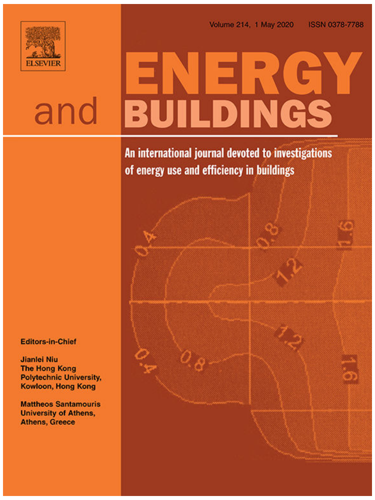

Evaluation of Thermal Comfort in Library Buildings in the Tropical Climate of Kumasi, Ghana

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Title Page

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Evaluation of Thermal Comfort in Library Buildings in the Tropical Climate of Kumasi, Ghana

Abstract

Adaptive comfort considerations and passive design are crucial in tropical, hot and humid climates where the straightforward response to discomfort in this climate, such as in Ghana, has been the adoption of air conditioners and mechanical cooling. This approach, along with following the provisions of current international comfort standards, has resulted in higher electricity demand and excessive emissions of greenhouse gases into the atmosphere. This paper presents an adaptive thermal comfort field study in library buildings in the tropical Aw climate of Kumasi, Ghana considering naturally-ventilated (NV) and air-conditioned (AC) buildings. The proposed models in this study are compared with existing studies and current international standards. Using the Griffiths coefficient of 0.5, the mean neutral temperature of 27.4^{o}C and 30.3^{o}C were predicted for AC and NV mode, respectively. Although Fanger's predicted mean vote (PMV) method overestimates the extent of changes in thermal sensation votes (TSV) by indoor operative temperature in AC mode, the neutral temperature predicted from PMV (27.8 ^{o}C) is analogous to the one estimated using TSV. The adaptive equations for Kumasi's hot and humid climate predict higher slopes of 0.17K^{-1} and 0.41K^{-1} in AC and NV modes, respectively, than the standards; this indicates that the Ghanaian respondents were more sensitive to the outdoor temperature changes. The average difference of 2.1 ^{o}C in AC mode and 1.8-3.3 ^{o}C in NV mode were estimated when comparing the proposed model with those in the international standards.

Keywords: Adaptive comfort models, Hot and humid climate, Air-conditioned building, Naturally ventilated buildings

1. Introduction

Comfort is influenced by personal and cultural assumptions and a combination of other variables, so it is difficult to predict an individual's ideal temperature precisely [1]. However, designers and engineers usually turn to international standards, such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), when sizing the heating, ventilation, and air conditioning (HVAC) system and deciding what temperatures to use in their calculations. This approach, along with HVAC technological evolution, does not consider buildings' ability to perform satisfactorily and occupants' tolerance in meeting the temporal variations in external temperatures and solar gains. Consequently, environmental issues, such as overheating or overcooling, are inappropriately conceived, and buildings have led to the growing use of mechanical systems – with a consequent impact on energy consumption, energy costs, and carbon emissions [2].

Furthermore, international comfort standard requirements may not be suitable for all climates. People in different parts of the world and climate zones might feel comfortable at different indoor air temperatures compared to the suggested comfort range by ASHRAE or other international standards [3]. For instance, while the 2017 ASHRAE Handbook [4] recommends a temperature range of 15–25°C and a Relative Humidity (RH) of less than 60% for general libraries, a thermal comfort field study of occupants at a library in Brazil's tropical climate shows that library users prefer a higher temperature of 25.7°C [5] and find a 70% humidity level comfortable.

Another study by James et al. [6] shows a higher heat tolerance for the residents in tropical countries like Ghana. Their field study results from a school in Accra, Ghana, show that most of the interviewees accepted the thermal environments, which surpassed the ASHRAE summer thermal comfort by 1°C to 5°C, of 26°C and 28°C. To establish thermal comfort criteria for different climatic regions of Mexico and determine the lower limit for active cooling and the upper threshold of indoor air temperature for passive cooling, Oropeza-Perez et al. [7] conducted questionnaire research on a residential building with 74 participants. The results indicate that in all the studied Mexican climate territories, people can tolerate 30°C or more. This outcome contrasts with the fact that the air conditioner (AC) thermostat temperature setpoint is very low in most studied buildings, around 19°C.

In general, the basis of the thermal comfort studies is (i) the static approach based on heat balance studies known as the Predicted Mean Vote (PMV) model developed by Fanger [8, 9, 4], and (ii) the adaptive approach based on field survey results linked to climatic conditions data [10, 11, 12]. In adaptive comfort studies, the occupants, their interactions with the environment, how they modify and adapt their interactions, and their preferences are the active actors [13, 14].

International standards (i.e. ASHRAE and European Standard EN15251) have recognised the possibility that the comfort temperature can differ with varying outdoor thermal conditions and have developed and introduced adaptive standards to apply in naturally ventilated buildings [12]. Nicol et al. [3] believe that a similar relationship could be assumed for mechanically conditioned (heated or cooled) buildings, and, undoubtedly, no validated explanations have been proposed why this should not be so. A variable standard requires comfort temperatures to change with a 'building's surrounding climate and reduces the average indoor-outdoor temperature difference, considerably reducing energy requirements compared to a single-temperature standard [3, 15, 16].

Much research in the area of adaptive thermal comfort has been carried out in the thermal comfort field regarding educational buildings in temperate and cold climates. Nonetheless, very few studies have been conducted in hot and humid climates [6]. Tropical regions are where current standards are generally the weakest [17]. Adaptive comfort considerations and passive design are crucial in tropical, hot and humid climates because the straightforward response to discomfort in tropical countries has been adopting AC and mechanical cooling. In addition, it is predicted that by 2050 half of the global population will reside in the tropic regions [18, 19, 20]. Therefore, the question is: what is the appropriate adaptive comfort range for indoor environments in the tropics?

Similarly, the current climatic comfort standards and modernist building designs deployed in Ghana were not intended for the tropical climate but calibrated for temperate zones. A study by Dodoo and Ayarkwa [21] in the Greater Accra region suggests that the cooling energy demand for residential buildings can increase by 31% and 50% for the projected climates in 2030 and 2050, respectively. Climate change risks and increasing cases of above-average temperatures underpin the demand to improve the buildings we occupy without relying on the grid and mechanical equipment to protect ourselves from future climate conditions [22]. Many new builds and refurbishments are being designed to achieve interior conditions that are probably inappropriate or uncomfortable in this climate.

In addition, Ghana is home to a significant 'tropical modernist' architecture [23, 24, 25]. Identifying an appropriate model for assessing thermal comfort in the tropical climate of Ghana is essential for preserving these significant cultural resources. With over 50% of Ghanaians living in cities and with rapid urbanisation, Ghana and West African cities in general present many urgent challenges, and the quest to deliver healthy, sustainable and liveable cities are crucial.

Therefore, this study investigated users' perception of comfort, examined the prevailing thermal conditions in the university libraries in Ghana's hot and humid climate and intended to assess the comfort standards based on data gathered in Kumasi and on large buildings with a potentially high cooling energy demand. Moreover, a comparative analysis of the results with worldwide accepted recommendations, such as ASHRAE, CEN, and CIBSE, was carried out.

2. Methodology

2.1. Climate

Kwame Nkrumah University of Science and 'Technology's (KNUST) library in Kumasi, Ghana, West Africa, was selected as the case study. Kumasi is the capital city of the Ashanti region in southern Ghana. It is 257m above sea level and has a tropical climate with rainy and dry (harmattan) seasons. According to the Köppen-Geiger climate classification, this climate is classified as Aw, a tropical wet and dry or savanna climate. There are two main seasons in Kumasi: the dry season from November to February, with the least amount of rainfall occurring in January, and the wet or rainy season from March to October [26]. Figure 1 demonstrates the on-site measured outdoor temperature and humidity in Kumasi in 2020.

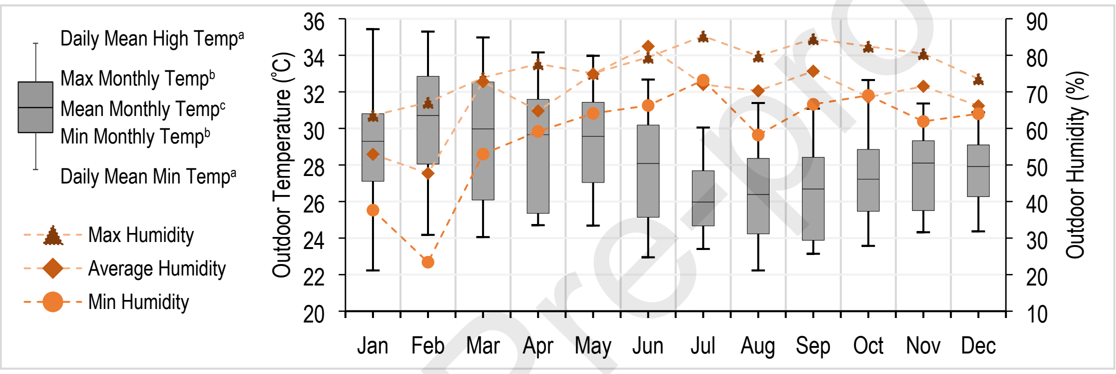


Figure 1–Outdoor weather conditions measured on-site from January 2020 to December 2020.

[a] *maximum and minimum of average daily temperatures measured during a month*

[b] *maximum and minimum temperatures measured in a month*

[c] *average temperatures measured in a month*

The lowest and highest average monthly temperatures of 25.8˚C and 30.4˚C were recorded in July and February, respectively. The lowest average monthly humidity of 53% and the highest average monthly humidity of 82% were recorded in January and June, respectively.

2.2. Site description

Figure 2 shows two library buildings on the Kwame Nkrumah University of Science and Technology campus in Kumasi, Ghana, West Africa. The building on the left, known as the old block, was designed by British architect James Cubitt and opened in 1959. It is naturally ventilated (NV) and has an innovative lightweight structural roofing system that liberates the internal space from columns while indirectly lighting it, as well as an internally fully adjustable louvred screen wall. The old block is carefully oriented to take full advantage of the southern breezes and to avoid the oppressive heat of the southeast and southwest suns.

The building on the right in Figure 2 shows the later brutalist extension that opened in 2001, known as the new block, which features a twin façade arrangement. [27, 28, 29]. The new block is orientated west to east and is equipped with air conditioners (ACs) that have a setpoint temperature of 26°C. Staff can turn the ACs on and off, but they cannot alter the setpoint temperature. The ACs are turned off at night when the library is closed and on again before the library reopens in the morning. Figure 3 depicts the buildings' interiors. ' Figure 3(a), and Figure 3(b) show the locations of the ACs.

Figure 2–Old library block (constructed in 1959) on the left side, facing north and naturally ventilated; and the new library block (opened in 2001) on the right side, facing west and equipped with ACs

Figure 3–a) new block-west facing windows shaded by the balconies and blocked by the bookshelves, b) new block-second floor with ACs. c) old block-second floor with louvres for natural ventilation and shading, d) old block-ground floor and mezzanine

2.3. Data collection

2.3.1.The survey and questionnaire

This paper presents field survey results and measurements conducted in January 2020 (the dry season) in both the old block, which is naturally ventilated and the new block, which is equipped with ACs. Students who use the library buildings in the study areas on the ground, mezzanine and second floors of the old block, and the second, third, and fourth floors of the new block, were surveyed on their thermal comfort. 'The questions and how the responses are scaled are presented in Appendix A and Table 1. The questionnaire contained four sections. In the first section, the location and orientations of the room are specified to classify the AC and NV mode. The second section consists of the 'participants' demographic information (gender and age). The third section includes thermal comfort questions on the subject's thermal sensation vote (TSV), thermal preference (TP), thermal acceptance (TA), the humidity feeling (HF), the airflow movement feeling (AF) and the airflow preference (AP). The fourth part corresponds to the activity level and clothing insulation according to the ASHRAE standard 55 and ISO 7730 [4, 8].

Table 1–The response options and scales for the thermal comfort section of the questionnaire [30].

Scale Value	Thermal Sensation Vote (TSV)	Thermal Preference (TP)	Thermal Acceptance (TA)	Airflow Feeling (AF)	Airflow Preference (AP)	Humidity Feeling (HF)
3	Hot			Much too breezy		Much too humid
2	Warm	A bit warmer		Too breezy		Too humid
1	Slightly warm	Much warmer	Acceptable	Slightly breezy	Smaller than now	Slightly humid
0	Neutral	No change		Just right	Exactly how it is	Just right
-1	Slightly Cool	Much cooler	Not acceptable	Slightly still	Greater than now	Slightly dry
-2	Cool	A bit cooler		Too still		Too dry
-3	Cold			Much too still		Much too dry

Librarians explained the questionnaire and scales to the students before conducting the survey on each floor. The questionnaire was written in English because it is Ghana's official language. Respondents completed the questionnaire during the daytime in the morning or afternoon. We asked the students to wait at least 15 minutes after arriving and settling in the library before responding to the questionnaire. A total of 269 students voluntarily participated and responded to the questionnaire, with 257 classified as valid questionnaires that included the required information on the location and thermal measurements or were not filled by the same respondent. The average age of respondents was 22 years, with 76% being male participants. During the study, most respondents did not make any adaptive thermal modifications.

2.3.2.Indoor and outdoor data measurement

Parallel to the survey, the indoor environmental variables of air temperature (T_a), globe temperature (T_g), relative humidity (RH), and air velocity (V_a) were measured at approximately 1.1 m above the floor (seating height) and 1m away from the occupants, in two locations in the library's study rooms using the instruments presented in Table 2. Figure 4 illustrates an example of where the measurements were carried out during the survey.

In addition to these, temperature and humidity data loggers were installed on the second floors of the old and new blocks for long-term measurements. The outdoor data logger was installed on a shaded north-facing wall before the surveys, and recorded temperature and humidity data before and after the field study dates for one year.

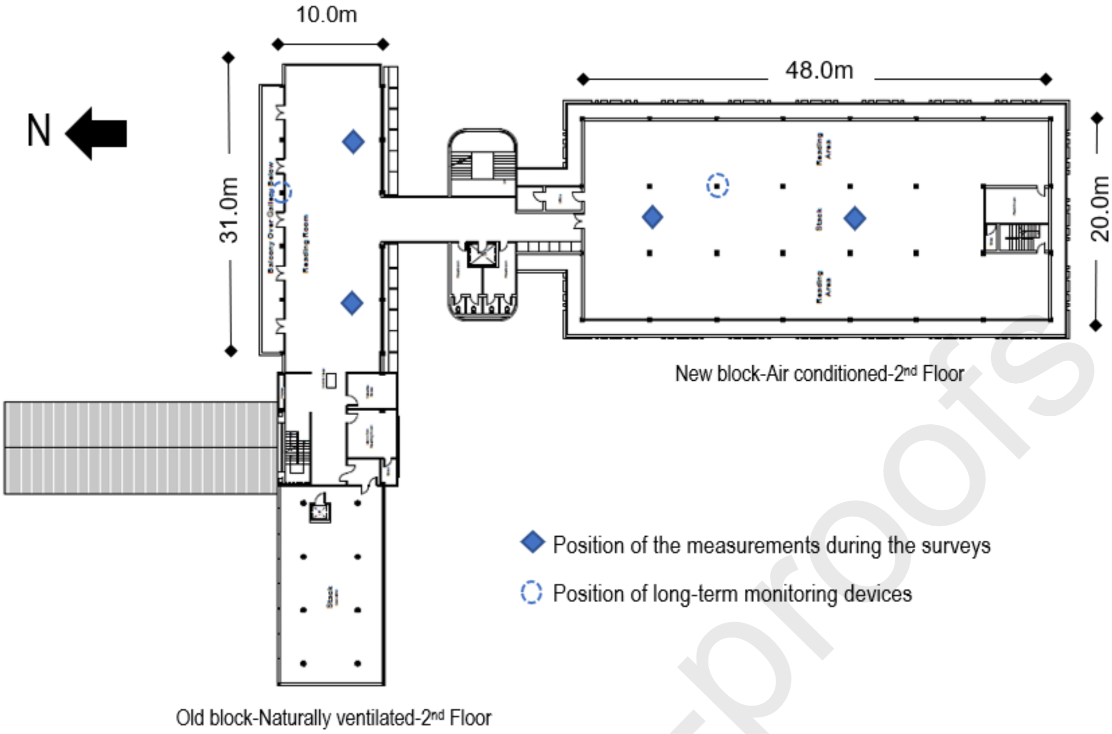


Figure 4–An example of the position of measurements in the second-floor reading rooms of the two blocks

Table 2–Instruments used in the field survey.

Parameter measured	Sensor/Model	Measuring range	Accuracy	Resolution
Long term measurement of indoor T_a and RH	WiFi Temperature & Humidity Data Logger EasyLog-EL-WiFi-TH	$T_{a:}$ -20 to +60°C, RH: 0 to 100% Measured at a 1-minute interval	±0.3°C ±2% RH Typical	NA
Long term measurement of outdoor T_a and RH	Temp/RH data logger HOBO onset UX100-011	$T_{out:}$ -20° to 70°C Measured at a 1-minute interval	±0.21°C from 0° to 50°C	0.024°C at 25°C
Indoor T_a and RH and T_g	Heat Stress WBGT Meter Tenmars TM-188	T: 0~50.0, RH: 0~80.0	@15~40°C ±0.8	0.1
V_a	Air Flow Anemometer Testo 405 NTC	V: 0 to 5m/s (-20 to 0°C), 0 to 10m/s (0 to 50°C)	±5% + 0.3 m/s	0.01m/s
	hot wire thermo-anemometer/datalogger EXETECH SDL 350	V: 0.2 to 25m/s	±5%	0.01 m/s

The mean radiant temperature (T_r) and operative temperature (T_{op}) were determined with the measured data at the site. T_r was calculated using Equation (1) [4].

$$T_r = \left[(T_g + 273)^4 + \frac{1.1 \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}} \times (T_g - T_a) \right]^{\frac{1}{4}} \tag{1}$$

Where D, the diameter of the globe was 0.05mm, and ε, the emissivity of the surface was 0.9. During the survey, in the new block that has ACs, and low airflow, a slight temperature variation was caused by radiant temperature asymmetry owing to the large, unshaded glazing (see Figure 3(b)). This radiant temperature variation instigated a higher operative temperature in the west-to-east-facing new block, with the morning and afternoon temperature differences of 2.5–3.2°C. The radiant temperature in NV mode rooms was similar to the air temperature.

The operative temperature is calculated using Equation (2) and consists of the T_r, the convection heat transfer coefficient (h_c) and the radiation heat transfer (h_r).

(2)

$$T_{op} = HT_a + (1 - H)T_r \quad \text{Where:}$$
$$H = h_c/(h_c + h_r)$$

The h_r was considered 4.7 W/m^2 °C, and h_c was estimated according to the ASHRAE Standard 55 [4] for an air velocity of less than 0.2m/s.

3. Methods of data analysis

The neutral or comfort temperature (T_{comf}) or comfort zone is the operative temperature at which the average person will be thermally neutral, or the most significant proportion of a group of people will be comfortable [3]. In recent years, thermal comfort assessments have been mainly driven by the 'buildings' energy efficiency and the occupants' long-term well-being and comfort are overlooked [31, 32]. Therefore, several models and indices have been established to represent and include the 'occupants' thermal feeling. According to Kiki et al. [32], these models can be categorised into three types: static, adaptive and hybrid.

3.1. Statistic and hybrid models

Statistic models only allow for heat exchanges between the human and thermal environment. The PMV by Fanger [9] and the standard effective temperature (SET) developed by Gagge et al. [33] are two widely used models in this sense. The PMV index, a steady-state thermal comfort model, has been adopted by various international standards [8, 12, 4], and depends on the six variables of T_a, T_r, RH, V_a, activity and clothing level. However, PMV does not consider the 'occupants' expectations and adaptability; therefore, an extended PMV model was developed by Fanger and Toftum [34], via integrating an expectation factor (e) into the basic PMV equation. This factor was proposed to calibrate the inconsistencies between the occupants' perceived TSV and the calculated PMV in the NV buildings [34, 32]. This extended PMV is calculated using Equation (3).

(3)

$$PMV_e = e \times PMV$$

Fanger and Toftum [34] suggest an e of 0.5 for regions where the weather is warm all year or most of the year, and there are none or few other air-conditioned buildings. However, Yao et al. [35] suggest the hybrid Equation (4) for calculating e when TSV is available:

(4)

$$e = \frac{\sum_{i=1}^{n} TSV_i \times PMV_i}{\sum_{i=1}^{n} (PMV_i)^2}$$

This paper used this model to calculate the e and extended PMV for the NV rooms and compared it with the factor suggested by Fanger and Toftum [34]. The PMV was calculated using the 'Center for the Built Environment's (CBE) online calculator [36].

3.2. Adaptive models

3.2.1.Thermal comfort votes and operative temperature

The logical process of defining T_{comf} varies between the international adaptive comfort standard, ASHRAE 55 [4], and its European equal CEN [12] due to the different sample sizes used [37]. In the ASHRAE database, statistically significant regression models are used to predict the T_n for individual buildings using a wide range of temperatures and a substantial number of data [38]. In contrast, the so-called 'Griffiths method' for each comfort vote is applied, addressing smaller sample sizes in the SCATs database analysis to calculate T_n in the EN 15251 adaptive model [37, 31, 39]. In addition, the regression analysis estimates the mean T_{comf} over the several days or weeks of the survey period. In contrast, the proposed Griffiths method estimates a comfort temperature of a particular person in a particular building in that particular month [39].

The Griffiths method introduced the Griffiths slope (G), which is also called Griffiths coefficient, the constant of the thermal sensation rate for the linear relationship between surveyed thermal sensation votes and operative temperature, to assess a neutral temperature for a small number of comfort votes or a small temperature range. Based on the Griffiths method, the neutral temperature can be calculated using the following relationship from T_{op}, TSV, and G:

$$T_{comf} = T_{op} - \frac{(TSV - TSVn)}{G} \tag{5}$$

Where the TSV is the thermal sensation vote, the TSV_n represents the neutral condition, and G is the Griffiths coefficient. For this case study and sensitivity analysis, G was set at 0.25, 0.33, and 0.50, according to [40].

3.2.2.Thermal comfort votes and outdoor data measurement

Amongst the three types of thermal adaptation (i.e. physiological, behavioural and psychological), behavioural adaptive processes have faster time constants than the more profound physiological adaptations [38, 37]. Accordingly, several equations are developed and presented in the literature assessing the acceptable comfort temperature ranges to the outdoor meteorological parameters [40]. These equations mainly consider the weighted running mean temperature (T_{rm}) as an independent variable for outdoor temperature. Equation (6) determines the T_{rm} calculations.

$$T_{rm} = \{T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3}...\}/\{1 + \alpha + \alpha^2...\} \quad (6)$$

Where T_{od-1} is the daily mean outdoor temperature for the previous day, T_{od-2} is the daily mean outdoor temperature for the day before and so on. The constant α is a time constant that shows the time needed for thermal adaptation. The half-life (λ) calculation of an exponentially weighted T_{rm} [40, 41] is given in Equation (7).

$$\lambda = 0.69/(1 - \alpha) \quad (7)$$

The optimal rate of α can be estimated by deriving the strongest correlation between T_{comf} and T_{rm}. However, ASHRAE 55 [4] recommended considering a range of 0.33 to 0.9 for α. The α=0.8 (seven days) has been used by researchers for climates with negligible day to day temperature difference, such as the tropical Aw climate [19, 42, 43, 44]. EN 15251 [12] and McCartney and Nicol [41] also suggest 0.8, which represents a half-life of 3.5 days (λ = 3.5), as the best value for α. For the climate region of this paper, Kumasi, Ghana, although the average day to day temperature is not much different, the temperature during the day varies significantly. A detailed review by Haddad et al. [37] on the subject concludes the importance of the α-coefficient in the adaptive comfort temperature standard and the necessity of a sensitivity analysis. Accordingly, for the purpose of this study, a sensitivity analysis was performed to obtain the appropriate value of the α-coefficient. Then the comfort temperature calculated using Griffiths method is compared with the outdoor temperature parameters (i.e. measured mean daily temperature and T_{rm}) to suggest an adaptive model.

4. Results

4.1. Subject sample size and environmental conditions

Table 3 compares the indoor and outdoor thermal conditions recorded in NV and AC modes during the survey in January 2020. Over the survey period, the T_a and T_r in AC mode were lower than the NV mode, with average differences of 4.0°C for T_a and 1.0°C for T_r. No significant differences were recorded for RH, I_{cl}, T_{out} or the activity level between both operation modes of the buildings during the survey period. ASHRAE standard 55 [4]'s clothing insulation values for typical ensembles were used to calculate the garment value for each respondent. 'Trousers, short-sleeved shirt and sandals (I_{cl}=0.57)', followed by 'Trousers, long-sleeved shirt, sandals (I_{cl}=0.61)', were the most used garment, which resembles the garments generally worn during the dry season in Ghana.

Table 3–Measured indoor and outdoor environmental conditions.

	AC rooms				NV rooms			
Number of valid surveys	121 (85% Male, 15% Female)				136 (70% Male, 30% Female)			
Variable	Mean	SD	Max	Min	Mean	SD	Max	Min
Respondents age	22	4.9	46	16	22	4.7	51	18
Outdoor Daily Mean Temperature (°C)	31.4	1.6	33.7	29.8	31.4	1.6	33.7	29.8
Indoor air temperature (°C)	26.5	1.1	28.6	25.5	30.5	1.8	34.1	27.8
Indoor Operative Temperature (°C)	26.8	1.0	28.7	25.6	30.5	1.8	34.1	27.8
Indoor Daily Mean RH (%)	70.7	8.5	77.2	46.5	69.1	10.6	76.1	44.5
Air Velocity (m/s)	0.2				0.1>			
Clothing	0.57	0.10	0.96	036	0.55	0.11	0.96	0.36
Activity	1.19	0.43	3	1	1.18	0.47	3	1
Thermal sensation vote	-1	0.8	1	-3	0.13	0.8	2	-1
Humidity vote	-0.4	0.9	2	-2	0.1	0.9	2	-3
Airflow vote	-0.2	1.0	2	-3	-0.6	0.8	1	-3
PMV (AC) and PMVe, e=0.5 (NV)	-0.4	0.5	1.4	-2	0.81	0.1	1.3	0.2

The predominant activity was ‘sitting, active work (1.1 MET)’, followed by ‘sitting, passive work (1.0 MET)’, corresponding with representative activities in educational and library buildings. In general, the surveyed sample reflects the whole population's features, behaviours, and tendencies.

4.2. Thermal comfort votes and operative temperature

In this section, the respondents' thermal comfort votes to the survey questions on TSV, TPV, and TA are examined to recognise the relationship between comfort vote and indoor temperature.

Figure 5(a) illustrates the frequency distribution of the votes in AC and NV modes.

In AC mode, the air conditioning system was set at 26.0°C and, therefore, depending on the radiant temperature (T_r), a small operative temperature range was recorded. At the mean T_{op} of:

- 26.9 ± 0.6°C, the greatest percentage (79.1%) of thermal discomfort was due to the ‘slightly cool’ or ‘cool’ sensation.
- 28.8 ± 0.0°C, 18.1% of all the participants felt ‘neutral’.

However, the TP votes in Figure 5(b) show that the greatest percentage (49.0%) in AC zones preferred ‘No change’, and only 33.0% of participants preferred ‘a bit warmer’ temperatures.

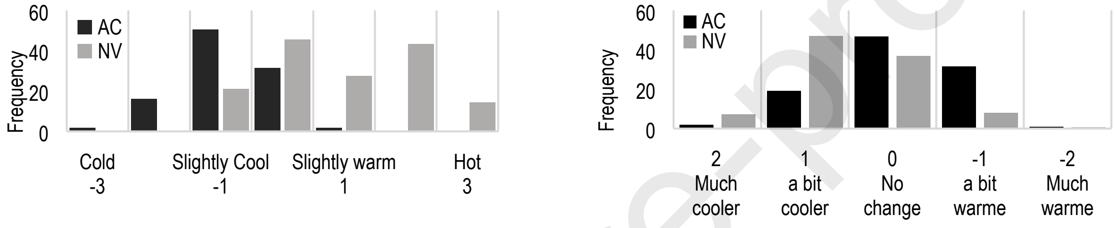
As seen in Figure 5(a), a higher percentage of the respondents in naturally-ventilated rooms feel comfortable at higher temperatures of about 2.6°C above the accepted T_{op} in zones with ACs. In NV mode at the mean T_{op} of:

- 30.4 ± 1.9°C, around half (45.7%) of the surveyed felt ‘neutral’.
- 31.0 ± 1.9°C, 27.5%, of all the participants felt ‘slightly warm’.
- 28.5 ± 1.4°C, 21%, voted for a ‘slightly cool’ sensation.

Though, as seen in Figure 5(b) the greatest percentage (47.1%) preferred ‘a bit cooler’ temperature in NV mode, and 37.5% of respondents voted for ‘no change’. According to a study by Rijal et al. [45]

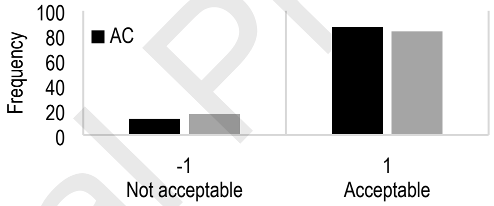
applicable to Nepalese people, the contradiction between the TSV and TP occurred for persons who lived in a consistently hot climate and chose a ‘cooler’ temperature. The study suggests that it could be the natural inclination of most people living in hot climates to prefer a ‘cooler’ environment, even though they most likely accepted the current conditions [46]. This can explain the TP results for the NV mode in this study.

In NV mode, 83.3% of surveyed found the mean T_{op} of 30.6 ± 1.8°C ‘acceptable’. In AC mode, 86.7% of the occupants felt the mean T_{op} of 27.5 ± 0.7°C temperature was ‘acceptable’. The high proportion of ‘acceptable’ votes could be due to the occupants’ psychological adaptation to their thermal environment (See Figure 5(c)) [44]. For both modes, the comfort zone, as a function of the mean T_{op}, was predicted based on the comparison of the distribution frequency between TPV and TSV.



(a) Thermal sensation votes

(b) Thermal Preference



(c) Thermal acceptance

Figure 5–Frequency distribution of (a) the thermal sensation vote, (b) the thermal preference, and (c) the thermal acceptance

Considering the votes between ±1 as an indicator of ‘comfortable feeling’, Table 4 presents the comfort zone and neutral temperatures in AC and NV mode, based on the thermal comfort votes. The Table also demonstrates the correlation coefficient (R^2) between TSV with mean T_a, mean T_r and mean T_{op}. As in the AC rooms, the temperature was set at 26.0°C at all times; there is no significant correlation between TSV and T_a, but there is a correlation between the votes and T_{op}. There was no significant correlation between TP and different measure temperatures.

Table 4–The comfort zone, neutral temperature and correlation and linear regression of T_a with T_{op} and T_r

Mode	N	Comfort zone (°C) based on TSV 0 and ±1	T_n (°C)	TSV:T_a			TSV:T_{op}			TSV:T_r		
				R^2	P	r	R^2	P	r	R^2	P	r
AC	121	26.9 (± 0.6)–28.9 (± 0.5)	27.8 (± 0.8)	0.02	< 0.05 (not significant)	0.26	0.10	< 0.000	0.32	0.12	< 0.000	0.34
NV	136	29.4 (± 1.4)–31.5 (± 1.9)	30.4 (± 1.9)	0.14	< 0.000	0.38	0.12	< 0.000	0.34	0.09	< 0.000	0.31

4.3. Relative humidity and humidity feeling

Figure 6 depicts the distribution of the HFV in NV and AC modes. During the survey period, slight changes in the relative humidity were measured. The RH of the environment lead to 'acceptable' votes, and most of the participants felt 'slightly dry' to 'neutral'. This is expected since the survey was carried out over the dry season.

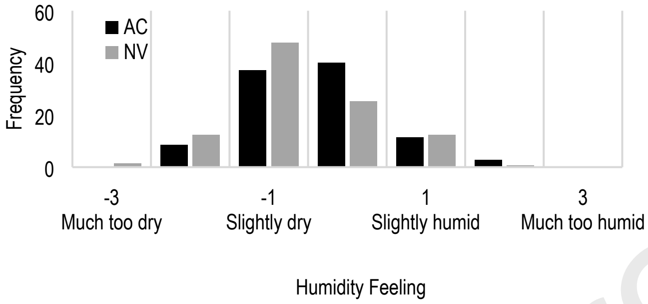


Figure 6 –Frequency distribution of the humidity feeling

4.4. Airflow and airflow feeling

It is typical in a tropical climate only to have slight air movement, and during the survey, the airflow level was less than 0.1m/s in NV rooms. In AC mode, the air movement was as little as 0.2m/s at the head level of seated participants. Figure 7 shows the AF and AP frequency distribution in both modes.

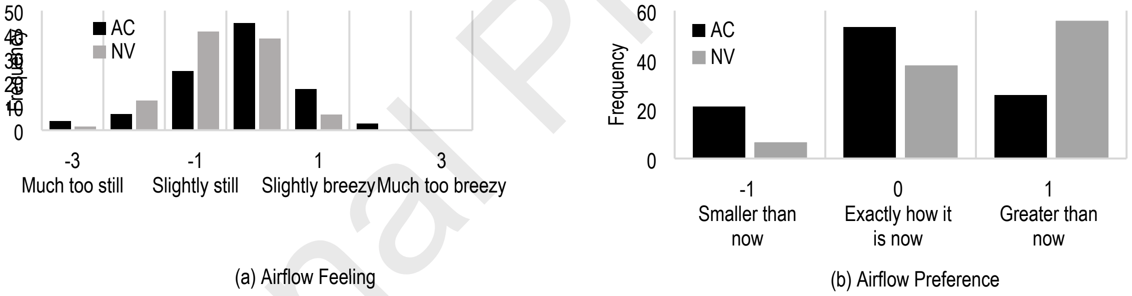


Figure 7–Frequency distribution of the (a) airflow movement feeling and (b) airflow movement preference

Considering the votes between ±1 as an indicator of comfortable feeling, all the female participants and 84.3% of the males surveyed found the airflow rate 'just right' in AC mode. However, only about half of all participants preferred no change in the airflow. Interestingly, there is an asymmetrical distribution of the votes for the 'smaller airflow' and 'greater airflow'.

In NV mode, most of the participants' votes fell in the 'neutral' or 'slightly still' categories and only 6.5% of participants felt the airflow was 'slightly breezy'. Additionally, the greatest percentage (55.8%) of participants preferred a 'greater airflow' while 37.7% voted for 'no change' in the NV mode.

4.5. Evaluation by Fanger's PMV

Figure 8 compares the TSV with PMV and PMV_e, using both the Fanger and Toftum's [34] extended factor of 0.5 and the calculated factor (0.11) obtained from Equation (4). Figure 8 illustrates the mean values for PMV and PMV_e against indoor operative temperatures.

In NV mode, results show a significant underestimation of the adaptability of surveyed to the high indoor temperatures. An apparent discrepancy between the PMV indices and the occupants' average TSV results in a much lower neutral temperature of 24.4˚C than the predicted ones using other methods (see Table 5). Each point in Figure 8 (a) represents a single response, and the given points would have been very close to the diagonal if there was a similarity between the TSV and the PMV_e. This suggests that PMV_e underestimates respondents' comfort temperature.

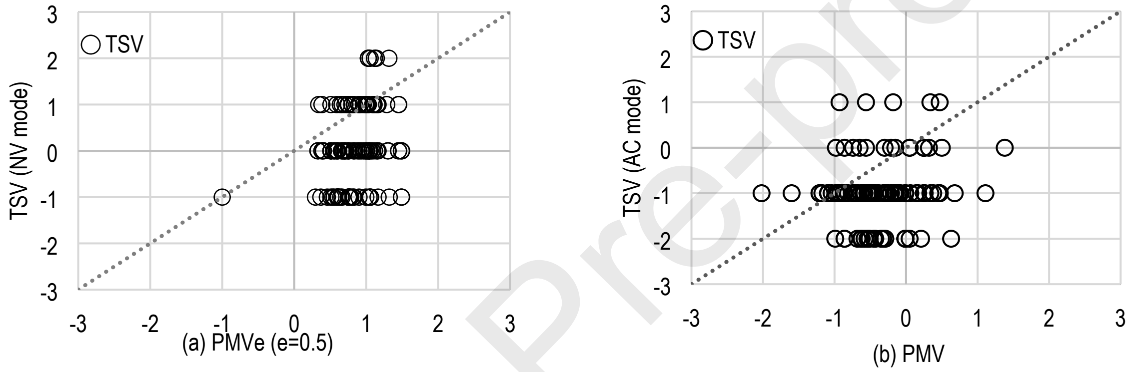


Figure 8–Representation of TSV as a function of PMV_e in NV mode (a) and PMV in AC mode (b). Each point represents a single response.

Considering that all the six thermal comfort variables were recorded directly from the surveyed students, the variations between PMV and TSV in buildings can be explained by the psychological component of comfort and the inhabitants' adaptability [32, 17].

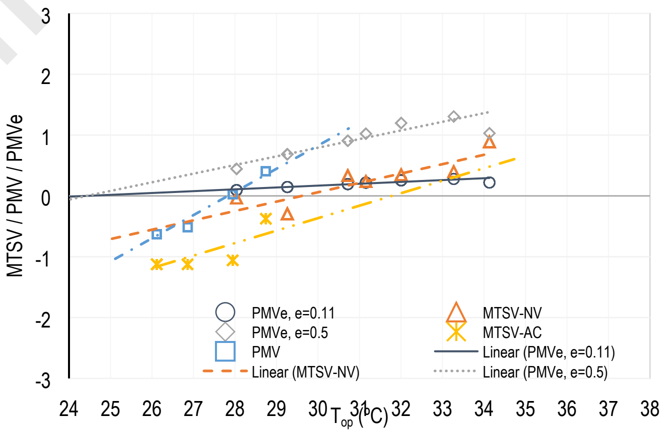


Figure 9–Linear regression of the Mean thermal sensation votes (MTSV) and predicted mean votes (PMV) as a function of operative temperature in NV and AC modes. Binned data at 1°C T_{op} are presented here.

For the AC mode, as seen in Figure 9, the neutral temperature of PMV (27.8°C) is is about 3.8 ºC lower than the neutral temperature of 31.5 °C predicted by the linear regression method (Please see Equations (8) and Figure 10). It should be noted that considering the sample size, the Linear regression method is not as reliable as the other methods used in this paper (see section 2.4.2).

4.6. Linear regression method

The relationship between participants' TSV and T_{op} variations was examined and presented in Figure 10 for both modes. Equation (8) shows the linear regression of the surveyed thermal sensation votes against T_{op} for AC mode and Equation (10) for NV mode.

The binned data at 1°C is also evaluated to identify trends in the scattered plots of the raw data, as done in prior studies [47, 48, 30], for AC and NV modes, respectively.

For the binned data, the authors used weighted regression analysis. There is a minor difference between the raw and binned slopes and constants in both modes, but more visible in NV mode. This is because the temperature assigned to a bin, known as the bin-centre temperature, does not always equal the mean temperature of the data within the bin. Humphrey et al. argue that binning is employed considerably more than is required or desired in thermal comfort field data analysis. Initially, the goal of binning was to decrease the labour involved in the statistical calculation. This was a significant factor before the availability of statistical computations [40]. However, as binning is a common practice in thermal comfort studies and to compare the result of this study with previous research, we have presented both raw and binned data.

AC mode:

Raw: $TSV = 0.20T_{op} - 6.39$ ($N=121$, $R^2 = 0.07$, $S.E.=0.085$, $P<0.001$) (8)

Binned: $TSV = 0.21T_{op} – 6.63$ ($N=8$, $R^2 = 0.62$, $S.E.=0.21$, $P<0.001$) (9)

NV mode:

Raw: $TSV = 0.16T_{op} - 4.81$ ($N=136$, $R^2 = 0.14$, $S.E.=0.074$, $P<0.001$) (10)

Binned: $TSV = 0.15T_{op} – 4.56$ ($N=10$, $R^2 = 0.55$, $S.E.=0.21$, $P<0.001$) (11)

Where R^2 is the coefficient of determination, N is the number of respondents, p is the significance level of the regression coefficient, and S.E. standard error of the correlation coefficient is taken as $(1−R^2)/\sqrt{(N−1)}$ [40].

As seen in Equations (9) and (11), the slope and constant have slightly changed, but the R-squared has increased significantly. The slopes of the linear lines signify the range of thermal sensation variation with T_{op} or respondents' sensitivity to T_o [49, 39] $_p$.

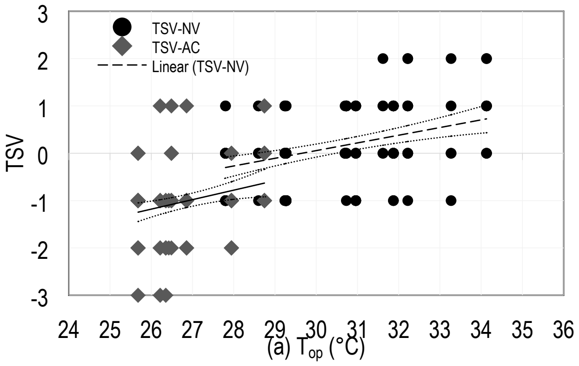


Figure 10–Linear regression between individual thermal sensation votes, and the operative temperature in AC mode (solid line) and NV mode (dashed line). The polylines show 95% confidence intervals.

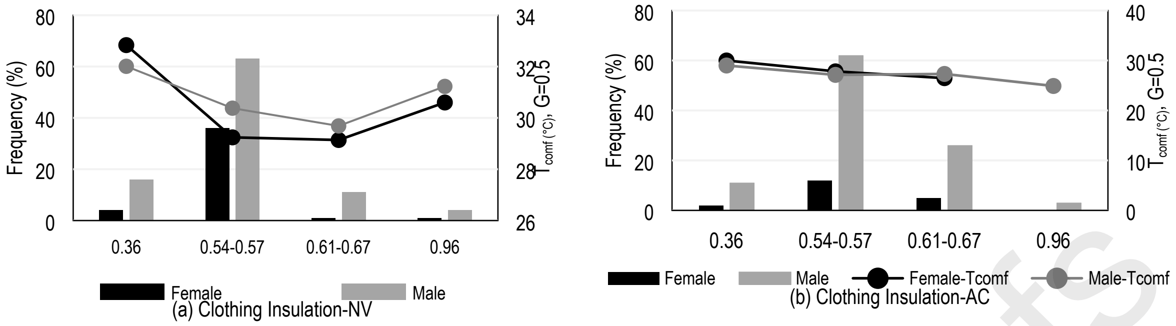
In AC mode, the increase in the slope can be explained by the high percentage of people feeling 'slightly cold' (62%). Although around half of the respondents (47%) voted for a neutral feeling in NV mode, the lower than expected slope can be explained by the other half of votes for either a slightly warm (26%) or slightly cool (22%) temperature.

4.7. The Griffiths method

Comparison of the mean T_{comf} using the three Griffiths coefficients over the thermal sensation votes in NV and AC modes can be seen in Table 5. Rupp et al. [50] argue that users are approximately half as responsive to temperature fluctuations in naturally ventilated environments as air-conditioned ones. According to the study, AC users had thermal sensitivities ranging from 0.448-0.527/K^{-1}, whereas NV users had sensitivities ranging from 0.219-0.418/K^{-1}. Therefore, for this study the three G constants of 0.25, 0.33, and 0.50 were applied, according to [40, 49], and the neutral temperatures and the comfort zone are identified by the TSV (0) and the TSVs (±1). The predicted temperatures were steadier in both modes with lower standard deviation (SD) when G=0.50 in which T_n of 27.4 ± 1.6°C and 30.3 ± 1.9°C were predicted for the AC and NV modes, respectively.

4.7.1. Relation between gender, thermal comfort and clothing insulation

Age, gender, clothing, and climate have all been proven to be factors that can impact the thermal sensitivity of a building's inhabitants [50]. Majority of respondents in both modes aged between 18 to 22. However, although most of the participants were male in both modes, the percentage of women who participated in NV mode (30%) was higher than the women in AC mode (15%). Accordingly, the relationship between the Griffiths T_{comf}, respondents' gender and clothing insulation are presented in Figure 11.



(a) Clothing Insulation-NV

(b) Clothing Insulation-AC

Figure 11–The relation between Griffiths neutral temperature, respondents' gender and clothing.

In AC mode, there is a negative relationship between I_{cl} and T_{comf} and no significant difference between males and females. In the case of NV mode, Figure 11(a) shows that I_{cl} does not directly affect the respondents' T_{comf}. Overall, females felt comfortable at slightly lower temperatures. As the mean clothing insulation for male and female respondents are similar, it can be concluded that there are no significant differences between the T_{comf} and gender or clothing insulation.

4.7.2. Comparison with previous studies

Table 5 compares the predicted neutral temperature using various methods for the AC and NV in Kumasi, Ghana, during the survey in January (dry season) with the results of similar investigations in other countries on the thermal comfort relevant to hot climatic conditions.

Table 5–Calculation of the neutral temperature using different methods and other studies

Ref.	Year	Country/Region	Mode	Sample size	T_{out} (°C)	Thermal index/ methods of analysis	T_{comf} (°C)
[51]	2017	Japan	AC	2537	24.9	Tg (summer time surveys)	25.4°C
[46]	2017	Malaysia	AC	872	31.4	T_{op}	25.6 (±2.4)
[46, 52]	2016	Malaysia	AC	1114	31.2	T_{op}	25.6
[52]	2015	Indonasia	AC	91		T_{op}	26.3
[32]	2019	Benin	AC	29	25.5-28.5	T_a	24.8- 28
Current study		Ghana, Kumasi	AC	121	29.8-33.7	T_{op}/TSV and TP mode	27.8±0.8
						T_{op}/ Griffiths method (0.50)	27.4 (±1.6)
						T_{op}/ Griffiths method (0.33)	27.6 (±2.6)
						T_{op}/ Griffiths method (0.25)	27.9 (±2.9)
						PMV	27.8
[43]	2020	Kano region, Nigeria	NV	1382	33.5-36.8	TSV: T_{op} (summer surveys only)	30.3
[46]	2017	Malaysia	NV	106	29.9	T_{op}	26.8 (±1.9)
[46]	1998	Hawaii, USA	NV	1052	24.0–33.0	T_{op}	27.4
[53]	2010	India	NV	3962	27.0-41.7	T_g	29.23
[54]	2003	Singapore	NV	506	-	T_{op}	28.9
[55]	2018	Indonasia,	NV	1594	29.7	T_{op}	29.0
Current study		Ghana, Kumasi Dry Season	NV	136	29.8-33.7	T_{op}/TSV and TP mode	30.4±1.9
						T_{op}/ Griffiths method (0.50)	30.3 (±1.9)
						T_{op}/ Griffiths method (0.33)	30.2 (±2.4)
						T_{op}/ Griffiths method (0.25)	30.1 (±3.0)
						PMV_e (e=0.5 and 0.11)	24.4

Based on the present study, for AC mode, the comfort operative temperature in Kumasi was approximately 2 to 4°C higher than those indicated in other studies. This may be due to the exclusion of wet season data, which is one of the limitations of this study.

For NV mode, the results of Ali, et al. [43] study, which shows an average T_n of 30.3°C during the dry season, is almost identical to this study, but other studies estimated a lower comfort temperature.

4.8. The adaptive model

Considering the limited T_{op} variations during the survey and the small number of respondents, methodologies in the study of the SCATs data have been adopted to determine the comfort equation between respondents' comfort temperature calculated using Griffiths method and the climate metrics [37, 40, 56]. The T_{rm} is calculated via Equation (6) and employs different α constants, ranging from 0.33 to 0.80, as each value suggests different adaptation durations [41]. Table 6 summarises the sensitivity study of the selected factors for λ and α. It shows the correlation coefficient (R^2) between the T_{rm} resulting from different values of α and the T_{comf} estimated from the surveyed thermal sensation votes and the Griffiths coefficients of 0.25, 0.33, and 0.50. Moreover, the obtained values are statistically significant ($p < 0.001$).

Table 6–Pearson correlation coefficient (R^2) between the exponentially weighted running mean outdoor temperatures resulting from different values of α and the comfort temperatures calculated from respondents' TSVs using various Griffiths constants

Griffiths constants (G)	**T_{rm} using measured data**										**Daily mean T_{out} on which the survey took place**	
	α=0.33 λ ~ 1		α=0.45 λ ~ 1.3		α=0.65 λ ~ 2		α=0.7 λ ~ 2.3		α=0.8 λ ~ 3.5			
	NV	AC	NV	AC	NV	AC	NV	AC	NV	AC	NV	AC
0.25	0.002	0.022	0.001	0.023	0.002	0.022	0.003	0.021	0.001	0.023	0.011	0.014
0.33	0.010	0.033	0.007	0.036	0.007	0.034	0.011	0.031	0.006	0.035	0.038	0.018
0.5	0.036	0.059	0.024	0.065	0.022	0.061	0.032	0.055	0.021	0.053	0.107	0.027

As can be seen from Table 6, the Pearson correlation coefficient (R^2) between the exponentially weighted running mean outdoor temperatures and comfort temperature is strongest when the Griffiths constant is G=0.5. Consequently, the G=0.50 was considered in this work which has been used in several studies in hot and humid climates [44, 57, 47, 56]. Table 6 suggests that the correlation coefficient between T_{comf} and T_{rm} for all values of λ is strongest when α=0.45 for the AC mode. However, the strongest correlation is with the measured daily mean outdoor temperature (T_{out}) in the NV mode and then α=0.33. A higher correlation coefficient between the smaller value of λ was also found by Haddad, et al. [37]. The results on the faster response to outdoor temperature might be due to the lightweight building fabric or short survey time.

More samples and research are required to understand the relationship between time constant (α) and thermal comfort. Accordingly, in the following sections, the mean daily outdoor temperature rather than T_{rm} is used to understand the relationship between outdoor air temperature and the respondents' thermal comfort (adaptive model). The Adaptive comfort model for the AC and NV mode is illustrated in Figure 12.

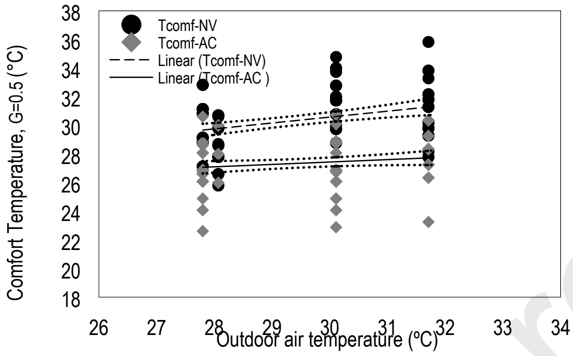


Figure 12–Relationship between the estimated comfort temperatures and the measured outdoor air temperatures.

The Figure presents the raw data, and Equations (12), (13), (14), and (15) present the weighted linear regression for raw and binned data [52]. The equations are statistically significant at $p< 0.001$ for both modes, and their slopes are significantly different from the international models.

In both modes, the slopes and constants of the binned and raw data are slightly different, but a much higher coefficient of determination resulted from the binned value [40]. The Equation obtained from this study for AC mode is the same as the one obtained from a thermal comfort field study in offices in India's hot and humid climate and of 4310 responses over 14 months [56].

AC mode:

Raw: $T_{comf} = 0.17T_{out} + 22.42$(N=121, $R^2 = 0.02$, S.E.=0.09, P<0.000) *(12)*

Binned: $T_{comf} = 0.15T_{out} + 23.00$ (N=4, $R^2 = 0.33$, S.E.=0.67, P<0.000) *(13)*

NV mode:

Raw: $T_{comf} = 0.41T_{out} + 18.21$ (N=136, $R^2 = 0.11$, S.E.=0.08, P<0.000) *(14)*

Binned: $T_{comf} = 0.44T_{out} + 17.40$ (N=4, $R^2 = 0.52$, S.E.=0.48, P<0.000) *(15)*

Higher than standards slope is obtained for NV mode as well. The statistical meta-analysis of the ASHRAE RP-884 database by Toe and Kubota [42] in naturally ventilated buildings in hot and humid climates also revealed a higher slope of $0.57K^{-1}$, approximately twice that of ASHRAE and CEN standards 55.

The higher slope than the international or European equations indicates that the Ghanaian sample was more sensitive to the outdoor temperature changes. This might be due to the lightweight structure of the building and lack of shading.

4.9. Comparison with the standards

International standards such as ASHRAE [4], EN 15251 [12], for naturally ventilated buildings and CIBSE Guide [12] for air-conditioned buildings are widely accepted and used to predict indoor comfort temperature using outdoor temperature.

Figure 13 illustrates a comparison of the adaptive comfort temperature and the comfort zone, using the proposed regression model with the ASHRAE standard 55, the CEN standard and the CIBSE guide. The dash lines show the predicted T_{comf} as the proposed model, the solid black lines demonstrate the T_{comf} calculated using the international standards models, and the segmented lines represent the comfort zone limits according to the standards.

The proposed adaptive models have shown a higher slope than those specified in the standards. This may indicate the more robust relationship between the surveyed neutral comfort and the outdoor temperature change. Overall, the standards predict a lower comfort band than this study's results.

For NV mode, the CEN standard equation (Figure 13(b)) predicts a higher comfort temperature than the ASHRAE equation (Figure 13(a)). Compared with the ASHRAE standard 55, almost all the data points and the regression line lie above the standard in NV mode. This clearly indicates that the ASHRAE standard is too conservative, and people are comfortable at warmer temperatures. Considering the acceptability of the 90% zone only 35.0% of the sample was within the comfort zone. Following the ASHRAE standard 55 adaptive model, the predicted comfort temperature was, on average, 3.3°C lower than the proposed model.

Compared to the projected model in CEN standard, only 13% of the sample was out of the comfort zone in the NV mode. However, the predicted mean comfort temperature of 28.54 ± 0.3°C by the CEN model is 1.8˚C lower than the average neutral temperature estimated in this study.

For the AC mode, when compared to the CIBSE guide (slope: $0.09K^{-1}$), the comfort temperature varied rather sharply with the outdoor temperature (slope: $0.15\ K^{-1}$). Figure 13(c) shows that less than half of the sample is predictable using the CIBSE comfort zone of ±2K. Using the adaptive model of the CIBSE guide, the mean T_{comf} would be approximately 2.1°C lower than the proposed model.

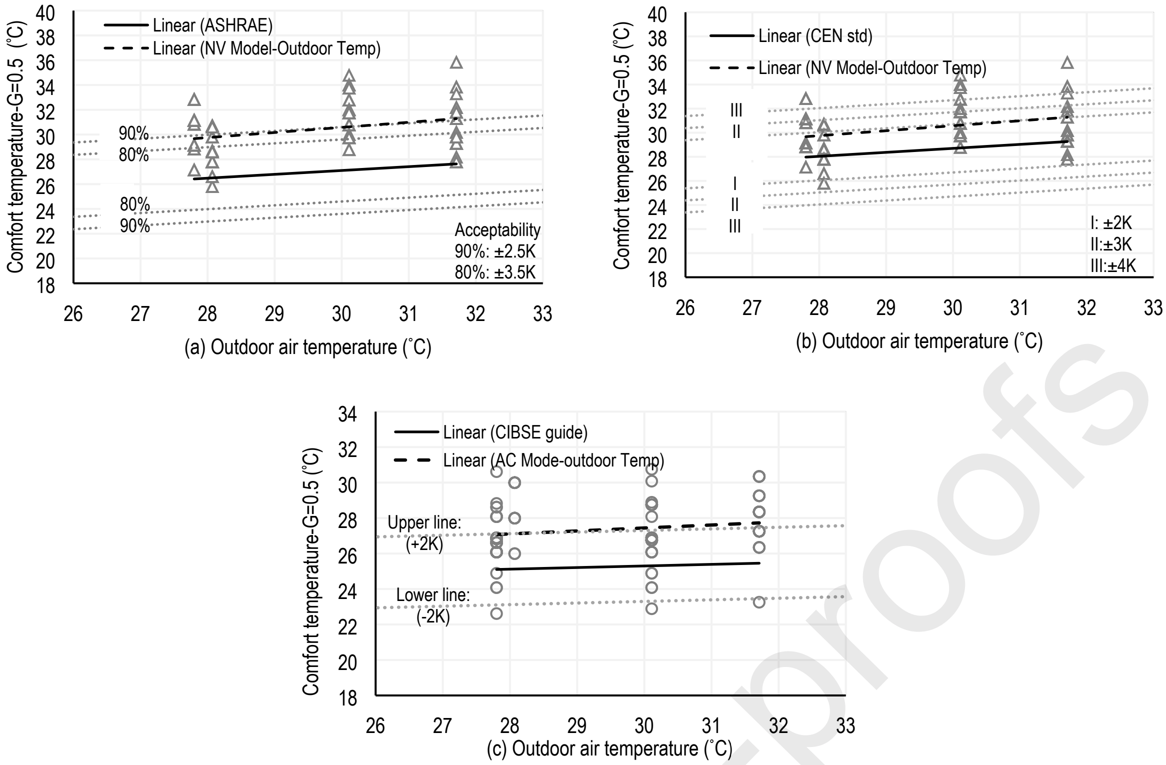


Figure 13–Comparison of the adaptive thermal comfort with existing standards: a) the ASHRAE standard 55, b) the CEN standard, and c) the CIBSE guide using both the prevailing mean outdoor temperature measured during the surveys

We have used the 'cooling degree-days (CDD)' method to understand the effect of the 2.1°C difference on energy consumption. The degree days are calculated by multiplying the days during which there is a temperature drop by the number of degrees temperature drops for each day. The outdoor-indoor temperature difference of 2K is assumed and outdoor temperature from the meteorological weather data from version 7 of Meteonorm for Kumasi is used for the analysis. In January, the number of design CDD for an indoor temperature of 27.5°C (T_{comf} in this study) is around 21, for 25.5°C (CIBSE model) is about 48. These figures indicate that in January, a drop of 2K in the indoor temperature increases the cooling energy by 56% – or additional consumption of about 28% for every degree.

5. Summary of the results and discussion

The paper presented the adaptive thermal comfort model in NV and AC rooms in library buildings located in an Aw climate zone. The thermal comfort field study on 257 collected datasets in two library buildings in Kumasi, Ghana, West Africa, during January 2020 (the dry season) was analysed.

1. In AC mode, at the mean operative temperature of 26.9°C, a significant percentage (79%) of those surveyed felt 'cool' or 'slightly cool'. In NV mode, at the mean operative temperature of 30.4°C, around half (45.7%) of those surveyed felt neutral.

The comfort temperatures of 27.4°C (±1.6) and 30.3°C (±1.9) were predicted using the Griffiths method (G=0.50) in AC and NV modes. There is a 2.9–3.7°C difference between the AC and NV modes' comfort temperatures. A similar variance was found in two studies conducted by de Dear et al. in the hot and humid climates of Singapore [58] and Busch in Thailand [59]. However, for both modes, the comfort temperature in Kumasi is noticeably higher than the results of other studies in the tropical climate [51, 46, 52, 53, 54], but within the estimated comfort range of two studies from West Africa [43, 32]. Accordingly, more studies in the region are required to understand the adaptive model in Ghana and West Africa.

2. For AC mode, the neutral temperature predicted by the TSVs is similar to the one estimated using predicted mean votes (PMV). In NV mode, an apparent gap between the average TSV and the PMV indices (PMV_e) resulted in NV mode's neutral temperature being predicted significantly lower than by other methods.
   A similar neutral temperature prediction for AC mode and the underestimation for NV mode using PMV could be explained by a thermal comfort study in Australian school classrooms by de Dear et al. [60]. The study shows that the PMV was well-matched with the TSV when the operative temperature was within the range of 25–27°C, and that PMVs tended to overestimate the students' TSVs after the operative temperature exceeded 27°C. In this study, the operative temperature ranges from 25.6°C to 28.7°C, and 27.8°C to 34.1°C, respectively. Other studies have also concluded that PMVs overestimate the respondents' TSVs in the tropics [55, 61, 14].
3. Fanger and Toftum [34], proposed an extended PMV model by integrating an extended factor (e) into the basic PMV equation to calibrate the inconsistencies between the occupants' perceived TSVs and the calculated PMVs in the NV buildings [34, 32]. An extended factor of 0.5 is recommended for regions where the weather is warm all or most of the year, and there are few other air-conditioned buildings. However, Yao et al. [35] suggest the hybrid Equation (4) for calculating 'e' when TSVs are available. The expectation factor calculated using Equation (4), 0.11, is significantly lower than Yao et al.'s factor of 0.5 and closer to the one calculated by Hamzah et al. [55] for a tropical city of Makassar.
4. According to the previous studies [40, 49, 50], various Griffiths constants were used to calculate the comfort temperature and Griffiths constant of 0.5 seemed appropriate for the sampled respondents for both AC and NV modes. The predicted temperatures were steadier in both

modes with lower standard deviation when G=0.50. López-Pérez et al.'s [44] and Haddad et al. [37] observations agree with the results of this study. However, Yan et al. [19] and Rupp et al. [50] found a lower constant of 0.20 more appropriate. It should be noted that their samples were residential buildings and so, different from the typology of this study's sample.

5. The respondents generally expressed higher comfort temperatures than the ones current international standards propose. The adaptive comfort equations based on the outdoor mean and indoor comfort temperatures were developed as $T_{comf} = 0.41T_{out} + 18.2$ for NV mode, and $T_{comf} = 0.17T_{out} + 22.42$ for AC mode. The models show that the Ghanaian sample was more sensitive to outdoor temperature changes than its European counterparts in both NV and AC modes. Previous studies with larger samples support this result [56, 42]. The adaptive model in current and prior studies anticipates that hot–humid climate regions will require their own adaptive thermal comfort standards [53, 42, 44, 52].

6. Conclusion and limitations

The enormous rise in cooling energy demand in buildings, occurring against the backdrop of the global climate emergency, necessitates further research into adaptive thermal comfort. Therefore, the outcomes of this study contribute to the much-needed understanding of adaptive thermal comfort in tropical Aw climates. The results of this study reveal that the respondents, who were all Ghanaian, are comfortable at temperatures that differ from those recommended by current adaptive models and international standards.

- The ACs' temperatures were set at 26°C, following existing standards. Given that the neutral temperature was as high as 30.4°C in NV rooms, 79% of respondents felt cold in rooms that had a mean operative temperature of 26.9°C. This points to some degree of overcooling in buildings, which is widespread in other mechanically cooled locations in Aw climates and could be contributing to excessive energy use.
- The adaptive equations for Kumasi's hot and humid climate predict higher slopes of $0.41K^{-1}$ and $0.17K^{-1}$ in NV and AC modes, respectively, than the standards; this indicates that the Ghanaian respondents were more sensitive to outdoor temperature changes.
- Most comfort temperature results from AC mode's adaptive model fell above the CIBSE guide's comfort zone, with the average comfort temperature above the guide's upper limit. This suggests that the existing HVAC building guidelines may potentially underestimate occupants' thermal

preferences in hot and humid regions where the general population may have a higher heat tolerance level, contributing to excessive energy consumption. A minimum saving of 56% on cooling energy consumption could be achieved following the adaptive comfort temperature rather than the CIBSE guide.

- When compared to other adaptive models with similar climate conditions to Ghana, the region appears to have a higher comfort temperature. This could be explained by the fact that the surveys were limited to the dry season; therefore, the thermal adaptation of the rainy season should be addressed in future studies to attain a more comprehensive representation of the adaptive model across a whole year.
- Thermal comfort field research in various climatic zones in Ghana may be required because, while all regions are categorised under the Aw climate zone, they have different climate and cultural conditions. This will provide a vast database and aid in creating Ghana's adaptive standard.

Acknowledgements

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Abbreviations and Acronyms

AC	Air-conditioned
AF	Airflow Feeling
AP	Airflow Preference
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
CBE	Center for the Built Environment
CDD	Cooling Degree Days
e	Expectation factor
G	Griffiths slope
h_r	Radiation heat transfer
h_c	Convection heat transfer coefficient
HF	Humidity Feeling
MTSV	Mean TSV
NV	Naturally-ventilated
PMV	Predicted Mean Vote
PMV_e	PMV indices
R^2	Pearson correlation coefficient
RH	Relative Humidity
SET	Standard effective temperature
T_a	Air temperature
T_{comf}	Comfort temperature
T_g	Globe temperature
T_n	Neutral temperature
T_{op}	Operative temperature
T_{out}	Daily mean outdoor temperature
T_r	Mean radiant temperature
T_{rm}	Weighted running mean outdoor temperature
TA	Thermal Acceptance
TP	Thermal Preference
TSV	Thermal Sensation Vote
V_a	Air velocity

Appendix: Survey Questionnaire

THERMAL COMFORT SURVEY

Date & Time:	Location (floor/room):	What is the location's orientation?

PART 1: PERSONAL DATA

Your name (optional)	Gender	Age

PART 2: THERMAL QUESTIONNAIRE

FEELINGS – At present I feel:						
Much too cool (cold)	Too cool (cool)	Comfortably cool (slightly cool)	Comfortable (neutral)	Comfortably warm (slightly warm)	Too warm (warm)	Much too warm (hot)

FEELING – How do you consider this room?				
Perfectly tolerable	Slightly hard to tolerate	Hard to tolerate	Very hard to tolerate	Intolerable

PREFERENCE – At present I would prefer to be:				
Much cooler	A bit cooler	No change	A bit warmer	Much warmer

SENSE – On the basis of your personal preferences, how would you consider the room temperature?	
Acceptable	Not acceptable

SENSE – At present your thermal sensation is:			
Comfort	Light annoyance	Annoyance	Heavy annoyance

FEELINGS – At present I feel the airflow is:						
Much too still	Too still	slightly still	Just right	slightly breezy	Too breezy	Much too breezy

PREFERENCE – Would you like to have an airflow:		
Smaller than now	Exactly how it is now	Greater than now

FEELINGS – At present I feel:						
Much too dry	Too dry	slightly dry	Just right	Slightly humid	Too humid	Much too humid

ACTIVITY – In the last 15 minutes:						
Sitting (passive work)	Sitting (active work)	Standing relax	Standing	working	Walking indoors	Walking outdoors

Other activity (Please specify): ____

CLOTHING – Tick as appropriate										
Short-sleeve	Dress	Socks	T-shirt	Athletic sweatpants	shirt	Trousers	Shoes	Sandals	Knee-length skirt	Ankle-length skirt

Please note if you are wearing something not described above: ______________________

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Highlights

- At the mean temperature of 26.9°C, 79% of the surveyed felt ‘cool’ or ‘slightly cool’
- At the mean operative temperature of 30.4°C, 45.7% of the surveyed felt ‘neutral’
- Higher slopes of adaptive comfort equations than the standards was predicted
- The neutral temperature of 27.4^{o}C and 30.3^{o}C was predicted for AC and NV mode
- Minimum saving of 56% on cooling energy consumption could be achieved