than females resulting from the prevalent socio-cultural practices. Moreover, there were instances of higher clothing insulation in summers than monsoon or winters due to peculiar contextual factors. A detailed analysis of behavioural adaptation of clothing adjustment with respect to gender and season has been presented in a supplementary study as Malik et. al 2020 (Malik, Bardhan, Hong, et al., 2020). The activity levels of the respondents within the past 15 minutes or less were logged at the time of the enquiry. The metabolic rates ranged from 0.7 Met (sleeping) to 2.0 Met (standing working). The most occurring value was found to be 0.9 Met which corresponds to the "passive seated" activity. Since about 40% of the observations recorded metabolic rate higher than 1.2 met, it was necessary to assess the clothing insulation in conjunction with activity levels. Dynamic clothing insulation (I_{cld}) which refers to the adjusted clothing insulation for occupants with dynamic activity levels (met>1.2) was considered. Figure 2 depicts the gender and seasonal distribution of dynamic clothing insulation worn by the participants. Figure 2 depicts the gender and seasonal distribution of clothing insulation worn by the participants. Figure 2 depicts the gender and seasonal distribution of clothing insulation worn by the participants.

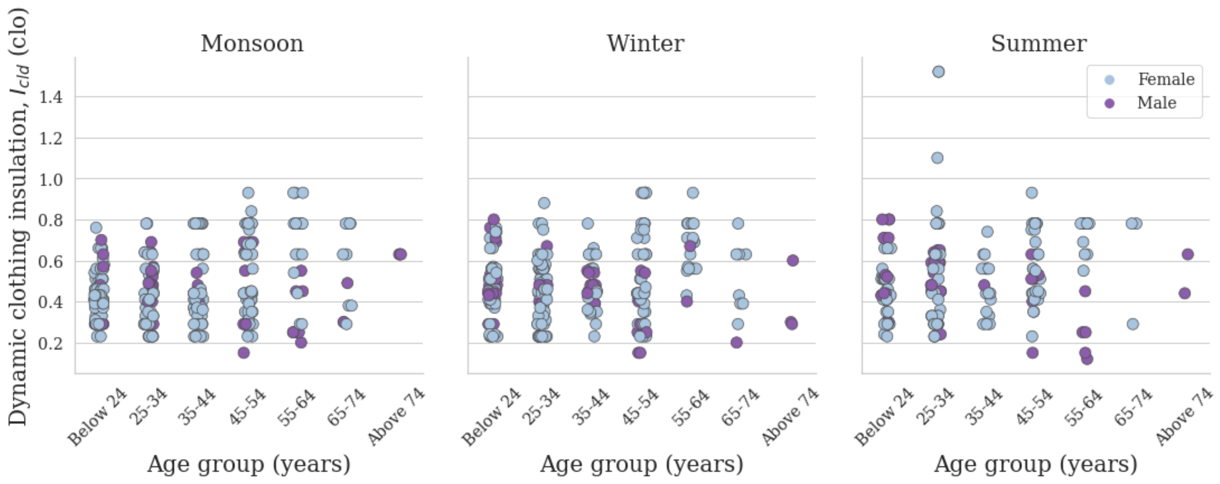

Figure 2. Seasonal distribution of dynamic clothing insulation levels with occupants' age and gender

3.3 Appliance ownership

Participants were enquired about the ownership of appliances in their respective households which included white goods (Cabeza et al., 2018) such as refrigerators, washing machines for covering the basic needs, brown goods such as TVs, computers for fulfilling secondary needs and small appliances such as microwaves, iron etc. Appliance ownership data, depicted in Figure 3, informed that refrigerators were owned by most of the households (94%) whereas washing machines ownership accounted for 70%. Space-conditioning white goods such as air-conditioners (AC) and evaporative coolers (EC) had a collective ownership of 29%. Brown goods such as TVs, laptops and computers were available in 86% and 18% of the households respectively. Additionally, the cumulative ownership of small appliances such as geyser, microwave, iron was 21%.

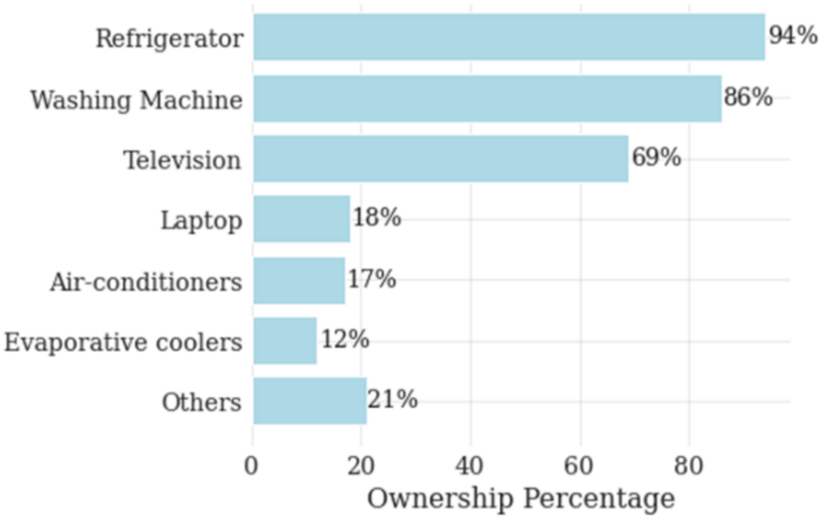

Figure 3. Appliance ownership within participants' households.

3.4. Environmental conditions

Outdoor environmental conditions comprised of wide-ranging temperature and relative humidity levels with lowest daily mean temperature of 23.1ºC in coolest month of January and highest temperature recorded at 31.4ºC in summer season in the month of May. Lowest daily mean outdoor humidity level at 39.0% was observed in winter season while humidity as high as 86.3% was logged during monsoon season.

Table 5 presents the descriptive of daily mean outdoor temperature and daily mean outdoor air relative humidity during the survey period. Indoor environmental variables namely- indoor air temperature (T_a), globe temperature (T_g), relative humidity, air velocity (V_a), carbon dioxide concentration (CO_2) and illuminance levels were recorded simultaneously while carrying out the questionnaire survey. In addition, mean radiant temperature and operative temperature were determined using standard calculations (M. Humphreys, Nicol, & Roaf, 2016). Illuminance levels analysis is not presented in this paper. Descriptive statistics of outdoor and indoor environmental conditions are described in Table 5.

Table 5. Seasonal averages of outdoor and indoor environmental data.

Environmental variable	Unit	Season 1: Monsoon			Season 2: Winter			Season 3: Summer		
		Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
Daily mean outdoor temperature, T_{out}	ºC	26.1	24.3	28.3	24.9	23.1	27.5	29.7	29.1	31.4
Daily mean outdoor air relative humidity, Rh_{out}	%	82.2	76.6	86.3	51.4	39.0	66.7	69.0	66.7	75.4
Air Temperature, T_{air}	ºC	28.4	27.0	30.5	27.0	24.2	30.6	31.2	28.1	34.2
Globe Temperature, T_g	ºC	28.5	26.9	30.5	27.4	24.8	30.8	31.8	29.4	33.8
Indoor air relative humidity, Rh_{in}	%	78.0	61.3	87.4	50.8	26.6	70.3	62.9	54.2	79.0
Indoor air velocity, V_a	m/s	0.5	0.0	2.9	0.1	0.0	1.0	0.4	0.0	1.3
Ambient carbon dioxide, CO_2	ppm	594	431	1522	664	457	1494	575	447	1005

Table 6 summarizes the strength of the relationship between indoor environmental variables logged during the field surveys. Robust positive correlations among air velocity, V_a and T_{air} (r=0.25, p<0.001); and Rh_{in} (r=0.36, p<0.001) suggest that the occupants may have adopted the use of environmental controls to improve indoor air velocity at high temperature and humidity conditions. This is in agreement with ASHRAE Standard 55 (American Society of Heating Refrigerating and Air Conditioning Engineers, 2017) which suggests that indoor operative temperature can be elevated above the still air limits up to a maximum of 3°C, if there are also higher air speeds ranging from 0.2 to 0.8 m/s. Previous studies have also observed that occupants make use of elevated air speeds to achieve comfort at higher indoor temperatures and humidity (Indraganti, 2011; Indraganti, Ooka, & Rijal, 2015; Manu et al., 2014; Mustapa, Zaki, Rijal, Hagishima, & Ali, 2016).

Mean radiant temperature (T_{mr}) witnessed significant but moderate strength of association with T_{air} ($r=0.79$, $p < 0.001$) indicating the presence of long wave radiations within the indoor built environment. This could be attributed to radiant heat gain through the building materials. Further, the presence of radiation sources cannot be established with a poor negative association of T_g and CO_2. This confirmation was necessary to ascertain the choice of temperature variable for carrying out analysis. Considering air temperature, T_{air} may be misleading due to the significance of radiant heat, operative temperature would be used for further analysis in this study.

Table 6: Correlation among environmental variables.

Variables	T_{air}	T_g	T_{mr}	CO_2	Rh_{in}	V_a
T_{air}	1	0.95^{**}	0.79^{**}	-0.03	0.21^{**}	0.25^{**}
T_g		1	0.94^{**}	-0.10^{**}	0.12^{**}	0.24^{**}
T_{mr}			1	-0.16^{**}	0.02	0.29^{**}
CO_2				1	0.04	0.14
Rh_{in}					1	0.36^{**}
V_a						1

**. Correlation significant at the 0.01 level (2-tailed),
*. Correlation significant at the 0.05 level (2-tailed).

3.5 Subjective comfort responses

3.5.1. Thermal sensation and thermal preference votes

Thermal sensation of affordable housing occupants was enquired on a seven-point scale (Refer Table 2). The distribution of thermal sensation votes (TSV) as presented in Figure 4(a), reveals that 90% of the participants voted within the comfortable range, corresponding to slightly cool (-1), neutral (0) and slighty warm (+1) sensation. Around 7.4 % selected for warm (+2), 1% for hot (+3) and 1.3% for cool sensations

(-2) . None of the participants reported cold sensation across the survey period. A mean TSV of 0.11 was observed which is close to neutrality but on the warmer side.

Thermal preference vote, TPV were recorded on the five-point Nicol scale. Mean TPV was towards the cooler side of preference scale (0.45) with a standard deviation of ± 0.73. Half of participants preferred no change (0) in their thermal environment whereas 36% voted for a bit cooler (+1) and 8% desired a much cooler environment (+2). Only 6% participants preferred a bit warmer environment (-1) and most of these votes corresponded to winter season. Figure 4(b) shows the cross tabulation of subjective thermal votes and informs that there was a stark difference in thermal sensation and preference among the occupants with only 60% of neutral sensation votes corresponding to neutral preference.

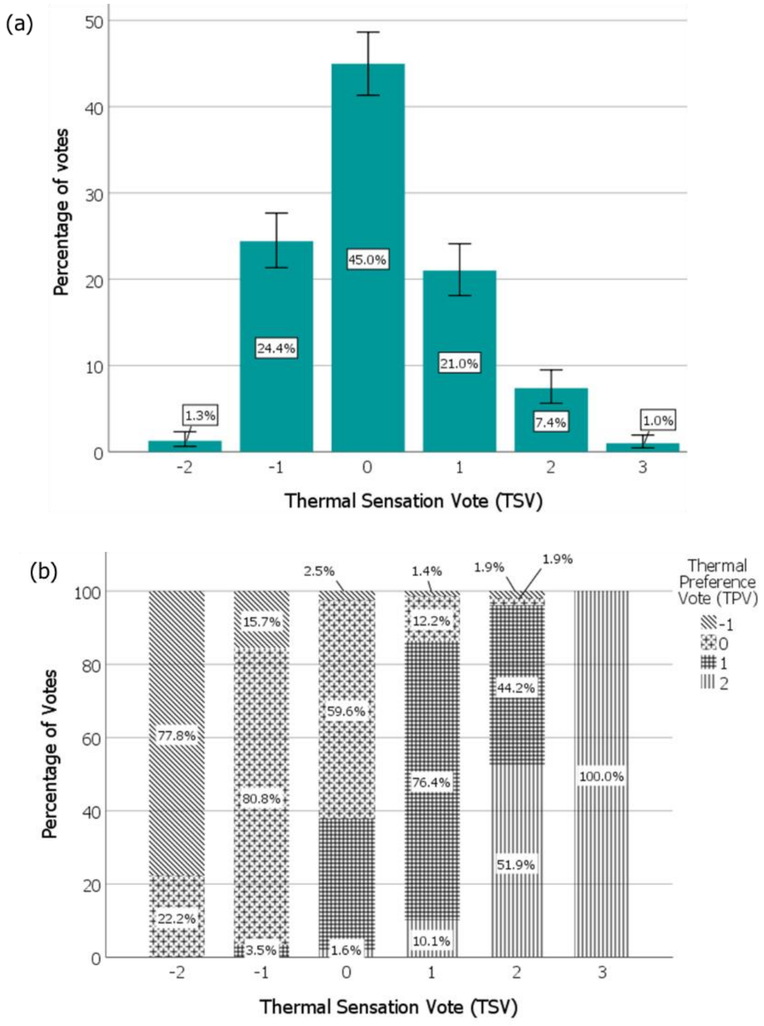

Figure 4. (a) Distribution of thermal sensation votes. (b) Crosstabulation of subjective thermal votes.

Correlation analysis among TSV and TPV yielded robust positive association (r=0.70, p < 0.001). However, a moderate correlation coefficient of 0.70 necessitated to understand the relationship between the subjective thermal votes.. TPV were divided into warmer and cooler sensations and plotted against the corresponding TSV as demonstared in Figure 5. The resultant graph indicates that 17% of the participants voting neutral on thermal sensation scale preferred a cooler environment while 1% desired a warmer environment. Further, the point of intersection of cooler and warmer preference votes is located on the cooler side of sensation scale. This finding is supported by Damiati et al.'s observation that most people living in a hot climate have natural desire to prefer a cooler condition, although they probably accepted the prevailing environment (Damiati, Zaki, Rijal, & Wonorahardjo, 2016). Other thermal comfort studies conducted in hot and humid Asian environments observed similar inferences (Indraganti & Boussaa, 2017; Rijal, Yoshida, & Umemiya, 2010).

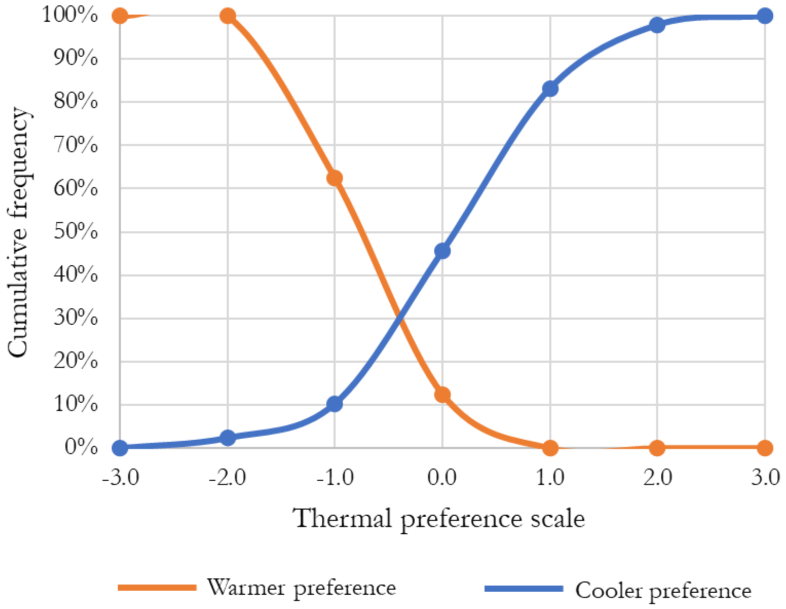

Figure 5. Relationship between TSV and TPV.

3.5.2. Humidity and air movement subjective votes

Literature suggests that relative humidity and air velocity play a significant role in thermal comfort within warm humid climate (F. Nicol, 2004). To gain a deeper insight about comfort conditions within low-income affordable housing, humidity sensation votes (HSV), humidity preference (HPV), air movement sensation (ASV) and air movement preference (APV) were enquired. The distribution of subjective humidity votes (HSVand HPV) are illustrated in Figure 6. As compared to the TSV, HSV had a significantly higher share of neutral sensation (0) with 86% votes. The rest 14% of the participants voted for humid sensations (+1 to +3) while none of the participants experienced drier sensations (-1 to -3). HPV corresponded well with HSV with 97% occupants who voted neutral on HSV preferred no change (0) in humidity levels. Mean HPV was observed to be -0.17 suggesting occupants preferred a slightly drier environment.

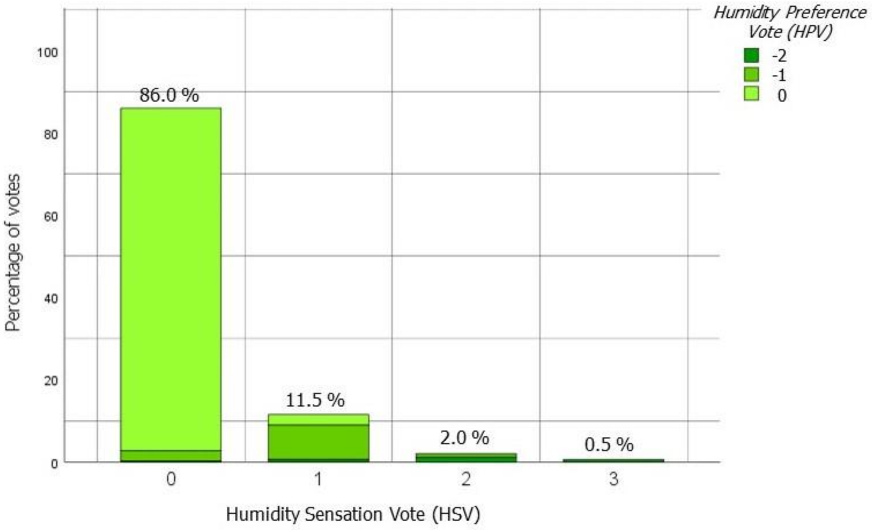

Figure 6. Distribution of humidity sensation and preference votes.

Similar to thermal and humidity sensation, a seven-point sensation scale was used to record air movement sensation votes (ASV). Distribution of ASV presented in Figure 7 is skewed towards the left side indicating most of the subjects reported neutral or lesser air speed than what they desire for thermal comfort. The mean ASV of -0.31 was observed which is towards still air movement sensation. 67.5% of the participants voted for neutral (0) while 28.4% percieved air to be slightly still (-1), still (-2) or very still sensations (-3). Only 4.1% of the participants voted positive on air movement sensation scale (+1 to +3). These votes corresponded to occupants residing in the corner housing units located near the arterial roads where drafts or breeze were experienced due to the built form massing. The air movement preference votes (APV) comprised of 53% occupants preferring no change (0), 35% preferring higher air movement (-1, -2) while only 2% voted for preference of lesser air movement (+1). The crosstabulation graph of ASV and APV demonstrate that only half of the participants voting for neutral sensation preferred no change. However, the rest 50% had varied preferences ranging from much higher air movement (-2) to lesser air movement (-1).

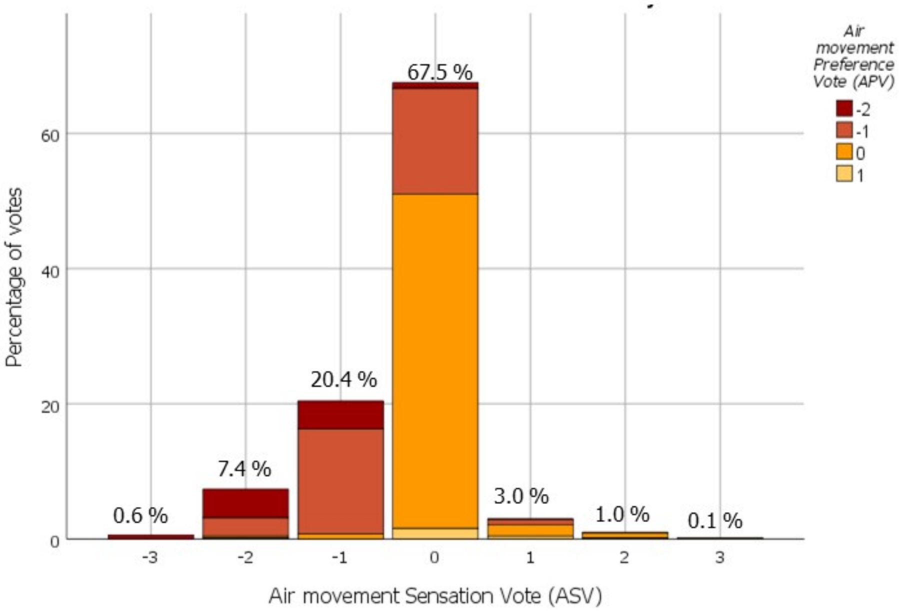

Figure 7. Distribution of air movement sensation and preference votes.

3.5.3. Overall Comfort acceptability

Participants were questioned about their overall comfort acceptability, CA which is influenced by physio-psychological variables apart from the six thermal comfort parameters (Indraganti, Ooka, Rijal, & Brager, 2014). The responses were recorded as a binary data i.e. 0 if the environment was acceptable and 1, if unacceptable. The results, as presented in Figure 8, reveal that around 80% of the participants accepted their environment while the rest reported unacceptable environment. The seasonal distribution of CA votes informs that winter season recorded the highest percentage (94.5%) of acceptable votes, followed by monsoon (76.2%) and summer (64.6%).

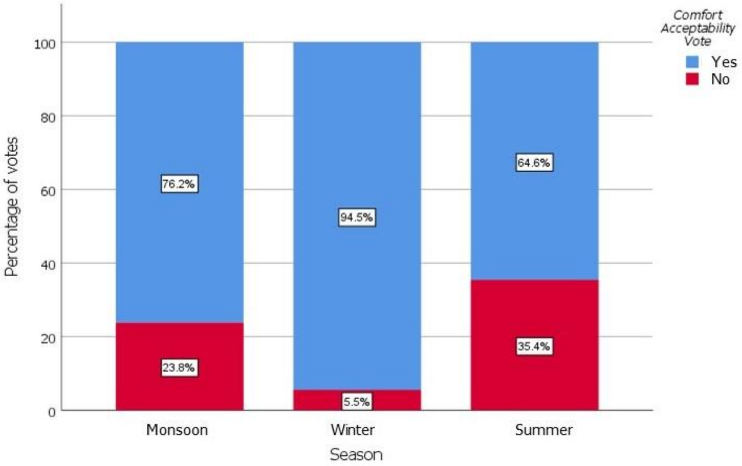

Figure 8. Seasonal distribution of comfort acceptability votes.

CA demonstrated moderate yet significant correlations with TSV (R = 0.48, p < 0.001), HSV (R = 0.43, p < 0.001) and ASV (R = 0.40, p < 0.001). Neutral sensations on thermal sensation scale did not match with 100% acceptability votes as shown in Figure 9. Instead, comfort acceptability coincided well with 95% neutral HSV and 78% neutral ASV but witnessed partial overlap with 49% neutral TSV. The analysis suggests that, in case of warm and humid climate, humidity and air movement are important factors influencing comfort acceptability other than widely accepted temperature variables. The current thermal comfort assessment models, often consider air movements effects by choosing operative temperature for analysis, however the effects of humidity are seldom considered.

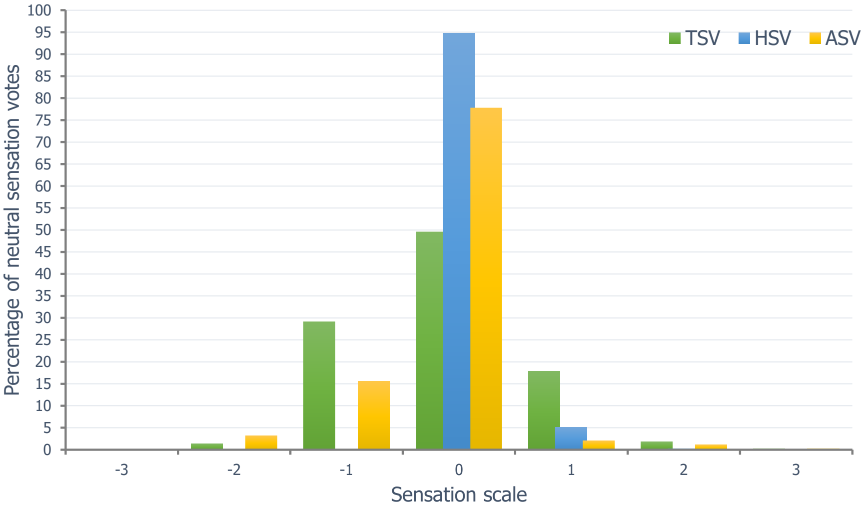

Figure 9. Comfort acceptability distribution over neutral sensation votes.

3.6. Thermal neutral temperature and preferred temperature

3.6.1. Thermal neutral temperature

Thermal neutrality is defined as the indoor temperature corresponding to neutral thermal sensation (de Dear et al., 1997). The indoor temperature variables such as air temperature (T_a), globe temperature (T_g) or operative temperature (T_{op}) have been widely used for in thermal comfort studies. In this study, T_{op} is adopted for analysis because it accounts for the radiant heat gain and air velocities, thus explaining the thermal sensation better. Linear regression of thermal sensation votes, TSV upon T_{op} was performed to identify the range of neutral temperature,T_n over which the affordable housing occupants feel comfortable. The analysis derived the following relationship:

$$TSV = 0.26T_{op} -7.46 \qquad (1)$$

The regression results yielded a significant relationship ($r = 0.56$, $p < 0.001$) between TSV and T_{op} as shown in Figure 10. T_n was calculated from the resultant equation (1) at TSV=0 and was found to be 28.7◦C. The neutral temperature band for 90% and 80% acceptability was observed as 26.5◦C- 30.2◦C and 24.6◦C-32.2◦C respectively. The slope of regression equation informs about the sensitivity of population to changes in indoor temperature. For every 3.8°C change in Top, TSV shifted one-point on the sensation scale which suggests low sensitivity and in turn higher level of adaptation by occupants as compared to other relevant Indian studies (Indraganti, 2010; Rajasekar & Ramachandraiah, 2010). A slope of $0.26^{o}C^{-1}$ suggests that occupants of affordable housing, in absence of space-conditioning equipment due to economic constraint, may have relied on the available adaptive opportunity for restoring comfort and are hence more tolerant to high temperatures and humidity conditions. Similar inferences were drawn by Indraganti and Rao (Indraganti & Rao, 2010) while analysing the effect of economic group on thermal comfort for Indian residences.

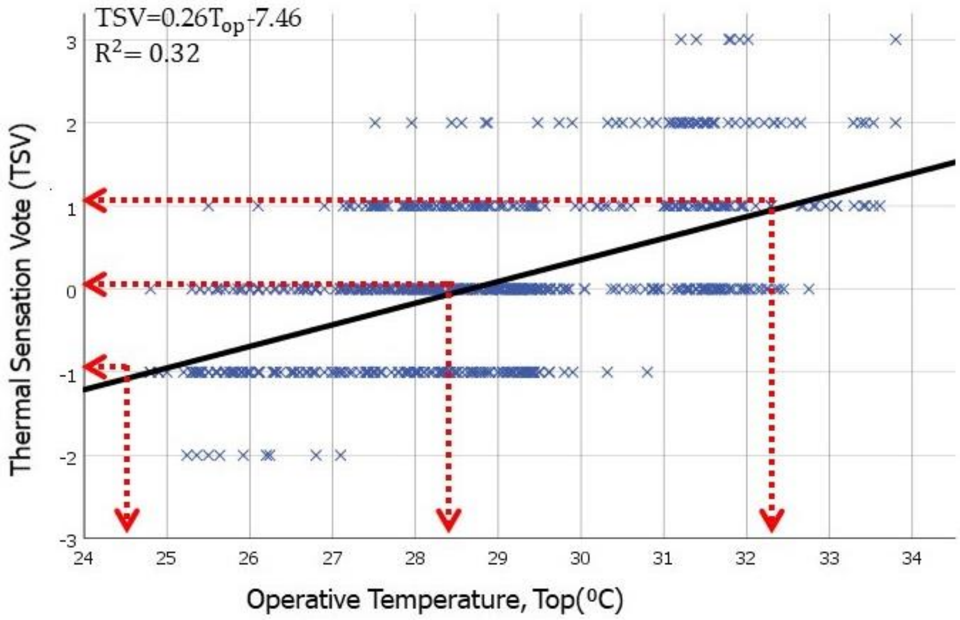

Figure 11. Neutral temperature band for 80% acceptability estimated by regression analysis of TSV and T_{op}.

3.6.2. Preferred temperature

Preferred temperature (T_{pref}) was also analysed in this study to understand the neutral and preffered condiitons of the occupants. Probit analysis was employed to calculate T_{pref} using the method described in (Singh, Ooka, Rijal, & Takasu, 2017). The thermal preference votes (TPV) corresponding to cooler preferences (+1 or +2) and warmer preferences (-1 or -2) were transformed into probit functions. The probability curves of prefering warmer preference (P_w) and colder preference (P_c) were plotted against operative temperature as depicted in Figure 12. The probit curves intersects the x-axis at 26.3 °C indicating the preferred tempertaure of the occupants. T_{pref} is 2 °C lower that the thermal neutral tempertaure, T_n of 28.3 °C which is in agreement with the findings of Humphreys and Hancock that people may not want to feel neutral (M. A. Humphreys & Hancock, 2007). The difference among T_{pref} and T_n suggests that occupants' may desire a different temperature than their thermal neutral tempertaure and supports our findings from section 3.5.1.

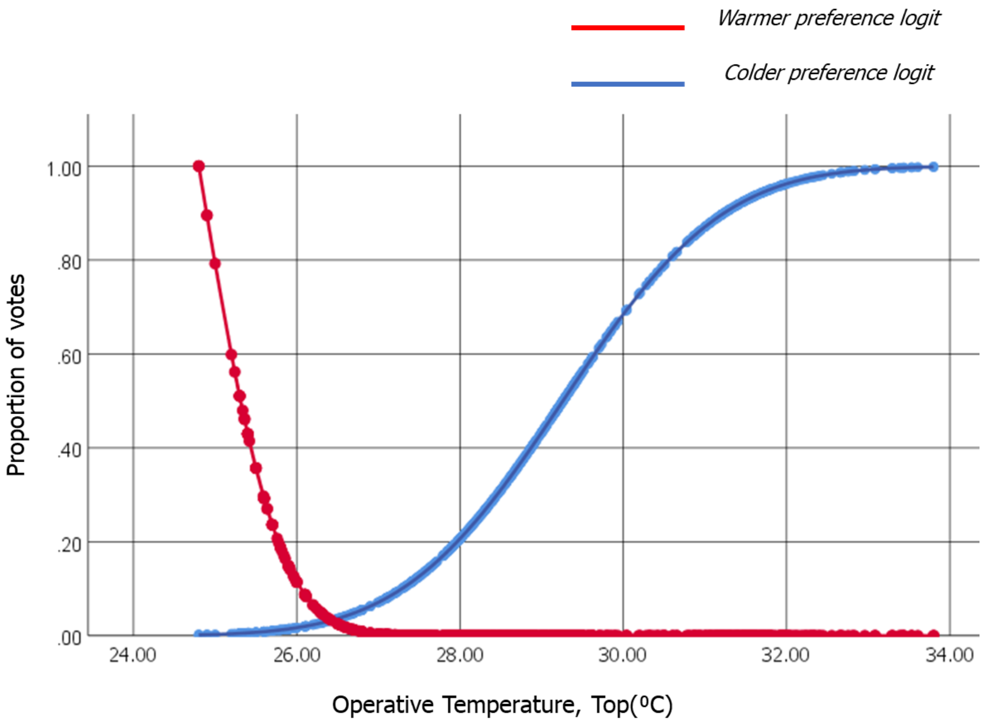

Figure 12: Preferred temperature analysis.

3.7. Psychological influence on comfort perception

The comparative analysis presented in the earlier section reveals that affordable housing occupants adapt to a wider band of comfort and are consequently more satisfied with their thermal environment. Thermal adaptation within the resource constrained low-income residences is recognized as a complex process influenced by a host of behavioural, socio-cultural, economical and contextual factors (Malik & Bardhan, 2020a; Pérez-Fargallo et al., 2018). Since the behavioural, socio-cultural and contextual aspects have been focused in supplementary studies to this paper, here we focus on the psychological aspect of thermal adaptation.

Psychological adaptation describes the extent to which expectation and habituation alter thermal perception of the occupants (de Dear et al., 1997). Income levels are analysed in relation to comfort acceptability (CA) to understand the psychological influence of expectations on comfort perception. Ownership of appliances, as explained in Section 2, is used as an income proxy since the pilot survey reported a response bias towards questions related to household income and expenditure. The number of appliances owned by a participants' household and the prices of those appliances are used to estimate household income score (HIS). Multiple studies have adopted this approach of using proxy indicators of income in the absence of direct measurement (Emorine, Anh, Lamballe, Oudin, & Vass, 2014; Po, Finlay, Brewster, & Canning, 2012). The proposed index is based on a normalised score ranging from 0 to 1 such that lesser the HIS for a participants' household, lower would be the income and vice versa. The distribution of HIS is shown in figure 13(a).

The grouping of the dataset into three income clusters using k-means clustering algorithm yielded in three distinct clustershaving minimum variance within groups and maximum variance between the groups. The resultant clusters: Cluster A, Cluster B and Cluster C are characterised by relatively lower, moderate and higher incomes respectively. The lowest income group, Cluster A has 83% occupants voting acceptable while the acceptability decreases to 75% and 67% for Cluster B and Cluster C. Figure 13(b) depicting the differences in comfort acceptability votes among the income clusters reveals a clear pattern that the lower income groups have higher comfort acceptability while the higher income groups have a lesser acceptance to their environment. This trend could be attributed to the occupants' altered expectations for thermal pleasure with increase in income levels. It is interesting to note that occupants of Cluster C own mechanical cooling devices such as air-conditioners and evaporative coolers, though none of them were operational at the time of the surveys. Infact, these group of occupants are least satisifed with their thermal environment. A possible explanation of such behaviour is the gendered electricity use within low-income housing of India acknowledged in literature. Female occupants, represenitng 76% of the samples, refrain from using energy-intensive electrical appliances for their own comfort practices, and only operate for the children and male occupants' needs (Sunikka-Blank, Bardhan, & Haque, 2019).

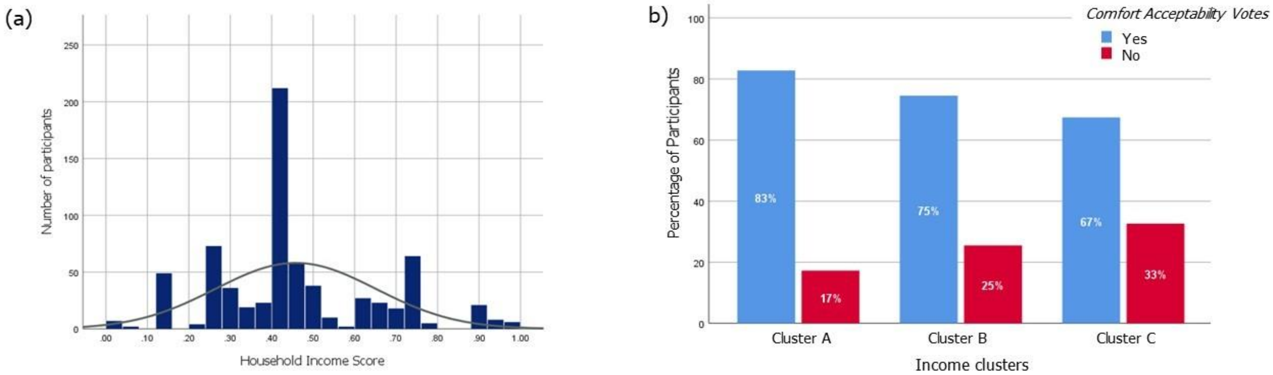

Figure 4. (a) Household income score distribution. (b) Comfort acceptability in relation to income.

The analysis of the availability of adaptive controls and its relation with thermal comfort revealed the psychological modification in occupants' comfort perception. Literature suggests that when people have an adaptive opportunity available through environmental controls to alter their thermal environment, they tend to overlook thermal inadequancies and are forgiving in nature (Deuble & de Dear, 2012; Doreen E. Kalz & Pfafferott, 2014). The analysis revealed no particular relationship between the available controls and neutral temperature indicating occupants perception of comfort did not change with the mere access to controls. In other words, the availability of controls such as window, exhaust fans, air-conditioners does not necessarily imply that low-income occupants are exercising that control. Instead, the perceived control, which is the interaction between different degrees of available and exercised control, should be considered (Sakellaris et al., 2019). However, such an investigation did not form the scope of this work and needs a separate study. Our general understanding is that low-income occupants limit the exercise of available controls due to barriers in form of high operating cost, maintenance, socio-cultural confortmities, contextual setting (Malik, Bardhan, Hong, et al., 2020).

4. Comparison with existing studies and thermal comfort standards

First, we present the comparison of thermal comfort conditions from the present study with relevant Asian studies. Existing studies selected for comparison are based on their suitability with respect to the climate and ventilation mode. The estimated mean neutral temperature , 28.3 ˚C is slightly lower than that obtained by Indraganti 2010, Rajasekar & Ramachandraiah 2010 and Han et al. (Han et al., 2007;

Indraganti, 2010; Rajasekar & Ramachandraiah, 2010). However, the results find close match with Nguyen et al.'s adaptive model for south-east Asian naturally ventilated buildings where occupants reported comfortable at mean neutral temperature of 28◦C (Nguyen et al., 2012). The regression between TSV and T_{op} yielded a small coefficient of determination, R^2 value of 0.32 suggesting large deviations in subjective comfort votes due to personal differences in adaptation . Similar inferences were drawn by Jindal 2018 for naturally ventilated Indian school buildings (Jindal, 2018). Furthermore, the present study identifies a wider neutral temperature band of around 7.6 ◦C for 80% acceptability in comparison to previous studies in Indian and Chinese context where a narrower band of around 5.8 ◦C to 6.6 ◦C was observed (Indraganti, 2010; Rajasekar & Ramachandraiah, 2010; Zhang, Wang, Chen, Zhang, & Meng, 2010). These differences in comfortable conditions suggest that low-income occupants differ in their perception of comfort which could be attributed to physiological (acclimitization), behavioural adjustment (use of environemntal controls, clothing adjustment etc.) or psychological (expectations) factors.

Next, a comparision with Toe & Kubota's study (Toe & Kubota, 2013) for hot and humid naturally ventilated buildings was performed. Toe & Kubota's adaptive model (TKM) uses ASHRAE RP-884 database representing the global population to predict comfort temperature as a function of outdoor temperature. Neutral operative temperatures derived from the present study were plotted against the daily mean running outdoor temperature and superimposed on TKM as illustrated in Figure 14. The resultant graph witnessed 57% of data lying above the upper limit of TKM hinting towards differences in comfort conditions between the global and Indian population. Furthermore, the present study yielded a slighly higher regression coefficent of 0.62 as compared to that of TKM (0.57) indicating that the occupants of Indian affordable housing are less senstive to changes in outdoor temperature.

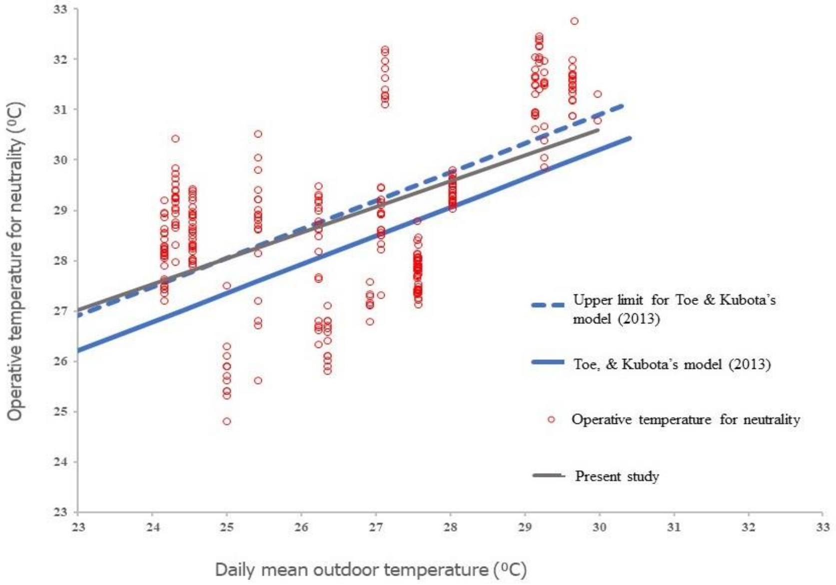

Figure 5. Comparison with Toe & Kubota's model (Toe & Kubota, 2013).

Next, we investigate the applicability of ASHRAE Standard-55 (American Society of Heating Refrigerating and Air Conditioning Engineers, 2017) and National Building Code (NBC) of India (Bureau of Indian Standards, 2016) in predicting occupant comfort within affordable housing of Mumbai. Both these standards prescribe adaptive comfort models for naturally ventilated buildings and predict indoor comfort temperature as a function of prevailing mean outdoor temperature. While ASHRAE model is derived from responses of global population located within different typologies and climatic conditions, NBC's Indian model for Adaptive Comfort is developed from field studies conducted in office buildings located in five distinct climatic zones of India. The neutral operative temperatures obtained from the present study were plotted against the prevailing mean outdoor temperature and superimposed on the prescribed ranges by ASHRAE and NBC as illustrated in Figure 15. The resultant adaptive comfort chart informs that much of the observed neutral temperatures fall on the warmer side and above the 90% acceptability limits of thermal comfort standards. The widely adopted international standard, ASHRAE as well as the Indian standard, NBC prescribe a narrow comfort band of around 5 ^{o}C while the observed neutraities are spread over a larger range(8.7 ^{o}C) of operative temperatures. Chart 12 demonstrates that the existing standards are unable to predict comfortable temperature for affordable housing residents and there is a need for tailoring the adaptive model to suit the comfort requirements of low-income group. The overestimation of ASHRAE model for Asian region is supported by Parkinson et al.'s (Parkinson, de Dear, & Brager, 2020) recent study analysing ASHRAE Global Thermal Comfort Database II. The study inferred that Asian population is better adapted to warmer temperatures and proposed a suitable modification to the ASHRAE adaptive model for Asian region. NBC's model, which is based on field surveys within Indian office buildings, considers the aggregated effect of thermal sensation across all the climatic zones. Additonally, the representative office population of NBC model might have a difference in the availability of adaptive opportunites, socio-economic constraints and contextual settings than the affordable housing residents, leading to significant differences in comfort perceptions and thus comfort requirements.

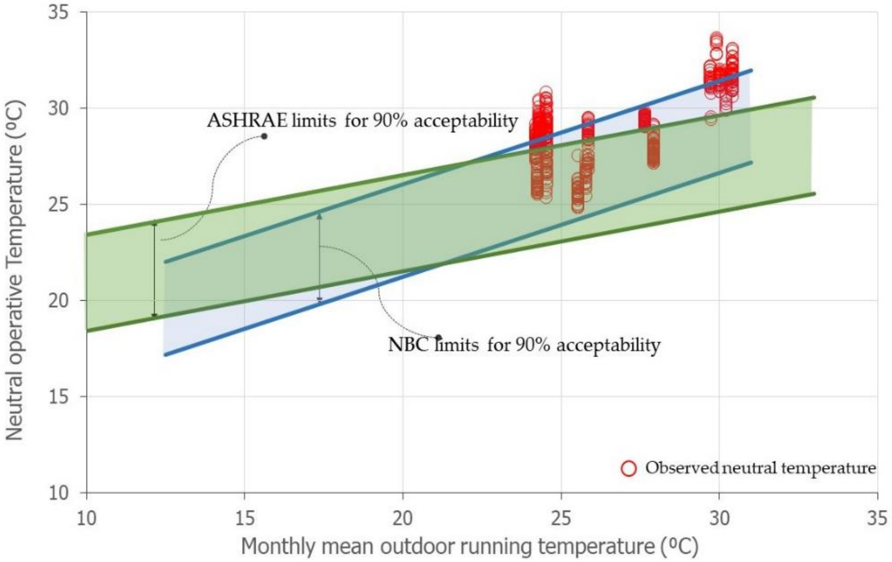

Figure 6. Comparison with adaptive comfort standards.

5. Discussion

Longitudinal field study was conducted in low-income affordable housing units during three seasons of Mumbai, India. Two government provided residential neighborhoods operating in free-running mode were investigated yielding 705 sets of thermal comfort data. The major findings drawn from this study are as follows:

1. Most of the occupants reported comfortable on thermal, humidity and air movement sensation scales. 90% of TSV were within the comfortable range while HSV and ASV corresponding to comfortable

conditions were 97% and 91% respectively. 17% of occupants experiencing neutral TSV preferred a cooler environment suggesting a natural desire for cooler environments.

2. 80% of the participants reported acceptable environment with highest acceptability of 95% in winter season followed by monsoon and summer season. Comfort acceptability coincided well with 95% neutral HSV and 78% neutral ASV but witnessed partial overlap with 49% neutral TSV indicating the importance of all three variables in determining comfort.
3. Based on the linear regression analysis, a mean neutral temperature of 28.3°C was found with 80% of occupants voting comfortable within operative temperatures of 24.6°C to 32.2°C. A slope of 0.26$^{o}C^{-1}$ suggests that affordable housing occupants experience lesser sensitivity to changes in operative temperatures and adapt to a wider range of temperature as compared to other Asian studies. The preferred temperature was observed as 26.3 °C indicating that thermal neutrality may not be sufficient for identifying thermal comfort needs of the occupants.
4. The effect of income levels on comfort acceptability votes revealed that as income increases, satisfaction with the thermal environment decreases. This hints towards the altered comfort expectations with higher income levels. Degree of adaptive control was not found to be an influencing factor in psychological adaptation owing to a difference in available and exercised adaptive controls.
5. Existing comfort standards, ASHRAE and NBC were ineffective in predicting comfort conditions within affordable housing of Mumbai. The standards prescribe a narrow comfort band while the observed neutralities are spread over a larger range of operative temperatures. Affordable housing occupants were found to be less sensitive to indoor temperatures due to the presence of high thermal adaptation.

The results presented in this paper are applicable to naturally ventilated affordable housing occupied by low-income people in warm-humid climate. The limitation of this study was related to the data collection timings. No surveys were conducted at night time (after 9:00 p.m.) when the adaptive opportunities such as opening of doors and windows are not fully exercised due to safety and security concerns.

The findings from this study would aid the development of design guidelines for affordable housing within warm humid climate thereby providing better quality of life to the occupants. Housing stock under government policies particularly “Housing for All” and “Slum Rehabilitation Scheme” could be benefited from this study. The present work could be of great interest to the recently launched India Cooling Action Plan (ICAP) by the Ministry of Environment, Forest and Climate Change, Government of India which aims at reducing energy guzzling and providing “Comfort to all” (MoEFCC, 2019). ICAP recommends certain thermal comfort strategies based on Energy Conservation Building Code (ECBC) for affordable housing policies under PMAY. However, neither ICAP nor ECBC focus upon the issue of difference in comfort perception and comfort requirements of LIG population. This matter needs to be addressed for effective implementation of ICAP and achieving building sustainability and this study is a step in that direction.

The results from this study would provide a pathway for development of a new adaptive thermal comfort model for low-income population. Such a model, reflecting the contextual influences of psychological and behavioural factors on thermal adaptation and comfort perceptions, is critical in improving energy performance gap and contributing to sustainable thermal comfort standards. The findings also ascertain the role of income in shaping comfort expectations within resource-constrained affordable units lending support to the economic dimension of comfort. It is important to note that this study does not argue about the premise of adaptive comfort model but rather emphasizes on the need of an advanced adaptive model considering the altered perception of comfort within low-income communities. Interdisciplinary studies should be carried out to understand the psychosocial factors and comfort affordances of low-income population.

Apart from the policy implications related to building design and thermal comfort, the study could potentially contribute to the building energy simulation (BES) domain through the estimation of realistic comfort levels and energy use. BES software, in the absence of accurate comfort requirements of LIG occupants, often consider standard comfort models such as ASHRAE or PMV for assessing comfort conditions. This poses a serious concern on the accuracy of input assumptions, i.e. comfort assessment models, which could lead to skewed comfort levels and energy consumption results. Hence, the analysis of actual thermal comfort expectations of occupants is central to the effectiveness of BES particularly for the special target groups such as low-income population. The comfort thresholds identified through this study should be leveraged for finding accurate comfort conditions and building energy consumption of the future low-income dwellings. Energy consumption for attaining thermal comfort within affordable housing may not seem to be significant in the present times, however higher disposable incomes and changing lifestyle are expected to change the notion of comfort (Centre for Science and Environment, 2014). People in a desire for higher comfort levels are likely to shift towards energy-intensive adaptive actions thereby consuming higher energy.

6. Conclusion

Indoor thermal comfort plays a substantial role in determining building energy but is often neglected in policies and regulations for energy efficiency. This study provides an understanding of thermal comfort requirement for affordable housing occupants which could aid in sustainability and livability within future affordable housing stock through design guidelines and recommendations. Further, it could also help in reducing building performance gap thereby leading to energy efficiency. As Pérez-Fargallo et. al identify comfort as an economic and cultural issue and advocates its articulation through building standards (Pérez-Fargallo et al., 2018), this study would serve as a stepping stone in this direction, particularly for the resource constrained communities of Global South. The results would enable the development of a novel adaptive comfort model for low-income population in view of the socio-cultural and economic dimension of comfort. Future effort should include field studies in different low-income regions to explore the effects of fuel poverty on thermal adaptation and comfort ranges in different contextual and climatic settings.

With the recent unprecedented outbreak of COVID 19, the housing conditions and livability of low-income population has gathered substantial attention especially in developing cities like Mumbai, Karachi and Manila. The city of Mumbai, housing 5.2 million people in slums for the want of affordable housing, is forecasted to register the highest cumulative residential demand growth of 23% in affordable segment (India Brand Equity Foundation, 2010). The post pandemic period would focus on integrating affordable housing policies with healthy living and ensuring thermal comfort is an important step towards that. Building resilient homes would help the urban poor in reducing vulnerabilities from energy perspective as well (Kumar, S., Singh, M., Chandiwala, S., Sneha, S., & George, 2018). It is hoped that findings from this study would also be valuable in formulating the housing policies and guidelines for post pandemic era.

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Conflicts of Interest

The authors declare no conflict of interest.

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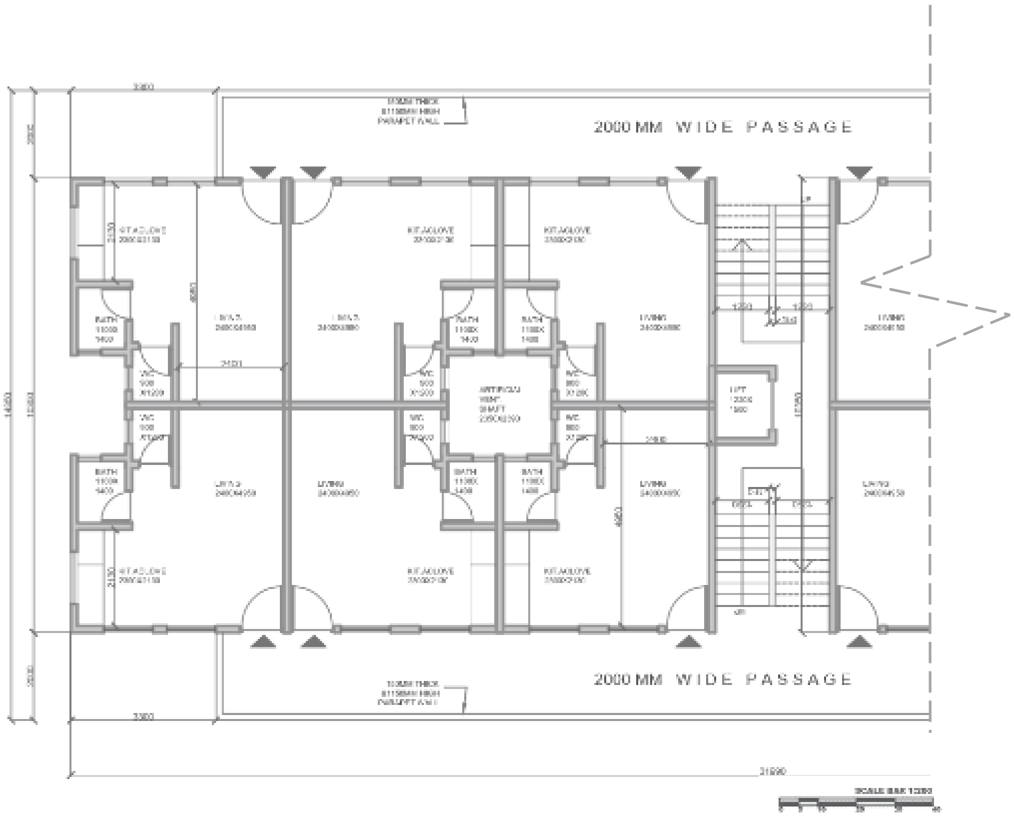
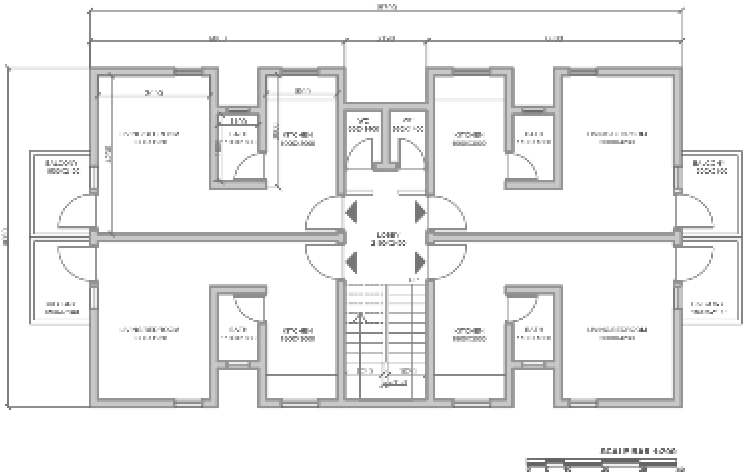
Appendix A: Floor Plans



Typical Floor Plan
Location 1

Typical Unit Size: 22.3 sq.m



Typical Floor Plan
Location 2

Typical Unit Size: 26.2 sq.m