The Influence of Clothing on Adaptive Thermal Comfort: A Study of the Thermal Comfort of Office Workers in Hot Humid Conditions in Enugu, Nigeria

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ABSTRACT

The aim of this thesis is to investigate to what extent regulated office clothing affects the perception and adaptation of office workers to the thermal conditions surrounding their work environments, focusing on the city of Enugu in South Eastern Nigeria which has hot humid climatic conditions.

Clothing, regarded as a second skin, allows us to adapt or adjust to the thermal conditions in our immediate surrounding environment. It also affects our perception of the thermal environment. In some offices however employees are expected to wear regulated clothing or uniforms, during the working day; for various corporate identity reasons.

Field studies were undertaken in office spaces in Enugu involving the behavioural and environmental analysis of thermal comfort conditions in six typical case study office spaces, at the Federal Radio Corporation of Nigeria (FRCN) and Federal Road Safety Corps (FRSC). The thesis adopted a mixed-mode methodological process; combining a quantitative and qualitative approach to data collection and analysis.

The field research analysis found that all office spaces analysed were in compliance with the adaptive thermal comfort component of the ASHRAE Standard 55-2013. The results however did not comply with the adaptive thermal comfort of CEN/EN 15251-2007. The thermal sensation component of the results suggests a neutral temperature of 28.8^0C, with 80% thermal satisfaction, in a comfort range of between 25.4^0C and 32.2^0C. The thermal comfort vote indicates that approximately 85% of office workers with flexible clothing policy were comfortable at that comfort range, whilst only 55% of workers who had to adhere to a strict uniform policy voted that they were comfortable.

The key research findings were: Firstly, the field observations and semi-structured interviews undertaken indicated that the strict uniform policy of FRSC office workers contributed substantially to the limited adaptation of staff to their workspace thermal conditions. Also, of all the thermal variables recorded during the field survey, clothing insulation had the strongest correlations to the thermal sensation of participants in the survey compared to indoor operative temperature, outdoor air temperature, relative humidity or metabolic rate. Furthermore, it is possible for workers in naturally ventilated office buildings in the hot humid climate zone of Enugu to achieve thermal comfort in higher temperature conditions through clothing adaptation.

DECLARATION

I confirm that this thesis presented for the degree of Doctor of Philosophy (PhD) in Architecture has

I. been composed entirely by myself

II. been solely the result of my own work

III. not been submitted for any other degree or professional qualification

Name: Meshack O. Efeoma

Signature: 

Date: 2016

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I thank the Giver and Sustainer of life, Jehovah God, for keeping me alive to complete this thesis. Without him, I would not be here today.

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DISSEMINATIONS

Efeoma, M. O. and Uduku, O. (2016), “Longitudinal Survey of Adaptive Comfort of Office Workers in the Hot Humid Climate Zone of Enugu, Nigeria”, paper presented at the 9th International Windsor Conference: Making Comfort Relevant, 07-10 April 2016, Cumberland Lodge, Windsor, United Kingdom. (Appendix E)

Efeoma, M. O. and Uduku, O. (2015), “Office Clothing and Its Effect on Thermal Comfort Amongst Office Workers in Hot-Humid Conditions: A Case Study of Office Workers in Nigeria”, paper presented at the 31st International Passive and Low Energy Architecture (PLEA) Conference, 09-11 September 2015, Bologna, Italy. (Appendix F)

Efeoma, M. O. and Uduku, O. (2014), “Assessing thermal comfort and energy efficiency in tropical African offices using the adaptive approach”, *Structural Survey: Journal of building pathology and refurbishment,* Volume 32, Issue 5, Pages 396-412. (Appendix G)

Efeoma, M. O. (2014), “Energy Efficiency and Thermal Comfort in Tropical West African Office Buildings: Understanding the Adaptive Approach”, paper presented at the 3rd International Conference on Infrastructure Development in Africa (ICIDA), 17-19 March 2014, Abeokuta, Nigeria. (Appendix H)

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LIST OF CODING AND ABBREVIATIONS USED

ACM	Adaptive Comfort Model
ADP	Ad Hoc Group on the Durban Platform for Enhanced Action
Age	1=<19, 2=19-29, 3=30-39, 4=40-49, 5=50-59
Am	Tropical Rainforest Climate
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
Aw	Tropical Savannah Climate
BSh	Semi-Arid or Tropical Dry Climate
C_TREND	Thermal Comfort Trend (1=Staying the same, 2=Deteriorating, 3=Improving, 4=Fluctuating)
CBE	Center for the Built Environment
CEN	European Committee for Standardization (French: Comité Européen de Normalisation)
CIBSE	Chartered Institution of Building Services Engineers
CLO	Clothing Insulation
CMP	Meeting of the Parties
CNS	Central Nervous System
COMF	Thermal Comfort (1=Very uncomfortable, 2=Uncomfortable, 3=Slightly uncomfortable, 4=Slightly comfortable, 5=Comfortable, 6=Very comfortable)
COP	Conference of the Parties
DISCOMF_LOC	Discomfort Location (0=Head, 1=Chest, 2=Back, 3=Pelvis, 4=Arms, 5=Hands, 6=Legs, 7=Feet, 8=All over)
ES	Enclosed Office Space
ET	Effective Temperature
ET*	New Effective Temperature
FRCN	Federal Radio Corporation of Nigeria
FRSC	Federal Road Safety Corps
GPS	Global Positioning System
H.D.	Hot Dry Zone
H.H.	Hot Humid Zone
INC	Intergovernmental Negotiating Committee
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standard Organisation
KP	Kyoto Protocol
Max	Maximum
MET	Metabolic Rate
Min	Minimum
MM	Mixed-Mode
MRT	Mean Radiant Temperature

MV	Mechanically Ventilated
NSCDC	Nigeria Security and Civil Defence Corps
NV	Naturally Ventilated/Natural Ventilations
OFF_TYP	Office Workplace Typology (1=Enclosed space, 2=Open plan)
OP	Open Plan Office Space
PMV	Predictive Mean Vote
PPD	Predicted Percentage Dissatisfied
PVC	Polyvinyl Chloride
RH	Relative Humidity
SCAT	Smart Controls and Thermal Comfort
Season	1=Dry Season, 2=Rainy Season
SET	Standard Effective Temperature
Sex	1=Male, 2=Female
Sig	Significant
SPSS	Statistical Package for Social Sciences
Std. Dev.	Standard Deviation
T.D.	Temperate Dry Zone
TA	Air Temperature
TIM_DAY	Time of the Day (1=Morning, 2=Mid-Day, 3=Afternoon)
TOP	Operative Temperature
TPREF	Thermal Preference (-3=Cold, -2=Cool, -1=Slightly cool, 0=Neutral, 1=Slightly warm, 2=Warm, 3=Hot)
TSENS	Thermal Sensation (-3=Cold, -2=Cool, -1=Slightly cool, 0=Neutral, 1=Slightly warm, 2=Warm, 3=Hot)
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
VEL	Air Velocity
VENT_SYS	Ventilation System (1=Naturally ventilated, 2=Mixed-mode ventilation)
W.H.	Warm Humid Zone
WCC	World Climate Conference
WMO	World Meteorological Organisation
YRS_ENU	Years Lived in Enugu (1=Less than 1Yr, 2=1-5Yrs, 3=6-10Yrs, 4=11-15Yrs, 5=More than 15Yrs)

CHAPTER 1

INTRODUCTION

1.1 Introduction

Climate change is a global issue that affects all parts of the planet. It is a burning subject among scientist, economist, politicians, professionals in different fields including the construction and the built environment. The impact of the global warming is felt on a local scale also. In a quest to save our planet from impact of this change, the United Nations has been at the forefront of many initiatives that have been taken in this regard.

Some of the key international initiatives that have been spearheaded in response to the climate change issue, according to the United Nations Framework Convention on Climate Change (UNFCCC) [1], have highlighted ***mitigation*** and ***adaptation*** as the main objective of the United Nations in combating climate change[2]. *Mitigation* approach involves human intervention to reduce the sources of greenhouse gases, the major cause of global warming (IPCC, 2014b). *Adaptation* is the process of adjusting to the effects of actual or expected climatic condition. In human systems, adaptation attempts to moderate, avoid or take advantage of beneficial opportunities. In some natural systems, the intervention of humans may speed up the adjustment process (IPCC, 2014a).

Furthermore, according to the United Nations Environment Programme (UNEP) report, the building sector contributes up to more than 30% of yearly greenhouse gas emissions in both developed and developing nations. The report also shows that buildings consume up to 40% of all energy production in many parts of the world (UNEP, 2009).

As a step in the right direction, the adaptive thermal comfort has been widely recognised as an innovative approach to achieve energy efficient

[1] http://www.unfccc.int (accessed on 27 February 2016)

[2] https://www.wmo.int/pages/index_en.html (accessed on 27 February 2016)

and sustainable building designs. This approach has been widely accepted in the Americans and Europe, which has led to its inclusion in both the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the European Committee for Standardization (CEN, French: Comité Européen de Normalisation) Standards (ASHRAE, 2004, 2010, 2013a; CEN, 2007). Also, some developing economy including India are moving toward developing their own model for adaptive thermal comfort (Manu et al., 2014).

This thesis is concerned with examining the *adaptation* aspect of the UNFCCC's objective in combating climate change in relation to the built environment in the hot humid climate of Nigeria. It focuses specifically on how clothing policy adaptation can impact on energy usage in office buildings.

1.2 Research Motivation

With a population of over 180 million, according to a 2015 estimate, Nigeria is the most populous country in Africa and the seventh in the world. According to the United Nations, it is estimated that by 2050, the population of Nigeria will be more than the United States (United Nations, 2015). This will make the country the third most populous country in the world after India and China. Aside from its population, Nigeria is also the largest economy in Africa with an annual Gross Domestic Product (GDP) of more than 568 billion US dollars in 2015 (World Bank Group, 2016). The Country's GDP experienced 6.3% growth in 2014. The World Bank has also projected an annual growth of 4-6% in GDP for the country's economy.

An effect of this level of increased population and economic growth has been the demand for more buildings and infrastructural development in Nigeria. The process of building and running of physical infrastructure requires energy. In Nigeria, as elsewhere in Africa, this energy demand is usually met by electricity. However, according to the Africa Progress Report 2015, more than 90 million Nigerians lack electricity (Africa Progress Panel, 2015). By way of comparison with other developing economies, Nigeria has nearly double Vietnam's population but generates less than 25% of the electricity that Vietnam does. Furthermore Nigeria's main businesses are Small and Medium Enterprises (SMEs), of which more than 80% rely on fuel-powered electricity generators to sustain their business (Scott, Darko, Lemma, & Rud, 2014).

In addition to this poor power supply situation, there is also the issue of climate change. Nigeria, as with Africa in general, is experiencing the most damaging effects of climate change (Africa Progress Panel, 2015). Climate change is increasing the need for cooling in order to keep building occupants comfortable. However, the limit to electricity supply in Nigeria makes cooling of buildings more difficult. Hence, in order to mitigate the impact of climate change and to reduce reliance on the poor electricity supply, there is need to focus on more energy efficient ways of designing and constructing buildings. This is especially important since cooling load alone is responsible for about 40% of electricity consumption in buildings, especially in office buildings, in Nigeria (Batagarawa, Hamza, & Dudek, 2011). Ultimately, the more efficient buildings are, the less cooling will be required.

Similarly, in Nigeria, there is no standard energy efficiency code for buildings, nor is there a national thermal comfort standard. The current National Building Code in Nigeria provides guidelines for the design and specification, costing, construction, alteration, addition to, moving, demolition, location, repair and use of any building or structure; but has no reference to either thermal comfort or energy efficiency (Federal Ministry of Housing and Urban Development, 2006). Besides, some of the recent proposals for the review of the Code, which have not been implemented yet, did not include the subject of thermal comfort either; the proposals are mainly focused on addressing the cases of incessant building collapses due to poor construction (Ayansian, 2013).

Also, while there has been significant research carried out in the field of adaptive thermal comfort in different parts of the world, especially in the East, the study of adaptive thermal comfort is still in its infancy in the Nigerian context.

The adaptive principle (Nicol & Humphreys, 1973) indicates that one of the major actions usually taken by subjects in order to adapt or adjust to any change in environmental conditions and in restoring comfort is clothing adjustment. However, in Nigeria and elsewhere in the emerging world; office workers are often required to wear official clothing or uniforms by their employers. The military and the paramilitary, wear uniforms, as do officials of state parastatals and other organisations. In private companies, employers have dress code policy for all staff, which is expected to promote the company's corporate image. Workers, in these situations, have little or no control over their choice of clothing. Hence, such dress code or uniform policies usually restrict the ability of workers to adapt to the thermal conditions surrounding their work environment.

This study therefore attempts to fill the gaps highlighted above through investigation of local office workers' adaptive thermal comfort in Enugu, a hot humid climate zone of Nigeria. It focuses on the adaptive opportunity that clothing, 'our second skin', provides for office workers in the climate zone to adjust to the thermal conditions surrounding their work environment.

1.3 Research Aim and Objectives

From the foregoing the main aim of this thesis is to investigate and examine the extent to which wearing of regulated office clothing affects the perception and adaptation of office workers to the thermal conditions surrounding their work environment in the hot humid climate zone of Enugu, South Eastern Nigeria. In order to achieve the main purpose of the research, the following specific research objectives guided this research work:

(i) To compare adaptive thermal comfort and its relationship to the thermal performances of office spaces in the hot humid climate of Enugu.

(ii) To explore office workers' thermal perception corresponding to office workplace typologies and ventilation systems.

(iii) To determine the neutral temperature and comfort range for office workers in the hot humid climate, focusing on adaptation.

(iv) To compare the thermal perception of office workers with strict uniform policy with those with flexible office clothing policy in the local climate of Enugu.

(v) To investigate the relationship between clothing insulation and the subjective thermal sensation of the local office workers in the hot-humid climate of Enugu.

1.4 Scope of Research

In any typical research study; factors such as finance, time and human resources always place constraints on the extent of coverage and level of details. In order to reduce the impact of these constraints, this study is limited to office buildings in the hot humid climate zone of Enugu. The research focused on how office clothing policies affect the perception and adaptation of workers in both mixed-mode and naturally ventilated office spaces. Figure 1.1 shows the scope of the research for this study.

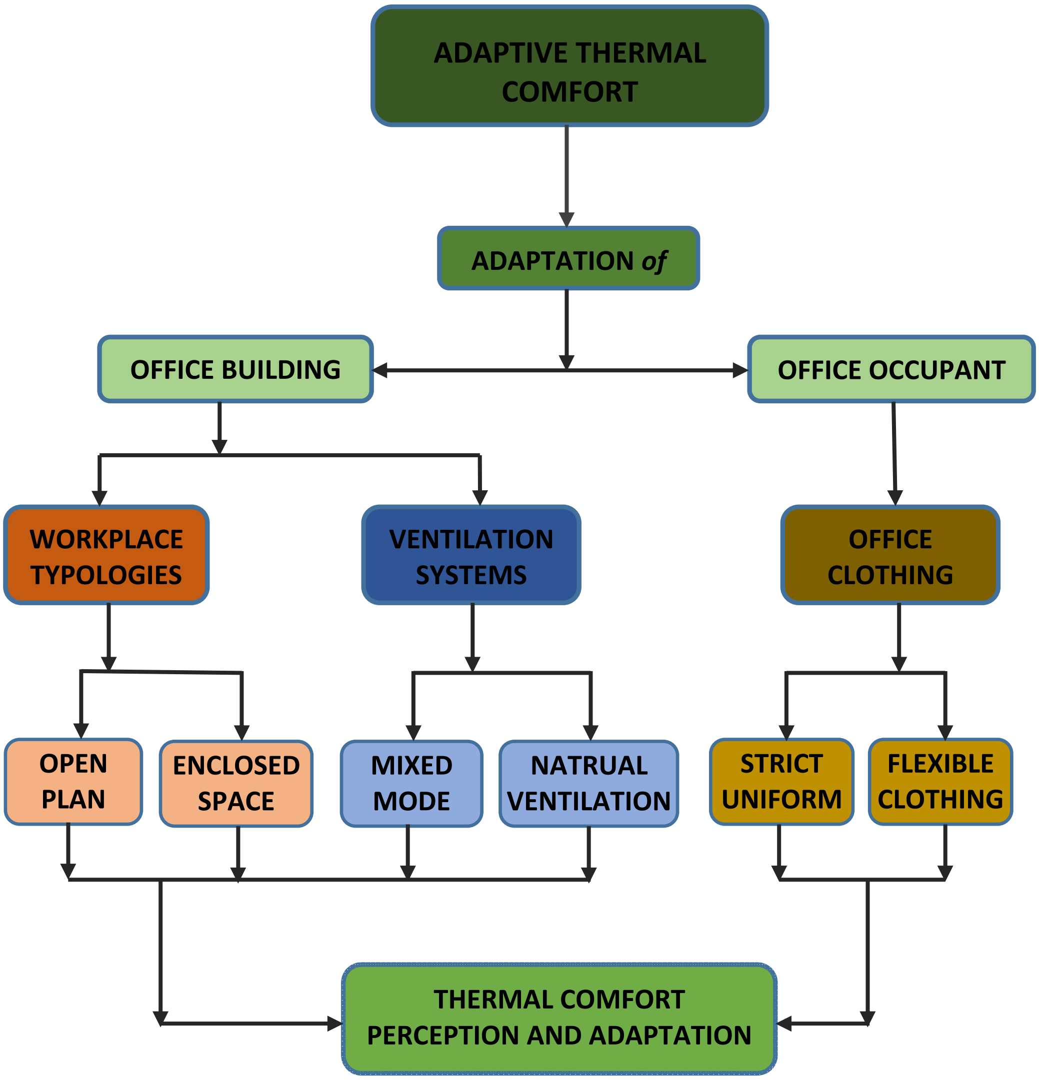


Figure 1.1: Scope of research framework

1.5 Research Methodology

This study employed field studies of local office workers in office settings as the main research methods. Both subjective and objective thermal data were collected from the field studies. These were processed using both quantitative and qualitative methods of analysis. The subjective thermal responses from the local office workers were compared with the corresponding objective thermal measurements and observations. This particular research approach has been explored by different researchers in the international communities in the field studies of adaptive thermal comfort (de Dear, Brager, & Cooper, 1997; Humphreys, Nicol, & Raja, 2007). A more detailed discussion of the methodology used in this study is presented in Chapter 4.

1.5.1 Field Studies

The main reason for adopting fieldwork for this study is that fieldwork studies human behaviours, responses and perception in natural conditions of their real living environments. Since thermal adaptation and perception is an active process between the human body and the thermal conditions surrounding it, a fully controlled laboratory experiment alone cannot design this diverse and complicated condition. The field study is a better method of investigating this complicated interaction between the human behaviour and its thermal environment.

1.5.2 Qualitative Methods

The major reason for adopting this methods in addition to the traditional quantitative methods employed in the field of thermal comfort is to draw on the strength of both approaches. The qualitative methods used in this study are semi-structured interviews and observations of office workers in their work environment. The semi-structured interviews will be very helpful in this research, as they will help to draw information about participants comfort perceptions in areas where they feel restricted in putting down on paper their actual responses for various reasons. It should help in getting a better view of the feelings and emotions of participants that are often left uncaptured in the traditional questionnaire. Also, the interviews and observation methods adopted for this research will help the researcher to gain a deeper understanding into the adaptive actions of participants and the problems associated with thermal comfort in the context of the study location. Thus, the purpose of including this qualitative approach is not to affirm the quantitative approach but to compliment those methods.

1.6 Significance of Research

One major significance of this research is to provide a basis for policy makers and employers in the tropical sub-Sahara African climate to review their current office clothing policies; which do not give office occupants the opportunity to adjust their clothing to the thermal conditions within their work environment.

Secondly, the limited studies of thermal comfort in Nigeria context have only employed the quantitative approach. This study, which employed both the quantitative and qualitative approach, highlights the importance of employing the qualitative approach to compliment the quantitative method which is often employed in the field of thermal comfort study.

The study also suggested the comfortable temperature range in office buildings in the hot humid climate of Enugu, focusing on adaptation. This will provide original contribution to the development of a new thermal comfort standard for the design, construction and operation of office buildings in the local climate, which will address the challenges of climate change in the region and reduce reliance on mechanical form of ventilation.

Finally, the research methods and results from the hot humid climate zone of Enugu can serve as useful information for the adaptive thermal comfort studies in other climate zones within Nigeria and other countries in the sub-Sahara Africa.

1.7 Structure of Thesis

This thesis is organised into seven chapters. These are described as follows:

- Chapter 1 is the Introduction.
- Chapter 2 gives a brief literature review of thermal comfort, the historical development of adaptive thermal comfort, a discussion of some previous thermal comfort studies done in hot humid climate zones and in Nigeria, as well as a review of the effect of clothing on thermal comfort.
- Chapter 3 presents a brief description of the climate of Nigeria in general and that of Enugu in particular. It also classified office

buildings in the study location, Enugu, according to their workplace typologies and ventilation systems. It includes a discussion of different office clothings that are worn by office workers in Nigeria. The chapter concludes with the review of some previous research focusing on factors which influence the choice of clothing.

- Chapter 4 is a discussion of the research methods employed in this research. The research framework and implementation methods are presented in this chapter. This include the investigation's design, the composition of data, the selection of participants and buildings, measuring instruments, the development of questionnaires, interview questions, observation methods, as well as the quantitative and qualitative analysis methods employed.
- Chapter 5 reports the survey results from the field studies. It presents the descriptive measurements of office buildings and spaces surveyed. Also, participants' subjective thermal behaviours and the results obtained from the physical measurements were also presented. It includes the quantitative and qualitative analysis of the results obtained from the field work.
- Chapter 6 discusses the research objectives based on the analysis of the results from the field studies.
- Chapter 7 concludes the research findings of this study, highlighting the research limitations and recommendations for future research work.

CHAPTER 2

LITERATURE REVIEW ON ADAPTIVE THERMAL COMFORT IN THE BUILT ENVIRONMENTS

2.1 Introduction

This chapter begins with the examination of literature on thermal comfort study and the development of adaptive thermal comfort. It also discusses the different international standards that are frequently used by the international community. The chapter concludes with the review of literature on thermal comfort research carried out in hot humid climate in different countries, thermal comfort research done in Nigeria as well as the effect of clothing on thermal comfort.

2.2 Thermal Comfort

"The term 'comfort' can be used to describe a feeling of contentment, a sense of cosiness, or a state of physical and mental well-being" (Chappells & Shove, 2004; Shove, 2003). The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) define the term "thermal comfort" as "that condition of mind that expresses satisfaction with the thermal environment" (ASHRAE, 2013a). The wider research community; architects, engineers, quantity surveyors and others in the building industry, accept this definition of thermal comfort. It is used as a basis for thermal comfort standards such the ASHRAE Standard 55 and the International Standards Organisation, ISO 7730 (ASHRAE, 2013a; ISO, 2005).

The specific ASHRAE definition of thermal comfort describes a person's psychological state of mind, and is used to describe a condition in which a person feels neither "too hot nor too cold". It is essentially a subjective response, or state of mind, where a person expresses satisfaction with his environment (Olesen & Brager, 2004). However, in deciding what people find thermally comfortable, one must take into account a range of environmental or climatic and personal factors.

2.2.1 Factors Affecting Thermal Comfort

The environmental or climatic factors and personal factors taken into account comprise the "human thermal environment" (Parsons, 2003). Historically, Fanger (1970) suggested that the six most important factors or variables that determine the thermal condition of a given space are as follow:

- air temperature;
- mean radiant temperature;
- air velocity;
- humidity;
- metabolic rate or activity level; and
- clothing insulation.

Jones (2008) defines thermal comfort as the achievement of a balance between metabolic heat production and heat loss, and suggests that it is a function of the thermal environmental conditions, including personal factors such as activity rate and clothing insulation (Jones, 2008).

As shown in Figure 2.1, the six factors suggested by Fanger can be grouped into two categories: environmental factors (air temperature, mean radiant temperature, air velocity and humidity) and personal factors (activity level and clothing insulation). Hence, thermal comfort in any given space can be achieved with a combination of the above factors.

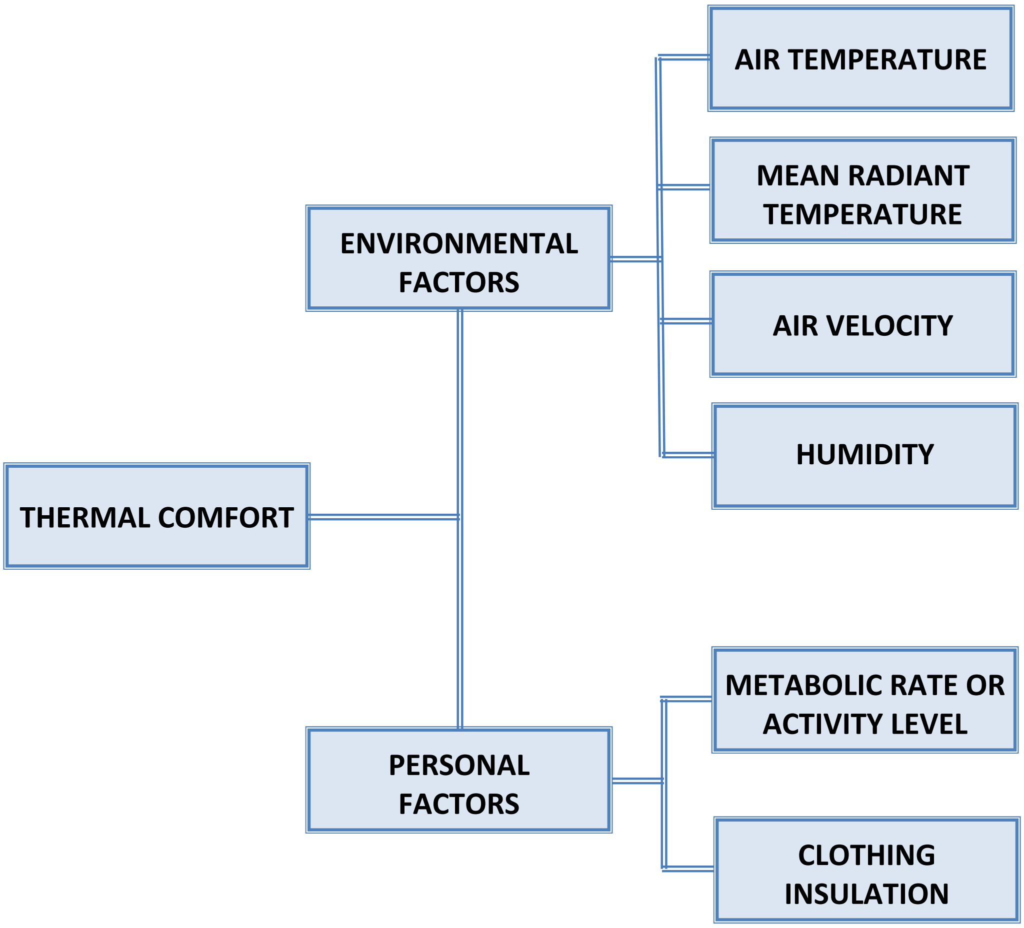


Figure 2.1: Factors affecting thermal comfort (Source: adapted from Efeoma & Uduku, 2014)

A. Air temperature, TA

This is "the temperature of the air surrounding the occupant" (ASHRAE, 2013a). According to the Chartered Institution of Building Services Engineers (CIBSE), air temperature in a given space is often the most important environmental variable that affects thermal comfort (CIBSE, 2006a). A thermometer that should not be affected by any radiant heat is usually the best instrument for measuring air temperature (CIBSE, 2006b).

B. Mean radiant temperature, MRT

ASHRAE defines mean radiant temperature (MRT) as "the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as the actual non-uniform space" (ASHRAE, 2013a). CIBSE also describe it as the relative effect of all the radiant heat transfers from the surfaces and object in space, such as walls, ceiling, windows heaters, lights, equipment (CIBSE, 2006b). MRT can be measured using a globe thermometer.

The value of MRT can be estimated from TA using Equation 2.1, based on the experiment conducted by Nagano and Mochida (2004).

$$MRT = 0.99TA - 0.01 \quad (R^2 = 0.99) \qquad (2.1)$$

Where,

MRT is mean radiant temperature

TA is air temperature

C. Air velocity

This is "an average of the instantaneous air velocity over an interval of time" (ASHRAE, 2013a). While there is no specified limit to air velocity that is required in a given space to achieve thermal comfort, increased air flow across a space or body can alter the comfort sensation of the skin/body to feeling cooler in warm spaces (ISO, 2005; Nasrollahi, 2007). Different research studies have also shown that, in hot and humid climate zones; increased in air velocity can influence thermal perception and adaptation of occupants positively in naturally ventilated spaces (Cândido, de Dear, & Lamberts, 2011; Cândido et al., 2010; Manu et al., 2014). Also, evaporation increases with increase in air movement and this result to a cooling effect (Aronoff & Kaplan, 1995). In a warm environment, air velocity can be increased with occupant controlled actions such as window opening or the use of fans, this in turn will help the occupant to adapt to the environment.

D. Humidity

Humidity is the water vapour or moisture content of the air. It can either be stated as relative humidity or absolute humidity (ISO, 2005). Relative humidity is defined by ASHRAE as "the ratio of the partial pressure (or density) of the water vapor in the air to the saturation pressure (or density) of water vapor at the same temperature and the same total pressure" (ASHRAE, 2013a). The lower the relative humidity, the higher the evaporative cooling, hence a person will feel more comfortable under a warm temperature with low humidity than the same temperature with a higher level of relative humidity (Aronoff & Kaplan, 1995).

E. Metabolic rate or activity level

Metabolic rate is “the rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface” (ASHRAE, 2013a). Metabolic rate is largely dependent on the level of activity (CIBSE, 2006a). The higher the level of activity, the more heat is produced. It is usually expressed in met units and one met is equal to 58.2 W/m^2, which is also “equal to the energy produced per unit surface area of an average person seated at rest.” The surface area of an average person is given as 1.8m^2 in both the ASHRAE and ISO standards (ASHRAE, 2013a; ISO, 2005). Any error in estimating the activity rate of a subject may result to a discrepancy between the actual mean thermal comfort vote and the predicted mean vote (Rowe, 2001).

The metabolic rates for some typical office tasks as derived from ASHRAE Standard 55 are summarised in Table 2.1.

Table 2.1: Metabolic rate for some typical office tasks (Source: ASHRAE, 2013)

Activity	**Metabolic Rate**	
	Met Units	**W/m^2**
Reading, seated	1.0	55
Writing	1.0	60
Typing	1.1	65
Filing, seated	1.2	70
Filing, standing	1.4	80
Walking about	1.7	100
Lifting/packing	2.1	120
Reclining	0.8	45
Seated, quiet	1.0	60
Standing, relaxed	1.2	70

F. Clothing insulation

According to the ASHRAE definition, clothing insulation is “the resistance to sensible heat transfer provided by a clothing ensemble.” It is usually expressed in clo units and 1 clo is equal to $0.155m^2\ ^0C/W$. Clothing insulation relates to heat transfer from the whole body, hence, the definition of clothing insulation also includes the uncovered parts of the body, such as the hands and the head (ASHRAE, 2013a). In both the ASHRAE Standard 55 and ISO 7730 thermal comfort standards, the user is required to determine the insulation values of clothing by matching garments to similar ones given in tables and assume that the evaporative resistance of every day clothing is low (McCullough, 2001).

Table 2.2 and Table 2.3 are summary of clothing insulation values for some typical clothing ensembles and individual garments respectively. From these tables, clothing insulation values for Western clothing can be calculated by comparing similar clothing ensembles or individuals garments with the ones given in the tables. For non-Western clothing, clothing insulation values for clothing ensembles and individual garments are presented in ASHRAE RP-1504 (Havenith et al., 2013, 2015).

Table 2.2: Clothing insulation values for typical ensembles (Source: ASHRAE, 2013)

Clothing Description	Included Garments[++]	clo value (I_{clu})
Trousers	(1) Trousers, short-sleeve shirt	0.57
	(2) Trousers, long-sleeve shirt	0.61
	(3) #2 plus suit jacket	0.96
	(4) #2 plus suit jacket, vest, T-shirt	1.14
	(5) #2 plus long-sleeve sweater, T-shirt	1.01
	(6) #5 plus suit jacket, long underwear bottoms	1.30
Skirts/Dresses	(7) Knee-length skirt, short-sleeve shirt (sandals)	0.54
	(8) Knee-length skirt, long-sleeve shirt, full-slip	0.67
	(9) Knee-length skirt, long-sleeve shirt, half-slip, long-sleeve sweater	1.10
	(10) Knee-length skirt, long-sleeve shirt, half-slip, suit jacket	1.04
	(11) Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	(12) Walking shorts, short-sleeve shirt	0.36
Overalls/Coveralls	(13) Long-sleeve coveralls, T-shirt	0.72
	(14) Overalls, long-sleeve shirt, T-shirt	0.89
	(15) Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37
Athletic	(16) Sweat pants, long-sleeve sweatshirt	0.74

[++] All clothing ensembles, except where otherwise indicated in parentheses, include shoes, socks, and briefs or panties. All skirt/dress clothing ensembles include pantyhose and no additional socks.

Table 2.3: Individual garment insulation values (Source: ASHRAE, 2013)

Garment Description^^	clo value (I_{clu})	Garment Description^^	clo value (I_{clu})
Underwear		***Dress and Skirts****	
Bra	0.01	Skirt (thin)	0.14
Panties	0.03	Skirt (thick)	0.23
Men's briefs	0.04	Sleeveless, scoop neck (thin)	0.23
T-shirt	0.08	Sleeveless, scoop neck (thick), i.e., jumper	0.27
Half-slip	0.14		
Long underwear bottoms	0.15	Short-sleeve shirtdress (thin)	0.29
Full slip	0.16	Long-sleeve shirtdress (thin)	0.33
Long underwear top	0.20	Long-sleeve shirtdress (thick)	0.47
Shirts and Blouses		***Suit Jackets and Vests##***	
Sleeveless neck blouse	0.12	Sleeveless vest (thin)	0.10
Short-sleeve knit sport shirt	0.17	Sleeveless vest (thick)	0.17
Short-sleeve dress shirt	0.19	Single-breasted (thin)	0.36
Long-sleeve dress shirt	0.25	Single-breasted (thick)	0.44
Long-sleeve flannel shirt	0.34	Double-breasted (thin)	0.42
Long-sleeve sweatshirt	0.34	Double-breasted (thick)	0.48
Trousers and Coveralls		***Footwear***	
Short shorts	0.06	Ankle-length athletic socks	0.02
Walking shorts	0.08	Pantyhose/stockings	0.02
Straight trousers (thin)	0.15	Sandals/thongs	0.02
Straight trousers (thick)	0.24	Shoes	0.02
Sweatpants	0.28	Slippers (quilted, pile lined)	0.03
Overalls	0.30	Calf-length socks	0.03
Coveralls	0.49	Knee socks (thick)	0.06
		Boots	0.10

^^ "Thin" refers to garments made of lightweight, thin fabrics often worn in the summer; "thick" refers to garments made of heavyweight, thick fabrics often worn in the winter.
** Knee-length dresses and skirts.
Lined vests.

G. Summary of Factors Affecting Thermal Comfort

A balance of the six factors discussed above is required to achieve thermal comfort. Building occupants may have little or no control over the four environmental factors (air temperature, mean radiant temperature, air velocity and relative humidity). However, if the design of a building is efficient, it will make it easy for occupants to adapt the building to prevailing environmental conditions in order to achieve thermal comfort.

In contrast to the environmental factors, the personal factors (metabolic rate and clothing insulation) discussed give occupants more flexibility to adapt or adjust to the thermal conditions prevailing in their environment. This makes either of the personal factors, in this case clothing, a more suitable subject for consideration in terms of adaptive thermal comfort.

2.2.2 Factors That Cause Local Thermal Discomfort

Apart from the six factors discussed above, there are other factors which might make a person to perceive his thermal environment as unacceptable. These are referred to in both ASHRAE Standard 55 and ISO 7730 as causing local discomfort and these include: draught (local air velocity), vertical air temperature difference, warm and cool floors and radiant temperature asymmetry (ASHRAE, 2013a; ISO, 2005; Parsons, 2001).

Local thermal discomfort is usually felt by respondents with low activity levels, normally for activity level below 1.2 met. These activities would include most medium levels office work as shown in Table 2.1. Respondents who are engaged in activities that are higher than that 1.2 met are less sensitive to local thermal discomfort.

A. Draught

Draught is one of the most critical factors that caused local thermal discomfort. It "is the unwanted local cooling of the body caused by air movement" (ASHRAE, 2013a).

Again this is a factor more identified by respondents with low activity levels. Suggesting that this respondent cohort are more sensitive to changes in their local environment. They are more sensitive to fluctuations in the local air velocity (ISO, 2005; Olesen, 2004).

B. Vertical air temperature difference

A high vertical air temperature difference between the head and ankles may cause thermal discomfort (ASHRAE, 2013a; ISO, 2005). This vertical air temperature difference is rare, and in most cases, it is perceived more favourably by the occupant.

C. Warm and cool floors

If the floor is too cool or too warm, the occupant may feel uncomfortable due to contact with the floor surfaces that are too warm or too cool for the feet. For people wearing shoes, it is the temperature of the floor and not that of the material of the floor covering which is most important factor for comfort (ASHRAE, 2013a; ISO, 2005).

D. Radiant temperature asymmetry

Hot and cold surfaces and direct sunlight might cause non-uniform thermal radiation field about the body. This asymmetry may cause local discomfort and may make it difficult for occupants to accept the thermal environment. Generally, people are most sensitive to radiant asymmetry caused by warm ceiling than those caused by warm or cold vertical surfaces (ASHRAE, 2013a; ISO, 2005; Olesen, 2004).

E. Summary of Factors That Cause Local Thermal Discomfort

As discussed above, where the activity level of occupants is less than 1.2 met, there is the likelihood that they will experience local thermal discomfort. On the other hand, where occupants are engaged in activities that are more than 1.2 met, they are less likely to be sensitive to local thermal discomfort.

The activity levels of medium office workers are usually less than 1.2 met. Hence, this research work focusing on the thermal perception of office workers in the hot humid climate of Enugu, Nigeria, will consider how the various factors causing local thermal discomfort as discussed above can influence their perception of thermal comfort.

2.2.3 Thermal Comfort Indices

In order to describe the combination of major factors affecting thermal comfort, many efforts have been made to develop a single scale that can be used to describe the combination of these factors (Bedford, 1936; Fanger, 1970; Gagge, Fobelets, & Berglund, 1986; Gagge, Stolwijk, & Nishi, 1971; Gagge & Nishi, 1976; Olggay, 2015; Yaglou & Minard, 1957). Some of the most frequently used scales that have be developed are explained briefly as follows:

A. Operative temperature, TOP

This scale was developed in the United States by Winslow, Herrington and Gagge. It combines the effects of air and radiant temperature without the inclusion of air movement or humidity (Winslow, Herrington, & Gagge, 1939). The operative temperature is calculated as the average of air temperature and mean radiant temperature for a given place in a room (Han et al., 2007). This is applicable when the following conditions are satisfied (ASHRAE, 2013a):

- occupants metabolic rates ranges between 1.0 and 1.3 met
- there is no direct sunlight
- average speed should not be more than 0.2m/s
- the difference between average air temperature and mean radiant temperature is less than 4^0C.

It is also permitted to use average air temperature in place of operative temperature when the following conditions are met in a given room (ASHRAE, 2013a):

- there is no radiant panel cooling or radiant panel heating system in place
- the area weighted average U-value of the outside wall or window satisfies the following inequality:

$$U_w < 50/(t_{d,i} - t_{d,e})$$

Where,

U_w is average U-value of the wall or window, $W/m^2.K$

$t_{d,i}$ is internal design temperature, ^0C

$t_{d,e}$ is external design temperature, ^0C

- The coefficients of the window solar heat again are less than 0.48

*B. Effective temperature, ET and New Effective Temperature, ET**

The thermal scale was developed by Houghton and Yaglou in 1923. The ET index was originally developed to provide a method of determining the relative effects of air temperature and humidity on comfort (Blazejczyk, Epstein, Jendritzky, Staiger, & Tinz, 2011). It became the most widely used index after its development until it was suspended in the 1970s.

The ET* was defined by Gagge et al. (1971), as the temperature of an environment at 50% relative humidity that produces the same total heat loss from the skin by radiation, convection and evaporation as the actual environment in question. It was developed using the 'two-node model', which involve, first the heat transfer from the body core to the skin, then from the skin to the environment (Auliciems & Szokolay, 2007). One problem with ET is that it did not take radiation into account, however radiation is taken into consideration in ET*.

C. Standard effective temperature, SET

This index was interpreted by Gagge et al., (1986) as a sub-set of ET* under a standardised clothing for given activities. It is defined as a temperature in a standardised environment (50% relative humidity, air temperature is equal mean radiant temperature, air speed is less than 0.15m/s) in which a person with standardised clothing would have the same heat stress and thermal regulatory strain as the same as the actual environment. For a person who is engaged in sedentary activity with light clothing, ET* is equal SET (Nilsson, 2004).

D. Predicted mean vote/Predicted percentage of dissatisfaction, PMV/PPD

The definition of PMV and PPD is presented in section 2.2.4(A). Both are actually a single evaluation tool that is expressed in two different ways. According to the PMV/PPD index, an ideal thermal environment is that environment with PMV value within the range of -0.5 and +0.5, where only 10% are dissatisfied with their environment. While, an acceptable thermal environment have a PMV value in the range of -0.85 and +0.85 with less than 20% dissatisfied occupants (Fanger, 1970).

2.2.4 Thermal Comfort Models

A model in this context is a set of calculated conditions that 'models' an optimal situation in terms of comfort conditions in a space where different thermal variables can be parametrically tested to study what best conditions can be achieved by moderating the variables.

To determine thermal comfort standards; environmental scientists work with models in which the neutral or optimal thermal comfort condition can be achieved, considering mainly the six factors affecting thermal comfort as discussed in section 2.2.1. The two most popular thermal comfort models that have been developed are shown in Figure 2.2. The first, the predictive mean vote (PMV) or heat balance model, was developed from Fanger's laboratories and chambers studies (Fanger, 1970). The second, the adaptive comfort model (ACM), was developed as a result of series of field studies carried out by various researchers over two decades (Auliciems, 1981; de Dear & Brager, 1998; Humphreys & Nicol, 1998).

In both models the concept of the predicted mean vote, which gives the percentage of people who are satisfied (PPS) or dissatisfied (PPD) with their comfort levels is often used as well to determine comfort. Where 100% suggest total satisfaction and 0% is complete dissatisfaction.

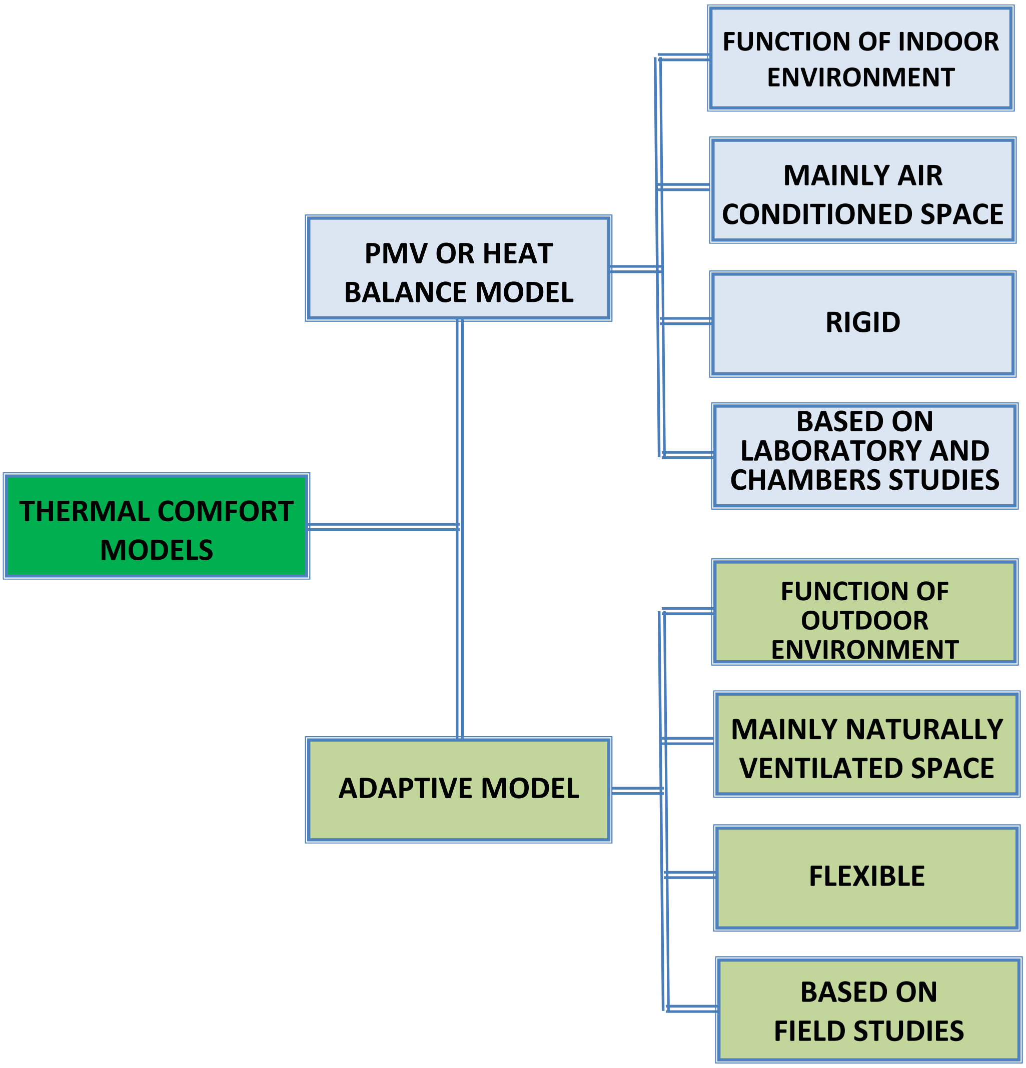


Figure 2.2: Comparison of the two thermal comfort models and their basic differences (Source: adapted from Efeoma & Uduku, 2014)

A. PMV or heat balance model

In 1970, Fanger developed the heat balance equation which is based on a combination of six factors affecting the thermal balance between the human body and the environment. These factors include four primary factors:

- air temperature – TA;
- mean radiant temperature – MRT;
- air velocity – VEL; and
- relative humidity – RH.

and two personal factors:

- activity rate–MET; and
- clothing insulation–CLO).

The basic equation for the thermal heat balance is shown in Equation (2.2), while Equation (2.3) shows the functional notation of the six factors affecting thermal comfort. As represented in Equation (2.3), within the skin temperature and sweat rate limits, a person will feel thermally comfortable if the thermal load of his body is equal to zero (Nicol, Humphreys, & Roaf, 2012; Xiong, 2011):

$$M - W = C + R + E + (C_{res} + E_{res}) + S \ [W/m^2] \qquad (2.2)$$

Where,

M is the metabolic rate

W is mechanical work done

C is convective heat loss from the clothed body

R is radiative heat loss from the clothed body

E is evaporative heat loss from the clothed body

C_{res} is conventive heat loss from respiration

E_{res} is evaporative heat loss from respiration

S is the rate at which heat is stored in the body tissues

$$f(TA, MRT, VEL, RH, MET, CLO) = 0 \qquad (2.3)$$

The PMV model predicts the thermal sensation as a function of these six factors listed above. The model quantifies the absolute and relative impact of these six factors in determining what is thermally comfortable. Using a seven-point thermal sensation scale as shown in Table 2.4, the PMV index predicts the mean value of the votes for a large group of person. It is used in determining the predicted percentage of dissatisfied (PPD) persons. The PPD then is the index that establishes a quantitative prediction of the percentage of dissatisfied persons in a given environment. These two indices are currently being used as the basis of thermal comfort evaluation in both the ASHRAE Standard 55 and the ISO 7730.

Table 2.4 shows the relationship among Bedford scale, the current thermal sensation scale that is currently included in both the ASHRAE Standard 55 and ISO 7730 and the modified ASHRAE scale by Humphreys and Nicol (2004). The corresponding thermal preference is also shown in the table. All three scales used the seven-point scale with little variation in nomenclature (Bedford, 1936; Feriadi, Wong, Chandra, & Cheong, 2003; Humphreys & Nicol, 2004). Going by the principle of "neutral equals heat balance," Fanger then constructed the PMV model to evaluate a particular thermal condition. The model calculates the thermal load and predicts occupant's vote of thermal sensation. Equation (2.4) as shown below is the model constructed by Fanger for predicting occupant's thermal sensation vote for a given space (Fanger, 1970).

$$PMV = (0.352e0.042(M/Adu) + 0.32)Load \qquad (2.4)$$

Where,

PMV is the predicted mean vote of thermal sensation

M/Adu is the internal heat production

Load is the heat load

Table 2.4: Comparisons of Bedford, ISO 7730, ASHRAE thermal sensation scale, modified ASHRAE scale in relation to thermal preference

Bedford (Bedford, 1936)	ASHRAE & ISO 7730 scale	Modified ASHRAE scale (Humphreys and Nicol, 2004)	Thermal Preference
+3 = much too warm	+3 = hot	+3 = much too warm	Much cooler
+2 = too warm	+2 = warm	+2 = too warm	Cooler
+1 = comfortably warm	+1 = slightly warm	+1 = slight too warm	Slightly cooler
0 = comfortable	0 = neutral	0 = Just right	No change
-1 = comfortably cool	-1 = slightly cool	-1 = slightly too cool	Slightly warmer
-2 = too cool	-2 = cool	-2 = too cool	Warmer
-3 = much too cool	-3 = cold	-3 = much too cool	Much warmer

B. *Adaptive comfort model, ACM*

The Adaptive model relates the indoor neutral temperature to the prevailing mean outdoor temperature (Figure 2.3 and Figure 2.4). The only variable input required for this model in finding thermal comfort is the mean monthly outdoor temperature.

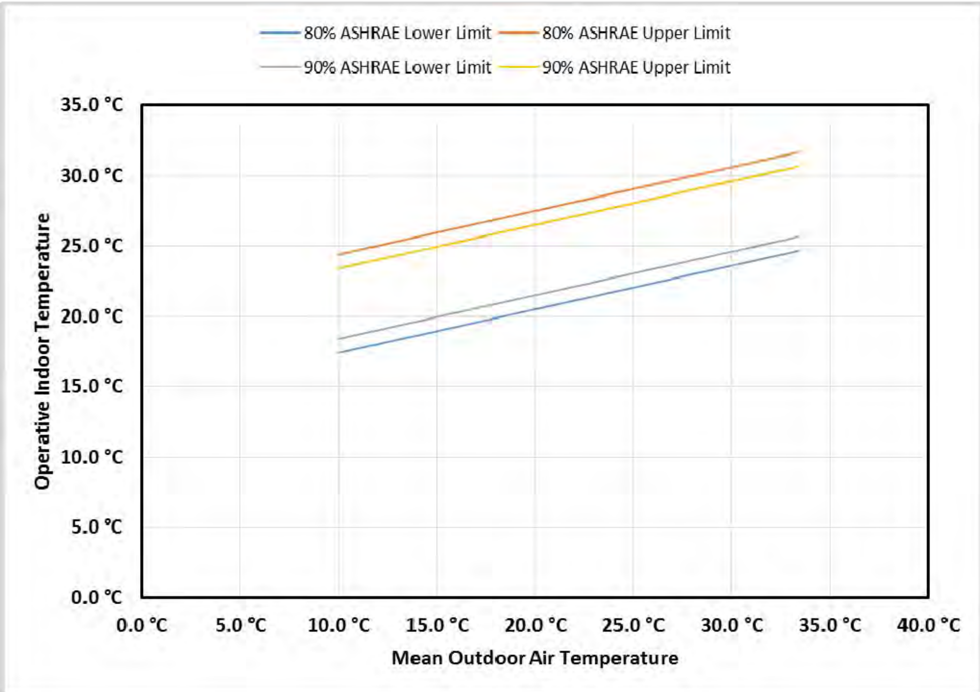


Figure 2.3: The ASHRAE adaptive comfort model for occupant-controlled naturally conditioned spaces (adapted from ASHRAE, 2013)

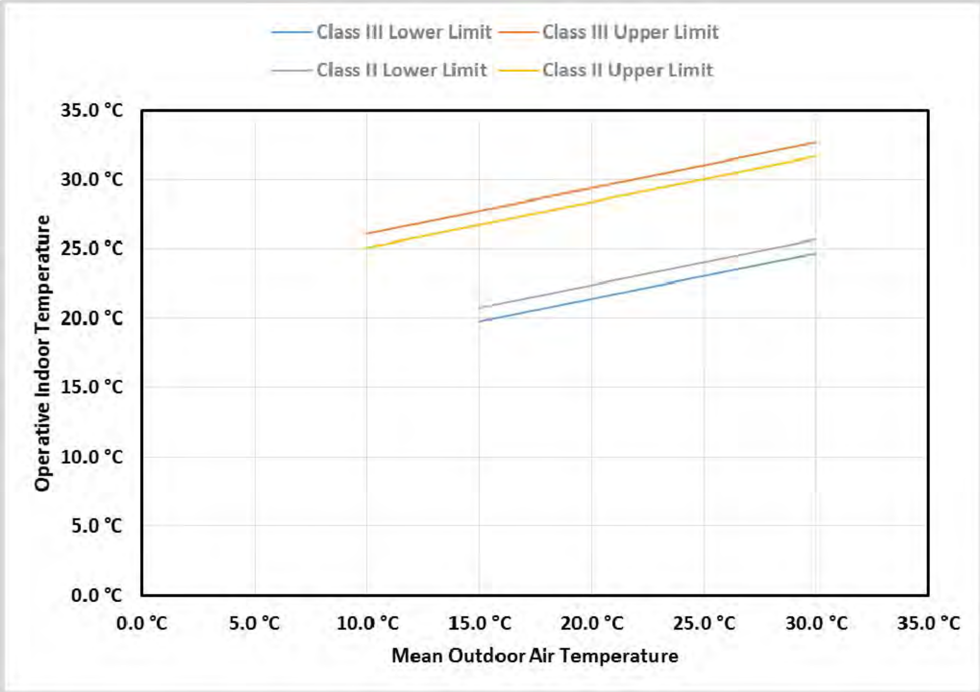


Figure 2.4: The EN 15251 adaptive comfort model for buildings operating in the free running mode (adapted from Humphreys et. al, 2016)

One major advantage of this model over the PMV model is the simplicity of its application for situations where it applies. While one will need to estimate the personal factors, clothing and activity, before using the PMV model; the relationship between these factors and climate has already been accounted for in the adaptive model.

Unlike the PMV or heat balance model, the adaptive model is based on a wide range of field studies across the world. The results from field studies in warmer climates in buildings without air-conditioning revealed that the PMV model predicts a warmer thermal sensation than the occupants actually feel (Brager & de Dear, 1998; Humphreys, 1978).

Field study results have shown that respondents from different climate regions, and of different socio-cultural and socio-economic backgrounds have different perceptions of comfort that straddle a large temperature spectrum. For example, Busch (1992) conducted field research into comfort perception amongst office workers in Thailand that showed that they were comfortable at higher indoor temperatures than those working in more temperate regions (Busch, 1992). Another study conducted in Pakistani offices shows that indoor thermal preference is a function of the local climate and season (Nicol, Raja, Allaudin, & Jamy, 1999; Nicol & Roaf, 1996). Furthermore studies carried out by de Dear and Auliciems (1988) in Australia, also showed a disparity between the thermal perceptions and preferences of occupants of air condition buildings and those that were naturally ventilated. The studies also related thermal comfort to cultural expectation and climatic conditions.

There are also field studies that shows that occupant behaviour can affect thermal comfort (Nicol & Humphreys, 2007). Instead of limiting thermal comfort to the six factors which determine the Fanger's PMV model, these field studies show that people tend to make themselves thermally comfortable by changing their clothing, activity and posture (Nasrollahi, 2007). Field studies have also shown that people can easily adapt to higher temperatures in occupant-controlled naturally ventilated buildings than those predicted by PMV or the heat balance model (Olesen, 2004). The results from these studies support the flexibility of adaptive comfort model compared to the rigidity of PMV model.

C. Summary of Thermal Comfort Models

As discussed above, there are advantages of applying the adaptive thermal comfort model over the PMV model in warmer climates; the main context of this study. The flexibility of applying the adaptive thermal comfort model when compared with the PMV model is another reason why this thesis adopted the adaptive model. Having selected the adaptive thermal comfort model as the most relevant for the dissertation work, a further discussion about its evolution and the key characters in its development is presented in section 2.3.

2.3 Evolution of Adaptive Thermal Comfort

The historical development of adaptive thermal comfort can be traced back to the 1950s. A number of researchers have been involved in the development of adaptive thermal comfort. Some key actors who have contributed immensely to this development, according to de Dear (ca 2011), are the following persons:

2.3.1 Charles Webb (1950s)

Charles Webb, a physicist and a field study comfort researcher at UK Building Research Station, is regarded as the originator of the adaptive thermal comfort concept (Nicol, 1974). Webb conducted longitudinal field studies in Singapore, North India, Baghdad and North London during the 1950s. From his studies, Webb observed that his subjects were comfortable at the mean temperature conditions they experienced, whether in Singapore, North India, Baghdad or North London. Hence, he concluded that they had adapted to their indoor climates (Webb, 1959).

2.3.2 Nicol and Humphreys (1970s)

Based on Webb's counterintuitive proposition (Nicol, 1974), Nicol and Humphreys proposed the idea that building occupants and their indoor climate were two parts of an integrated, self-regulating (feedback) system (Figure 2.5). These are the physiological adaptation (otherwise known as acclimatization) and behavioural adaptation (personal and environmental). They, therefore, postulated the adaptive principle: *If a change occurs that produces discomfort, people will tend to act to restore their comfort. That is to say, the target of the "controlled variable" in this homeostatic system was thermal comfort* (Nicol & Humphreys, 1973).

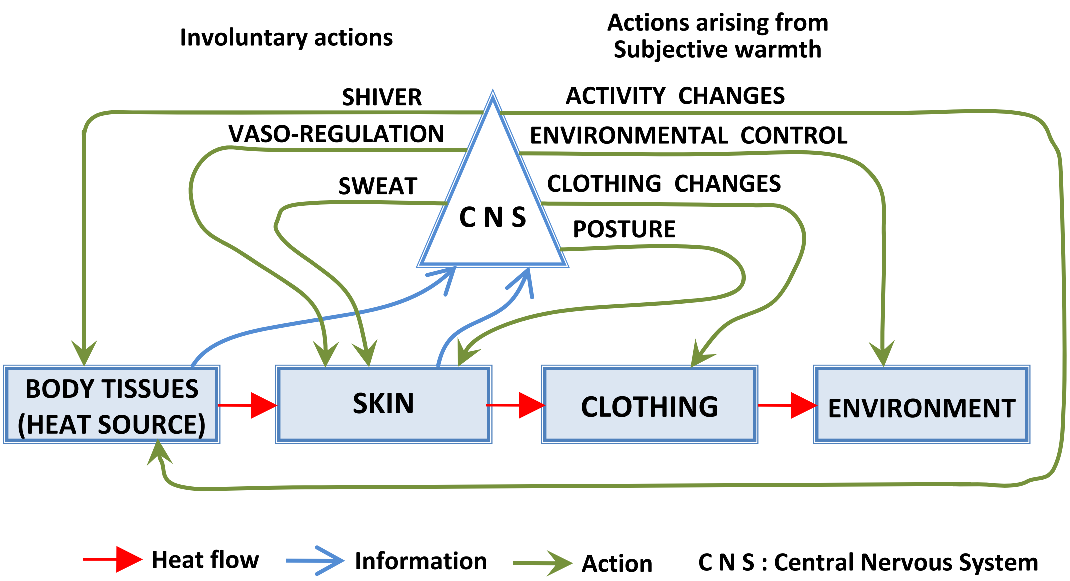


Figure 2.5: The thermal regulatory system (adapted from Nicol & Humphreys, 1973)

2.3.3 Andris Auliciems (1981)

Andris Auliciems postulated that the driver for adaptation was not only indoor temperature, but also outdoor climate. He, therefore, outlined the factors that determine adaptation to include: physiological adaptation (acclimatization), behavioural (adjustment), psychological (expectation) and cultural (technology) (Auliciems, 1981). He showed that the combinations of past and current thermal experiences, cultural and technical practices are the determinant of thermal expectation. Figure 2.6 is a schematic diagram developed by Auliciems to show the relationship among these factors that determine thermal expectation, adaptation and perception (Auliciems, 1981, 1989; de Dear et al., 1993; Nicol, 1993).

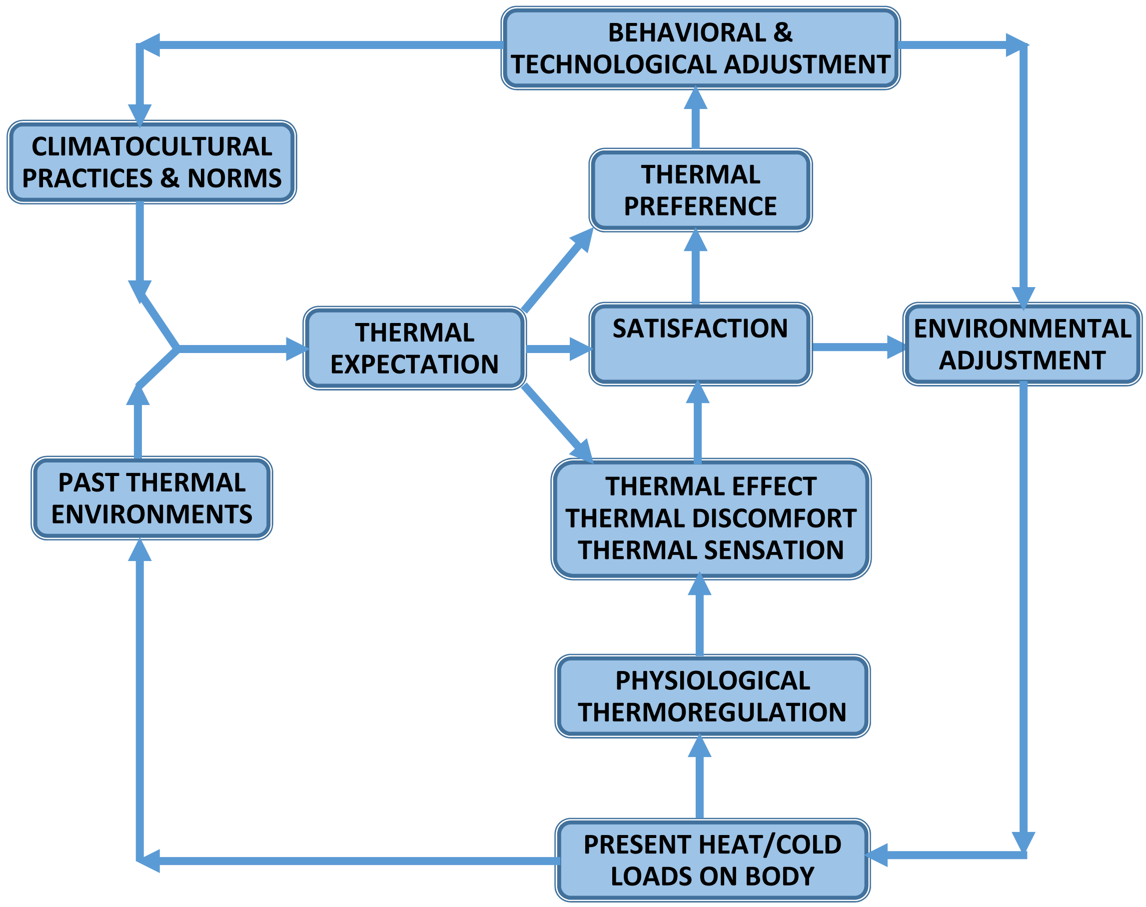


Figure 2.6: The schematic diagram developed by Auliciems to show the relationship among the factors that determine thermal expectation, adaptation and perception (adapted from Auliciems, 1981 and de Dear et al., 1993)

2.3.4 Richard de Dear (1980s)

In 1981, Richard examined this topic and made the following observation with regard to Humphreys', Nicol's and Auliciems' seminal ideas on the one hand, and Fanger's ingenious heat-balance approach to thermal comfort:

(1) Humphreys', Nicol's and Auliciems' seminal ideas had not progressed as far as he thought they should have, and

(2) Fanger's ingenious heat-balance approach to comfort had displaced the adaptive concept and its supporting evidence.

Hence, for his work, *Perceptual and Adaptational Bases for the Management of Indoor Climate,* he compared the adaptive approach with heat-balance approach in a series of field experiments in Australia (de Dear, 1985). The field experiments were carried out in the tropical Darwin, sub-tropical Brisbane and temperate Melbourne in Australia. In each of the climatic zones, he compared naturally ventilated office buildings with centrally air-conditioned office buildings, collected all six of Fanger's PMV model parameters, and compared actual comfort with predicted comfort (de Dear & Auliciems, 1985; de Dear et al., 1997).

At the end of the field experiment, he found out that there were systematic discrepancies, particularly in the warmer climate zones, that could not be explained by the classic six comfort parameters in Fanger's heat-balance model (PMV) (de Dear, 1985; de Dear & Auliciems, 1985).

With over 250 peer-reviewed papers and monographs on the subject of human thermal comfort, de Dear's works are the most cited among current researchers on the subject[3]. He played a key role in the field research studies and the development of the ASHRAE Adaptive Thermal Comfort Model. The development of the ASHRAE Thermal Comfort Model is discussed in the next section.

2.3.5 The ASHRAE RP-884 Comfort Database (1990s)

In order to bridge the gap between comfort theory and practice, in the 1990s ASHRAE became interested in field studies of thermal comfort. It therefore started funding field experiments on thermal comfort. A standardized procedure was adopted for collecting both physical and subjective thermal comfort data from field studies in different parts of the world. The resulting database from these field surveys contained about 21,000 sets of raw field data collected using objective measurements of indoor climate with laboratory precision and subjective assessments of those conditions using standardized questionnaires from 160 different office buildings spread across four continents, and covering a wide range of climate zones. The buildings in the database were separated into those that had centralized HVAC buildings and those that were naturally ventilated (de Dear & Brager, 2002).

The data of the PMV or the heat-balance thermal comfort model were all taken from the indoor environment immediately surrounding the building occupants. While those of the adaptive comfort models were based on the outdoor thermal environmental variables. As explained by de Dear and Brager (2002), the choice of outdoor climate for the adaptive comfort model was informed by the belief that our behavioural adaptations to the

[3] http://www.architecture.adelaide.edu.au/asa2016/keynote/ (accessed on 27 February 2016)

thermal environment is greatly affected by weather and seasons, and that our psychological adaptations in the form of thermal expectation is determined by weather, both recent past and predicted near-future, along with longer-term seasonal swings.

The result from those studies and many others carried out by different individuals in different geographical locations collected over many years is a consolidated database on the web[4]. This database forms the basis for the development of the adaptive component of *ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy.* The adaptive thermal comfort model was first included in the 2004 edition of the ASHRAE Standard 55; and subsequent revision of the Standard thereafter (ASHRAE, 2004, 2010, 2013a).

2.3.6 The SCATs Comfort Database (Smart Controls and Thermal Comfort)

Apart from the ASHRAE Standard 55; the adaptive thermal comfort component was also included in the European Standard, *CEN/EN 15251: Indoor environmental input parameters for design and assessment of energy performance of building–addressing indoor air, quality, thermal environment, lighting and acoustics.* The SCATs comfort database was the basis of the adaptive relation included in CEN/EN 15251 (CEN, 2007; Humphreys, Nicol, & Roaf, 2016). The database was a result of a year-long study of the indoor environmental conditions of selected offices in Western Europe. The office buildings selected for this project, were based in France, Greece, Portugal, Sweden and the United Kingdom. The studies

[4]http://sydney.edu.au/architecture/staff/homepage/richard_de_dear/ashrae_rp-884_appendc.shtml (accessed on 25 April 2014)

yielded about 5000 subjective thermal responses on the ASHRAE scale. The thermal variables collected during the surveys are air temperature, globe temperature, air speed, relative humidity, metabolic rate and clothing insulation. The corresponding outdoor hourly meteorological data were obtained from nearby weather stations (Humphreys et al., 2016).

2.3.7 Comparison Between the ASHRAE and SCATs Comfort Databases

The main differences between the ASHRAE RP-884 comfort database and the SCATs comfort database is summarised in Table 2.5 (de Dear, ca 2011; de Dear et al., 2013). As shown in the table, the geographical locations covered by the source data for the adaptive component of ASHRAE Standard 55 has wider coverage compared to those of CEN/EN. The data of SCATs database were collected from five western European countries (Humphreys et al., 2016; Nicol et al., 2012). On the other hand, the data of ASHRAE RP-884 were obtained from climate zones that cover four continents. These climate zones include (but are not limited to) the humid tropical, the tropical savanna, wet equatorial; which are the major climate zones that runs through the West African region (Efeoma & Uduku, 2014).

Table 2.5: Differences between ASHRAE RP-884 comfort database and SCATs comfort database (Source: Compiled from de Dear, ca 2011; de Dear, 2013)

	ASHRAE RP-884	**SCATs**
Geographical coverage	The data were obtained from four different continents	Data were collected from five countries in Western Europe
Size of database	A total of 9,000 votes from the 21,000 votes in RP-884 database collected from 36 of the 160 buildings surveyed were used for the adaptive comfort standard of ASHRAE	About 5,000 votes were obtained from the 26 offices covered in the SCATS database formed the basis for CEN/EN 15251 adaptive comfort standard
Scope of application	The derived adaptive comfort standard can only be applied to occupant-controlled naturally ventilated spaces without mechanical cooling	The derived adaptive comfort standard can be applied to any building with free running mode
Method of estimating comfort	Uses the regression of observed comfort votes on observed indoor temperatures for each building	Uses Griffiths' extrapolation from observed sensation to hypothetical neutrality by assuming 1 sensation category equal to 2^0C
Representation of outdoor temperature	Uses the mean monthly outdoor air temperature	Uses the exponentially weighted running mean daily outdoor air temperature

2.4 Thermal Comfort Standards

There are three international organisations that are involved in the development of well-known and widely used international standards that set the minimum requirement for temperature control and thermal comfort in the built environment (Nicol et al., 2012). These include:

(1) The ASHRAE – *ASHRAE Standard 55-2013: Thermal Environmental Conditions for Human Occupancy.*

(2) The ISO – *ISO 7730-2005: Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.*

(3) The European Committee for Standardisation (Comite´ Europe´en de Normalisation – CEN) – *CEN/EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings–addressing indoor air quality, thermal environment, lighting and acoustics.*

All three standards mentioned above are subject to continuous review. As at the time of this writing, the current edition of ASHRAE Standard 55 is that of 2013. The latest edition of ISO 7730 is that of 2005, while the latest edition of CEN/EN 15251 is that of 2007 (ASHRAE, 2013a; CEN, 2007; ISO, 2005). All these standards used the PMV/PPD index as a basis for defining the standard for temperature control or thermal comfort. As illustrated in Figure 2.7, the adaptive component has also been included in both the ASHRAE Standard 55 and CEN/EN 15251 (ASHRAE, 2004, 2010, 2013a; CEN, 2007).

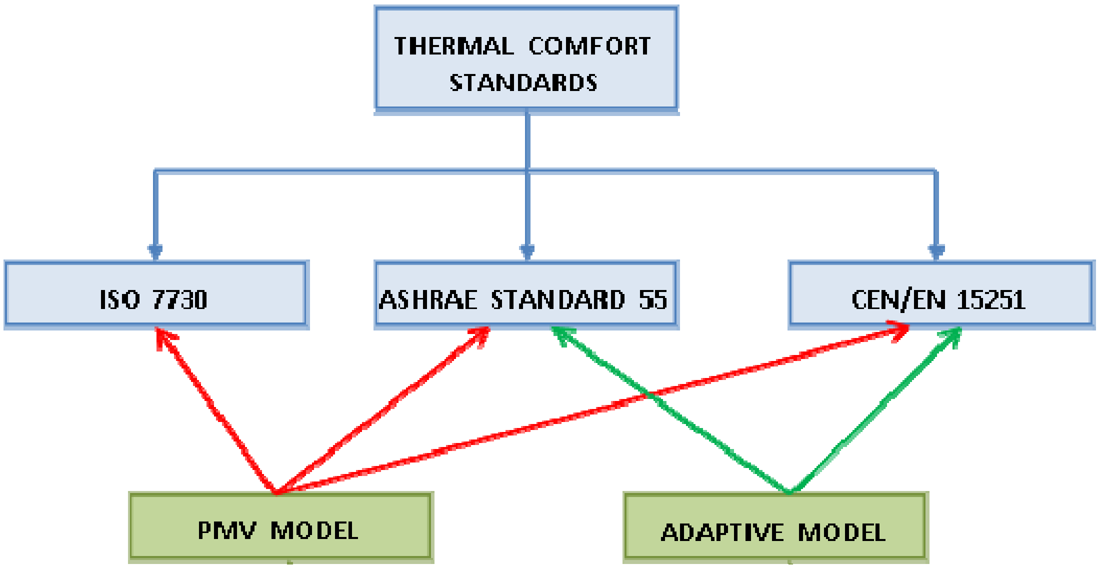


Figure 2.7: Thermal comfort standards and their respective models (Source: adapted from Efeoma & Uduku, 2014)

2.4.1 ASHRAE Standard 55

While this standard has America in its naming and is co-sponsored by the American National Standards Institution (ANSI), it's application goes beyond the United States. ASHRAE has many branches outside the United States and the United States air conditioning industry is dominant in the international market for mechanical cooling. Besides, the standard reflects the thinking and interest of international community of the Heating, Ventilation, and Air Conditioning (HVAC) industry, which is represented on the drafting committee (Nicol et al., 2012), hence, it is in effect an international standard.

The ASHRAE Standard 55 is the first international standard to have the adaptive model included in it. It was first included in the 2004 update of the standard and subsequent revisions thereafter including the current 2013 update. The development of the adaptive comfort standard was based on the data from ASHRAE project RP-884 (de Dear & Brager, 1998) and the extensive work of de Dear and Brager (de Dear & Brager, 2002). The ASHRAE adaptive comfort standard is applicable for occupant-controlled naturally conditioned spaces that meet all of the following criteria:

- ❖ there is no mechanical cooling system installed and no heating system is in operation
- ❖ the occupants of the spaces should be engaged in near-sedentary physical activities (metabolic rate should be between 1.0 to 1.3 met)
- ❖ occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions (clothing insulation should range at least as wide as 0.5 to 1.0 clo)

The adaptive comfort standard relates the indoor comfort temperature to the mean monthly outdoor air temperature in occupant-controlled naturally conditioned buildings (Figure 2.3). The standard specified zones within which 80% and 90% of building occupants might expect to be thermally comfortable. The zones specified are based on the comfort equation for occupant-controlled naturally conditioned buildings derived from ASHRAE RP-884 database (Equations 2.5 and 2.6).

$$\boldsymbol{T_{comf} = 0.31T_o + 17.8} \qquad \textbf{(2.5)}$$

Where,

T_{comf} is the optimal temperature for comfort

T_o is the mean outdoor temperature for the survey

$$\boldsymbol{T_{accept} = 0.31T_o + 17.8 \pm T_{lim}} \qquad \textbf{(2.6)}$$

Where,

$\boldsymbol{T_{accept}}$ is the limits of the acceptable zones

$\boldsymbol{T_{lim}}$ is the range of acceptable temperatures (for 80% or 90% of the occupants)

The limits are given as T_{lim} (80) = 3.5K and T_{lim} (90) = 2.5K

2.4.2 ISO 7730

ISO 7730 (Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria) presents the methods for estimating the general thermal sensation and degree of thermal dissatisfaction. *"It enables the analytical determination and interpretation of thermal comfort using calculation of PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) and local thermal comfort criteria, giving the environmental conditions considered acceptable for general thermal comfort as well as those representing local discomfort. It is applicable to healthy men and women exposed to indoor environments where thermal comfort is desirable"* (ISO, 2005). It is a source for which most member states' national standards are developed (Nicol et al., 2012). It is developed in parallel with ASHRAE standard 55. The standard has a table of measured values of the thermal insulation of various clothing items and ensembles, but does not specify what clothing people should wear. It also has a table of typical values for the metabolic rates for different activities. The standard categorises buildings according to the range of PMV that occurs within them. As shown in Table 2.6, buildings are either classed as category A, B or C.

Table 2.6: Categories of thermal environment (Source: ISO, 2005)

Category	Thermal state of the body as a whole		Local discomfort			
				PD %		
	PPD %	PMV	DR %	vertical air temperature difference	caused by warm or cool floor	radiant asymmetry
A	< 6	- 0.2 < PMV < + 0.2	< 10	< 3	< 10	< 5
B	< 10	- 0.5 < PMV < + 0.5	< 20	< 5	< 10	< 5
C	< 15	- 0.7 < PMV < + 0.7	< 30	< 10	< 15	< 10

PPD (Predicted Percentage Dissatisfied), **PMV** (Predicted Mean Vote), **DR** (Draught Rating), **PD** (Percentage Dissatisfied)

2.4.3 CEN/EN 15251

CEN/EN 15251 (Indoor environmental input parameters for design and assessment of energy performance of buildings—addressing indoor air quality, thermal environment, lighting and acoustics) was developed as a result of the calls from the European Union for standards to back up the Energy Performance of Buildings Directive (EPBD). The standard specifies criteria for indoor air quality, thermal environment, lighting and acoustics, which may have significant influence on the energy demand of a building (CEN, 2007). However, the major thrust of the standard is the definition of the criteria which determine the thermal comfort of a building (Nicol & Wilson, 2011).

Just like the ASHRAE standard 55, the adaptive component of thermal comfort model for assessing buildings in the free-running mode is also included in this standard. The adaptive comfort standard of CEN/EN 15251 is based on the data from the European SCATs project database, instead of the ASHRAE RP-884 database. The data of SCATs database were collected from selected office buildings in France, Greece, Portugal, Sweden and the United Kingdom (Humphreys et al., 2016; Nicol et al., 2012). The values of the acceptable indoor operative temperature are defined according to the comfort equation in Equation 2.7.

$$T_{comf} = 0.33T_{rm} + 18.8 \qquad (2.7)$$

Where

T_{comf} is the comfort temperature

T_{rm} is the exponentially weighted running mean of the outdoor temperature

This standard categorises buildings according to the nature of the building instead of referring directly to the quality of their indoor environment (Table 2.7). This categorisation is done in an attempt to overcome the tendency of the ISO 7730 to categorise buildings in favour of high-energy buildings.

Table 2.7: Categories of buildings and recommended criteria for the thermal environment for both mechanically conditioned (PMV) and free-running buildings in CEN/EN 15251 (Source: CEN, 2007)

Category	Explanation	Thermal state of the body as a whole		
		PPD %	**Limitation for PMV**	**Limitation for free-running building (K)**
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements such as handicapped, sick, very young children and elderly persons	< 6	- 0.2 < PMV < + 2	- 0.2 < K < + 2
II	Normal level of expectation and should be used for new buildings and renovations	< 10	- 0.5 < PMV < + 0.5	- 0.3 < K < + 3
III	An acceptable, moderate level of expectation and may be used for existing buildings	< 15	- 0.7 < PMV < + 7	- 0.4 < K < + 4

2.5 Selected Previous Thermal Comfort Research

This section presents a discussion of previous thermal comfort research focusing on the hot humid climates, thermal comfort research conducted in Nigeria, as well as research on analysis and effect of clothing on thermal comfort.

2.5.1 Selected Thermal Comfort Research Performed in Hot Humid Climates

In order to find an acceptable neutral temperature and preferred temperature in the hot humid climates, many research studies have been carried out in recent years. Findings from some of these studies are summarised in Table 2.8. These include; the field research experiment carried out by Hwang et al., in 10 naturally ventilated and 26 air conditioned classrooms in Taiwan (Hwang, Lin, & Kuo, 2006). The field studies in naturally ventilated classrooms in Singapore by (Wong & Khoo, 2003). Field study on thermal comfort of office workers in seven multi-storey office buildings in Jakarta, Indonesia, done by (Karyono, 2000). The study of Kwok (1998), carried out in tropical classrooms in Hawaii (Kwok, 1998). Also, the thermal comfort field experiments that were conducted in naturally ventilated residential buildings and air conditioned office buildings in Singapore by (de Dear, Leow, & Foo, 1991). The results from these studies as summarised in Table 2.8 indicated that people in hot humid climate who have acclimatised to the climate conditions can accept warmer thermal environment.

Table 2.8: Summary of selected research findings conducted in hot humid climates (Source: Author's compilation)

Year	Researcher	Location	Building	Key Research Findings
2006	Hwang et al.	Taiwan	Classrooms	1. Neutral temp. = 26.3^0C ET* 2. Preferred temp. = 24.7^0C ET* 3. Acceptable comfort zone = $21.1–29.8^0$C ET*
2003	Wong et al.	Singapore	Classrooms	1. Neutral temp. = 28.8^0C TOP* 2. Acceptable comfort zone = $27.1–29.3^0$C TOP*
2000	Karyono, T. H.	Jakarta, Indonesia	Offices	1. Neutral temp. = 26.4^0C TA* 2. Neutral temp. = 26.7^0C TOP*
1998	Kwok, A. G.	Hawaii	Classrooms	1. Neutral temp. = 26.8^0C ET* (naturally ventilated buildings) 2. Neutral temp. = 27.4^0C ET* (air conditioned buildings) 3. Acceptable comfort range = $22.0–29.5^0$C
1991	de Dear et al.	Singapore	Residential	1. Neutral temp. = 28.5^0C TOP* (naturally ventilated buildings)
			Offices	2. Neutral temp. = 24.2^0C TOP* (air conditioned buildings)

Note: *ET* (Effective Temperature), TOP* (Operative Temperature), TA* (Air Temperature)*

2.5.2 Thermal Comfort Research Conducted in Nigeria

In the field of thermal comfort research, there are limited works that have been done in Nigeria compared to what have been done or is being done in America, Asia, Australia and Europe. The results of the few research works that have been carried out regarding acceptable neutral temperature or comfort range are summarised in Table 2.9. This include; the work of Adunola, on residential comfort in relation to indoor and outdoor air temperatures in Ibadan (Adunola, 2012). Akande and Adebamowo, also conducted a field research on indoor thermal comfort for residential buildings in the hot dry climate zone of Bauchi (Akande & Adebamowo, 2010). In another study, Ogbonna and Harris undertook a field study of thermal comfort in residential buildings in the temperate climate of Jos (Ogbonna & Harris, 2008). Also, a study of thermal comfort in the urban residential buildings in the warm humid climate of Lagos was done by Adebamowo (2007). These are in addition to the historic works carried out by Ambler in the warm humid climate of Port Harcourt in the 1950s and the research done by Ojosu et al. in the 1980s (Ambler, 1955; Ojosu et al., 1988).

Some of the results from the field research works on acceptable neutral temperature that have been carried out as shown in Table 2.9 are quite comparable to the some works that were done by researchers in naturally ventilated buildings as discussed in section 2.5.1. The results of the neutral temperature and comfort zones also show that the adaptive model is a better thermal comfort assessment model for the climate of Nigeria when compared with the PMV model. They also showed the importance of adaptive opportunities in order for building occupants to accept much warmer temperatures.

Table 2.9: Summary of thermal comfort research done in Nigeria on neutral temperature and acceptable comfort range (Source: Author's compilation

Year	Researcher	Location (Climate Zone)	Building	Period (Season)	Key Research Findings
2012	Adunola A. O.	Ibadan (Hot Humid)	Residential	April	1. Regression equation: Y = 0.483*X – 15.59 (TSENS with respect to TOP*) 2. Neutral temp. = 32.3^{0}C TOP*
2010	Akande & Adebamowo	Bauchi (Hot Dry)	Residential	Dry and Rainy Seasons	1. Regression equation: Y = 0.357*X – 10.2 (Dry Season) 2. Regression equation: Y = 0.618*X – 15.4 (Rainy Season) 3. Combined neutral temp. = 28.44^{0}C TOP* 4. Acceptable comfort range = 25.5 – 29.5^{0}C TOP*
2008	Ogbonna & Harris	Jos (Temperate Dry)	Residential and Classrooms	July & August (Rainy Season)	1. Regression equation: Y = 0.3589*X – 9.4285 2. Neutral temp. = 26.27^{0}C TOP* 3. Acceptable comfort range = 25.5 – 29.5^{0}C TOP* (-0.5 ≤ TSENS ≤ +0.5) 4. PMV neutral temp. = 25.06^{0}C
2007	Adebamowo	Lagos (Warm Humid)	Residential		1. Neutral temp. = 29.09^{0}C
1988	Ojosu et al	Hot Dry			1. Acceptable comfort zone = 21 – 26^{0}C
		Temperate Dry			2. Acceptable comfort zone = 18 – 24^{0}C
		Hot Humid			3. Acceptable comfort zone = 21 – 26^{0}C
		Warm Humid			4. Acceptable comfort zone = 21 – 26^{0}C
1955	Ambler H. R.	Port Harcourt (Warm Humid)	Office		1. Neutral temp. = 23.13^{0}C ET*

Note: *ET* (Effective Temperature), TOP* (Operative Temperature), TSENS (Thermal Sensation Vote)*

2.5.3 Clothing Adaptation and Analysis of Clothing Insulation on Thermal Comfort

Clothing is one of the six primary factors that affect the thermal comfort or thermal dissatisfaction of humans in any given environment (Fanger, 1970). It is one of the two personal factors that provide occupants of any given space the opportunity to adapt to their thermal environment. Research has also shown that it influence how people perceive the thermal conditions surrounding them (Efeoma & Uduku, 2015; Schiavon & Lee, 2013).

The adaptive principle, as discussed in section 2.3 and illustrated in Figure 2.5, shows that when a change occurs that produces any thermal discomfort; clothing change is one of the action that people usually take to restore comfort (Nicol & Humphreys, 1973). Also, clothing is regarded as our second skin (Flint, 2011). In terms of thermal comfort, it act as an aid for thermoregulation just like the skin.

A. Analysis of Clothing Insulation on Other Thermal Variables

As discussed in section 2.2.1.(F), clothing insulation is the resistance to heat transfer between the clothing surface and the skin (Parsons, 2014). It is mostly expressed in clo unit. The approximate clo value for individual garments and some typical clothing ensembles are contained in different standards such as those of American (Table 2.2), European and International Standards (ASHRAE, 2013a; CEN, 2007; ISO, 2005).

The ASHRAE Standard 55-2013, recommends that for the adaptive thermal comfort to be applicable in occupant-controlled naturally conditioned spaces; occupants should be free to adjust their clothing within a range of 0.5 to 1.0 clo (ASHRAE, 2013a).

A number of researchers have worked on the relationship between clothing insulation and other thermal variables. Schiavon & Lee, (2013), developed a dynamic predictive clothing insulation models for office workers using he ASHRAE RP-884 and RP-921 databases. The study statistically analysed the relationship between clothing insulation and 20 other thermal variables. The median clothing insulation from that study was 0.59 clo (0.50 clo in summer and 0.69 clo in winter). The results also show that clothing insulation was strongly correlated to outdoor air temperature compared with other variables analysed.

Morgan and de Dear examined the relationship between dress code and the thermal environments in a call centre and a shopping mall located in Sydney, Australia (Morgan & de Dear, 2003). The call-centre had a strict dress code in force for employees from Mondays through Thursdays, except on Fridays were staff were free to wear casual clothes. The results indicated that the variation in the clothing insulation value for the call center was less than that in the shopping mall where dress code was not enforced. A linear regression equation that relates the daily mean clothing insulation value with the daily mean outdoor air temperature was developed.

de Carli, Olesen, Zarrella, & Zecchin, (2007), also analysed clothing behaviour by investigating how indoor and outdoor temperature affects people's choice of clothing. This analysis was based on ASHRAE RP-884 database as well as other field measurement from Singapore and Indonesia (Feriadi & Wong, 2004; Wong et al., 2002). The results showed that there is a correlation between clothing insulation and outdoor air temperature. Furthermore, while the indoor temperature did not influence clothing adjustment during the morning hours; it does affect the change of clothing during the day, where strict dress code are not enforced.

It can be seen that most of the analysis discussed above have related clothing insulation to either the prevailing mean outdoor air temperature or the indoor operative temperature. As stated in chapter 1, however, one of the objective of this study is to investigate the relationship between clothing insulation and the subjective thermal sensation of the local office workers in the hot-humid climate of Enugu.

2.5.4 Practical Case Studies of Clothing Adaptation

There are few contemporary case studies or reports on practical case studies related to clothing adaptation. The following two cases cited below are based on the campaign carried out by the Japanese Ministry of Environment. They were termed: Cool Biz campaign in 2005 and Super Cool Biz campaign in 2011.

A. Japanese Cool Biz Campaign

During the summer of 2005, the Japanese Ministry of the Environment began a campaign that is termed: Cool Biz campaign (Japanese Ministry of Environment, 2005). During the Cool Biz campaign, office workers in government ministries were expected to adopt a certain dress code. The Cool Biz dress code advises workers to wear short-sleeved shirts without ties or jackets. They were also expected to starch collars of their shirts to stand up and to wear trousers made from materials that breathe and absorb moisture. The purpose of this campaign, according to the Ministry of the Environment, is to reduce energy consumption by limiting the use of air conditioning. Hence, in all central government ministries the temperatures of air conditioners were set at 28^0C until the end of the summer.

At the end of the summer, the Ministry conducted a web-based questionnaire survey on the Cool Biz campaign (Japanese Ministry of Environment, 2005). Of the 1,200 men and women randomly selected for the survey, 95.8% of the respondents agreed that they knew about Cool Biz campaign. Based on the survey conducted, the Ministry estimated that the campaign resulted in a reduction in CO_2 emission that is equivalent the volume of CO_2 emitted by about 1 million households for one month.

B. Japanese Super Cool Biz Campaign

Following the great east Japan earthquake of March 11, 2011, the shutdown of many nuclear power plants for safety reasons led to energy shortage, which forced the Japanese government to mandate a 15% peak power reduction to address shortage in summer (Tanabe, Iwahashi, & Tsushima, 2012). The government recommended that the temperature of air conditioners should be set at 28^0C. The Super Cool Biz campaign was then launched to encourage workers to wear clothing appropriate for the office summer heat. Polo shirts and trainers were allowed in government office. Under certain circumstances, workers were also allowed to wear jeans and sandals. During the summer of 2012, the Super Cool Biz campaign was repeated in Japan.

While the Super Cool Biz campaign was a good strategy for saving energy, it however affected workers productivity. According to the result of field studies conducted by Tanabe et al, the self-estimated productivity in 2011 summer was 6.6% lower than that of the previous summer (Tanabe et al., 2012). Therefore, there is need to investigate good strategies of electricity savings that would not affect workers thermal comfort and productivity.

2.6 Summary

From the literature reviewed so far, especially those relating to thermal comfort research in the different climate zones in Nigeria, it can be concluded that building occupants in Nigeria are more adaptive to a much warmer temperature than those specified in International Standard such as the ISO 7730. Adaptive thermal comfort is certainly becoming a better standard for the assessment of thermal comfort. However, research focusing on adaptive thermal comfort in Nigeria is still at an early stage in terms of applicability and practical methodology.

The disparity between some of the researches carried out in Nigeria as well as comparison with some of the works done in the same climate zone in other part of the world highlights the need for further research focusing on adaption.

Also, some of the research works have only been carried out for a short period of time and not covering the two seasons usually experienced in Nigeria. This highlights the need for a more comprehensive research focusing on adaption, over a long period taking into account both the dry and rainy seasons.

Current studies in Nigeria have not really explored occupants' adaptive opportunities. Since occupants themselves play a crucial part in the interaction between subjective thermal comfort and the thermal environment, more in-depth investigation focusing on adaptive opportunities are urgently required. Also, the literature review on analysis of clothing clearly shows that there is a correlation between the mean daily outdoor air temperature and clothing insulation. The Japanese *Cool Biz* and *Super Cool Biz* campaign case studies, highlighted that while clothing regulation can significantly affects energy reduction strategies and the mitigation of greenhouse gas emissions; there is need to investigate appropriate strategies of saving electricity through appropriate clothing regulation without sacrificing workers thermal comfort.

Finally, while thermal comfort research has had a long history, and contrasting developments from the United States, Europe, Australia and now globally; in Africa and especially Nigeria and West Africa, research has been limited. This research work seeks to fill some of these gaps identified from the literature review.

CHAPTER 3

THE STUDY AREA:
LOCATION, CLIMATE, OFFICES AND CLOTHING ANALYSIS

3.1 Introduction

This chapter discusses the geographical location and climate of the study area as well as the justification for the choice of the location. It also includes a brief discussion of office classifications in the study location according to office workplace typologies and ventilation systems. It then focuses on the description of building fabric and orientation. It also discusses the different office clothing that are worn by office workers in the field study area; Enugu, Nigeria. The chapter concludes with a review of literature on the factors that influence clothing choice.

3.2 Location and Climate

This section covers the description of the geographical location and climatic characteristics of the study area. It started with a discussion of the geography and climate of Nigeria in general, before focusing on the study area, Enugu.

3.2.1 Geographical Location and Climate of Nigeria

A. Geographical Location of Nigeria

Nigeria is a country in West Africa, which lies between latitudes 4^0 and 14^0N, and longitudes 3^0 and 15^0E (Federal Ministry of Environment - Nigeria, 2014). It is bordered by Niger Republic to the North, Chad and Cameroon to the East, Benin Republic to the West and by the Gulf of Guinea in the Atlantic Ocean to the South (Figure 3.1). Nigeria covers a land mass of approximately 923,768km^2 and it is about 14% of the land area of West Africa. It is roughly the size of Venezuela and it about twice the size of California. The country is sub-divided into 36 States and the Federal

Capital Territory. As shown in Figure 3.2, the 36 States are grouped into six geo-political zones. These are north west, north central, north east, south west, south south and south east zone.

Nigeria is the most populous country in Africa. According to the 2006 national population census, the population of Nigeria stood at 140.43 million people with an annual growth rate of about 3.2% (Federal Ministry of Environment - Nigeria, 2014). At that growth rate, the projected population will double by 2030.

Figure 3.1: The geographical location of Nigeria in the map of Africa (Source: http://www.infoplease.com/atlas/africa.html accessed on 25/11/2015)

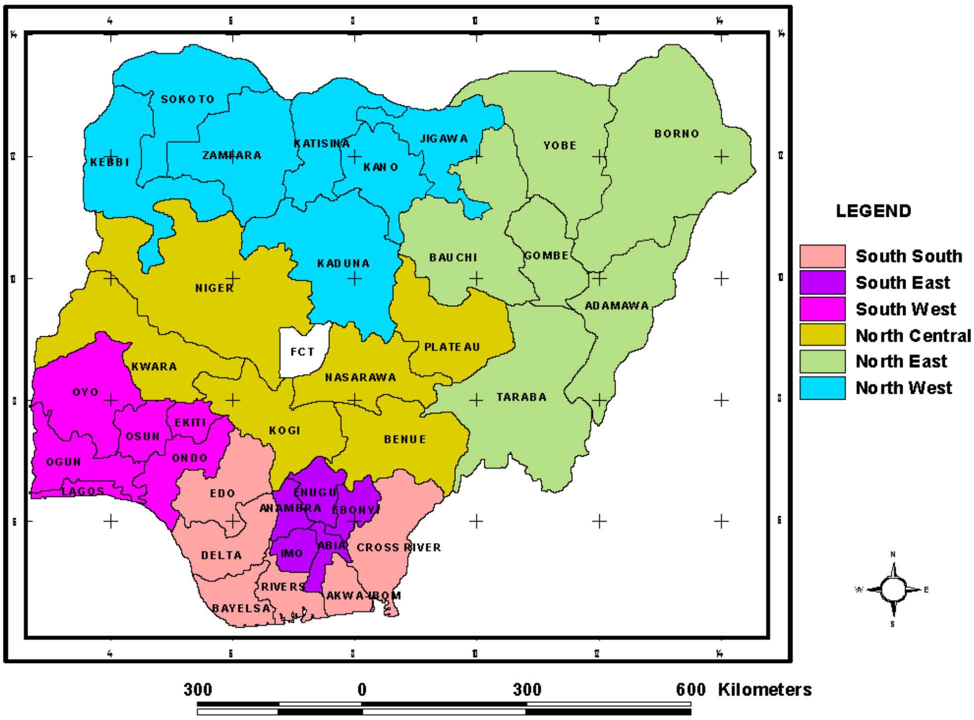


Figure 3.2: The geographical map of Nigeria showing the 36 States, the Federal Capital Territory and the 6 geo-political zones (Source: Nigeria's Second National Communication, 2014)

B. Climate of Nigeria

Nigeria is located just north of the equator, this makes it experience tropical climate which is characterised by hot and wet conditions associated with the movement of inter-tropical convergence zone both north and south of the equator. The country experiences two major seasons throughout the year, the dry season and the rainy season. For most part of the country, the dry season runs from late October to March.

While the rainy season starts towards the end of March and runs till mid-October. There is usually a short break from the rain during the rainy season in August, a period known as 'the August break'.

As shown in Figure 3.3 and Figure 3.4, according to the Köppen-Geiger climate classification (Peel, Finlayson, & McMahon, 2007), the three predominant climates experienced in Nigeria are the tropical savannah (Aw), tropical rainforest climate (Am) and the semi-arid or tropical dry (BSh) climate.

(i) **Tropical savannah climate or tropical wet and dry climate (Aw):** This is the most predominant climate affecting the country. It runs through the central part of the country from East to West. This is the climate that defines the dry and rainy seasons experienced in most part of the country. The dry season comes with high seasonal temperatures, which is accompanied by West African trade wind blowing from the Sahara Desert in the North. The wet or rainy season brings about heavy rainfall.

(ii) **Tropical rainforest climate or equatorial monsoon climate (Am):** This climate is found in the southern part of Nigeria. It is characterised by heavy rainfall and constant temperature range with little variation.

(iii) **Semi-arid climate or Sahel climate or Tropical Dry (BSh):** This is the predominant climate in the Northern part of the country. This climate is characterise by low rainfall. The rainy season is short lasting for a few months. The rest of the year is dry and hot.

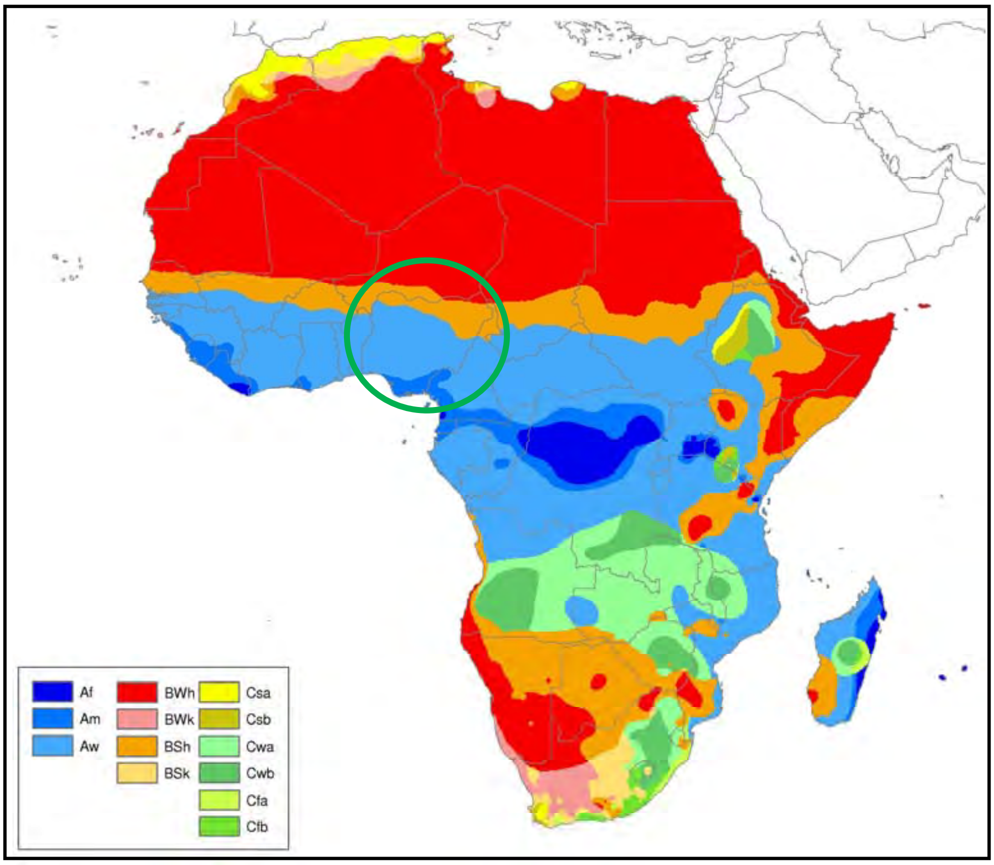


Figure 3.3: African map of Köppen-Geiger climate classification showing the three predominant climates in Nigeria (Source: Peel et al., 2007)

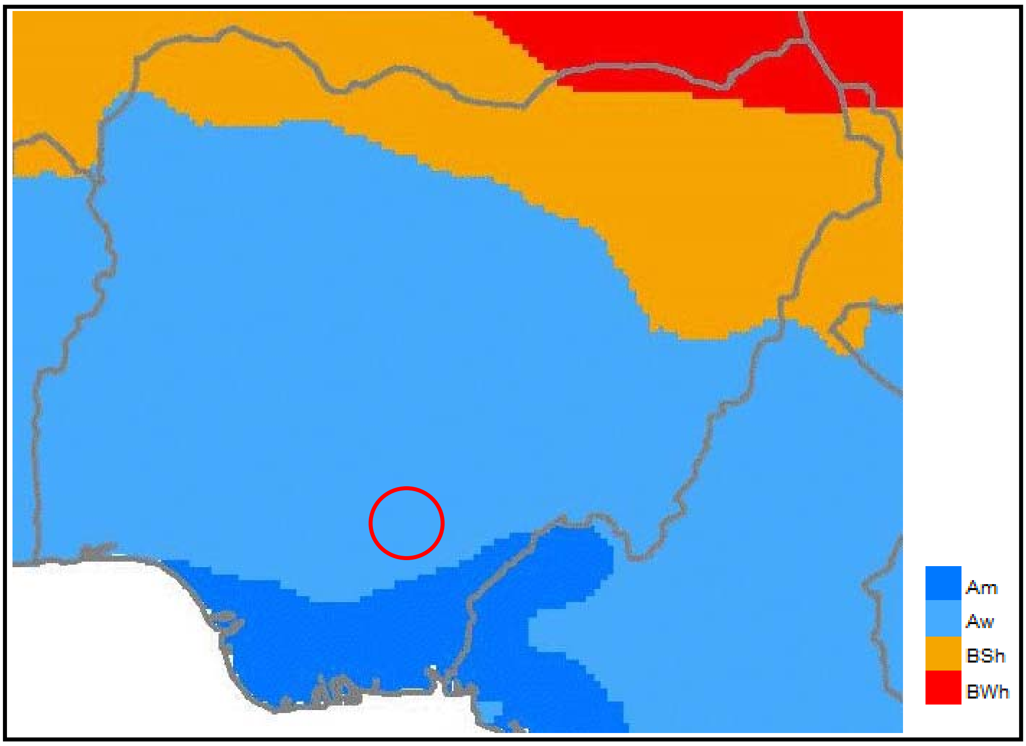


Figure 3.4: Expanded map of Köppen-Geiger climate classification showing the predominant climates in Nigeria (Source: Peel et al., 2007)

For the purpose of design of thermal comfort in buildings, Ojosu et al. (1988), divided Nigeria into four climatic zones. As show in Figure 3.5, the four climatic zone for thermal comfort design in buildings are: Hot Dry zone, Temperate Dry zone, Hot Humid zone and Warm Humid Zone.

(i) **Hot Dry (H.D.) Zone:** The diurnal temperature variation for this climatic zone ranges from about 15 to 20^{0}C. The mean annual rainfall ranges from 530 to 1000mm. Some of the major cities in Nigeria that falls into this zone are Maiduguri, Sokoto, Katsina, Bauchi, Kano and Yola

(ii) **Temperate Dry (T.D.) Zone:** For this climate zone, the diurnal temperature range is about 10^{0}C, with a mean yearly rainfall that ranges from 1070 to 1400mm. Some of the major cities which experience this climate include Zaria, Kaduna, Jos and part of Abuja.

(iii) **Hot Humid (H.H.) Zone:** The daily temperature variation between the highest and lowest temperature is less than 10^{0}C. This zone also experience mean annual rainfall that varies from 1180 to 1800mm. Some of the major cities within the climatic zones are part of Abuja, Enugu, Bida, Lokoja, Ilorin, Oshogbo, Ibadan and Onitsha.

(iv) **Warm Humid (W.H.) Zone:** This climate zone have the small amount of temperature variation throughout the year compared to other climate zones in Nigeria. The diurnal range of temperature is less than 8^{0}C, with a mean yearly rainfall of 1190 to 2800mm. Some major cities in this zone include Port Harcourt, Calabar, Benin City, Lagos, Warri and Asaba.

Figure 3.5: Climatological map of Nigeria showing the four climate zones (adapted from Ojosu et al., 1988)

3.2.2 Geographical Location of Enugu

Enugu, the location of the field research work undertaken, is the capital city of Enugu State. It used to be the administrative capital of the old Eastern Region of Nigeria. It is located at an altitude of approximately 223m above sea level and it lies between latitudes 5°55'15''N and 7°6'36''N, and longitudes 6°55'39''E and 7°54'26''E (Sanni et al., 2007). It has an undulating topography with scattered hills and knolls (Reifsnyder, William, & Darnhofer, 1989). It covers an approximate area of about 7,161km^2.

The State is sub-divided into seventeen local government area (Figure 3.6). The selected case study buildings surveyed during the field work are located in Enugu North local government area. In terms of geographical location; Enugu, as administrative city, parades a number of both public and private offices. Since this research work is focused on office workers, the location is therefore pertinent.

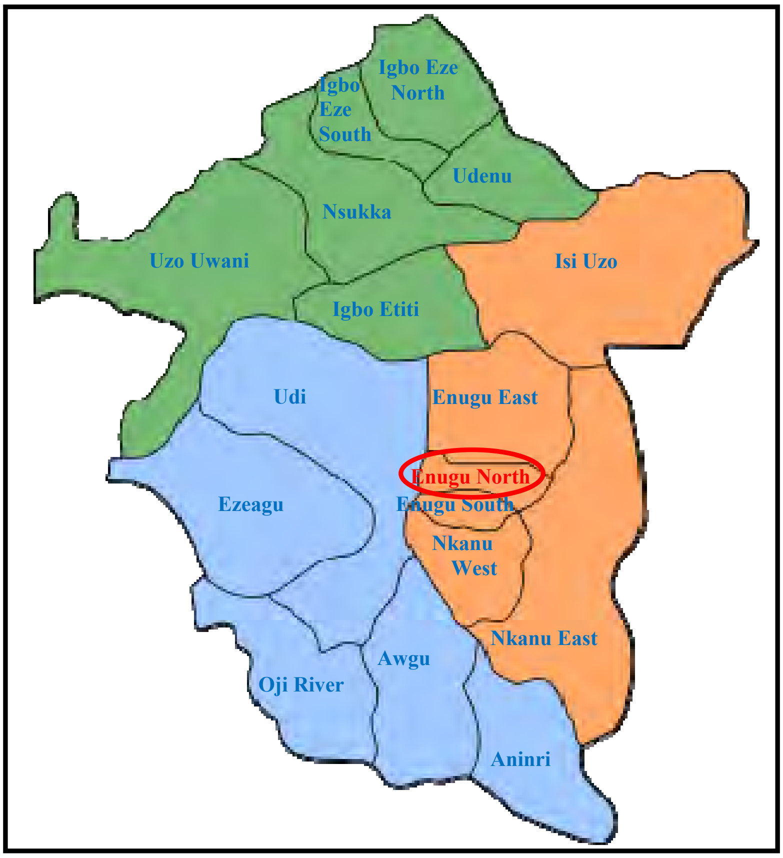


Figure 3.6: Map of Enugu showing the 17 local government areas (Source: adapted from www.nigerianstat.gov.ng)

3.2.3 Climate Characteristics of Enugu

The Köppen-Geiger climate classification, classified the climate of Enugu as tropical savannah, Aw, climate (Peel et al., 2007). While according to Ojosu et al., for the purpose of thermal comfort design in buildings, Enugu is in the hot humid climate zone of Nigeria (Ojosu et al., 1988).

Like the rest of the country, Enugu is hot all year round with a mean daily temperature of 26.7^{0}C (Sanni et al., 2007). The climate of Enugu is humid and the peak of the humidity is experienced between March and November (Reifsnyder et al., 1989). As it is with the rest of West African countries, Enugu experiences two major seasons, the rainy and dry seasons. During the months of December and January, the city is also affected by a weather condition called Harmattan, a dusty trade wind which usually occurs for a few weeks.

A. Air temperature

The climate statistics of Enugu's air temperature spanning a period of 30 years is summarised in Figure 3.7[5]. It shows that, with an average maximum temperature of 35^{0}C each, February and March are the hottest months in Enugu. While the lowest maximum temperature is experienced during the months of July to September. Overall, the temperature is almost the same all year round. The difference between the maximum mean daily temperature and the minimum mean daily temperature is less than 4^{0}C.

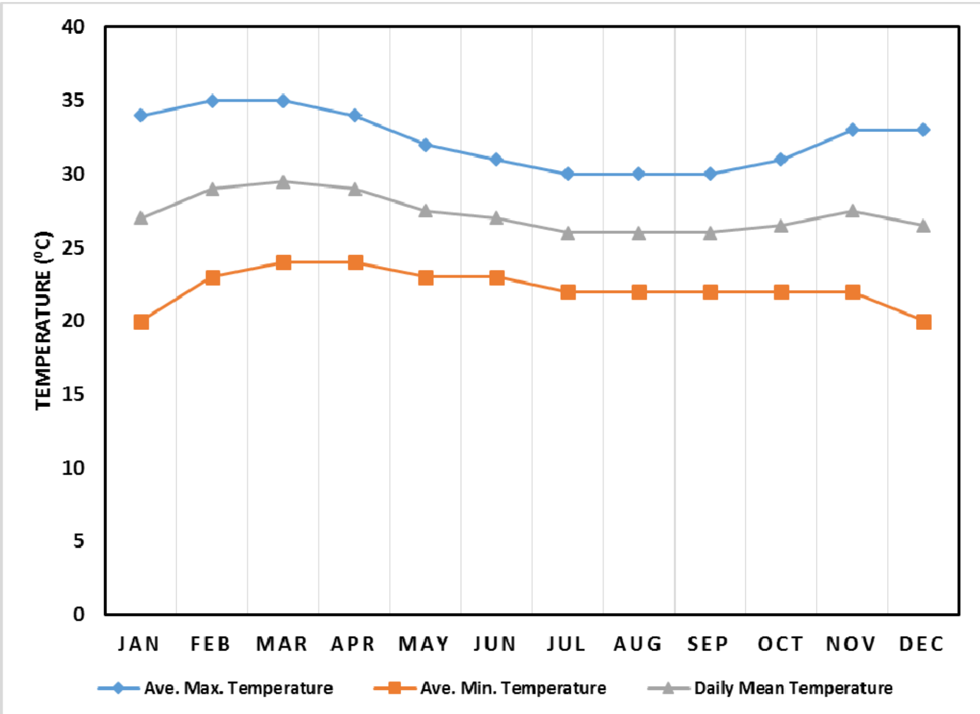


Figure 3.7: Average annual air temperature (^{0}C) for Enugu

[5] The climate statistics plotted in this chapter represent the mean value of each meteorological parameter for each month of the year. The sampling period for this data covers 30 years from 1961 to 1990. (Source: http://www.theweathernetwork.com, accessed on 01 December 2015)

B. Precipitation

The average precipitation data covering a period of 30 years is illustrated in Figure 3.8. It shows that the most precipitation is experienced during the month of September, with an average 292mm. While the least precipitation days are experience during the months of November to February. The driest month of the year is December, with a mean precipitation of 8mm.

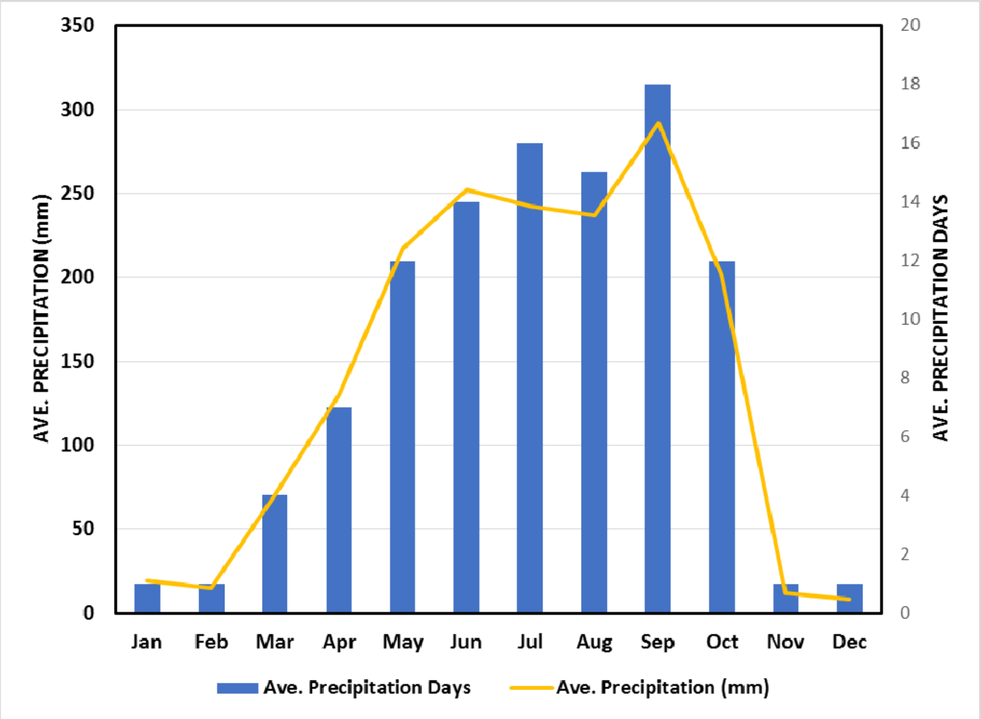


Figure 3.8: Average annual precipitation (mm) and average precipitation days for Enugu

C. Solar radiation

Figure 3.9 depicts the mean annual solar radiation for Enugu. The average least sunshine hours is experienced during the months of July and August. The months of November and December have the most average sunshine hours, 219 and 217 hours respectively.

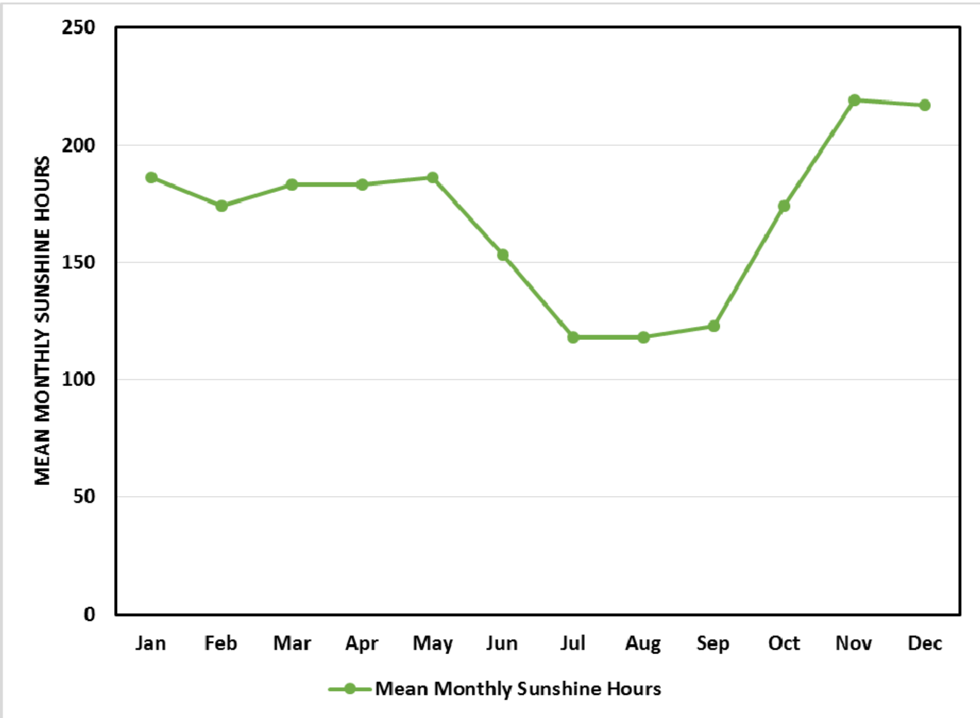


Figure 3.9: Mean monthly sunshine hours for Enugu

3.3 Office Classifications

While there is no existence of an internationally recognised standard for the classification of office buildings, researchers and different organisations have adopted different criteria for the classification of offices. Foremost among these are commercial or properties managers and organisations. For example, the Building Owners and Managers Association (BOMA), Canada, classified offices into three categories; Class A, B or C. The criteria adopted in the classification include: age of building, location, construction and architecture, management, tenants, leasing rate, building systems, elevators, security, environment, parking and services (BOMA, 2014).

Ho et al. (2005) used the following six building quality index (BQI) in classifying office buildings: presentation, management, functionality, services, access and circulation, and amenities. In his research in the local context of Abuja, Nigeria, Mu'azu (2015) classified office buildings using the following criteria: building vertical projection and budget. These classifications focused mainly on aesthetic and cost but did not address the most crucial climatic element that influences thermal comfort in the tropical region; ventilation.

Hence, taking the local context and the climate of Enugu into consideration, this research has classified office buildings using office workplace typologies and office ventilation systems. These criteria are discussed the following sub-sections.

3.3.1 Office Workplace Typologies

Two main categories were considered based on workplace typologies. These are enclosed office spaces (ES) and open plan offices (OP).

Enclosed office spaces (ES) in the context of the study area are similar to the United Kingdom cellular workplaces, which are predominantly enclosed private work spaces. These offices are usually arranged along a central corridors and their sizes usually varies according to the position or status of the intended occupant(s) (Allen, Bell, Graham, Hardy, & Swaffer, 2004). In the study area, some of the office spaces are also connected to a central open workspace (Figure 3.10). Other offices studied were arranged as single or double banked in relation to an internal access corridor. In some cases, these offices can also be accessed through a veranda, or corridor open to the elements (Figure 3.11).

Open plan office spaces (OP) refer to office environment with multiple workstations that do not have full dividing walls (Allen et al., 2004). In some instances, there may be either low-panelled or high-panelled partitions creating individual cubicles with work desks. Also a workplace with small group of desks in a room with no partitioning or screening at all, would be termed as OP.

For the field research undertaken, the researcher selected both ES and OP. Specific details of construction, building services, dimensions and occupancy densities of the selected case study office buildings are discussed in Chapter 4.

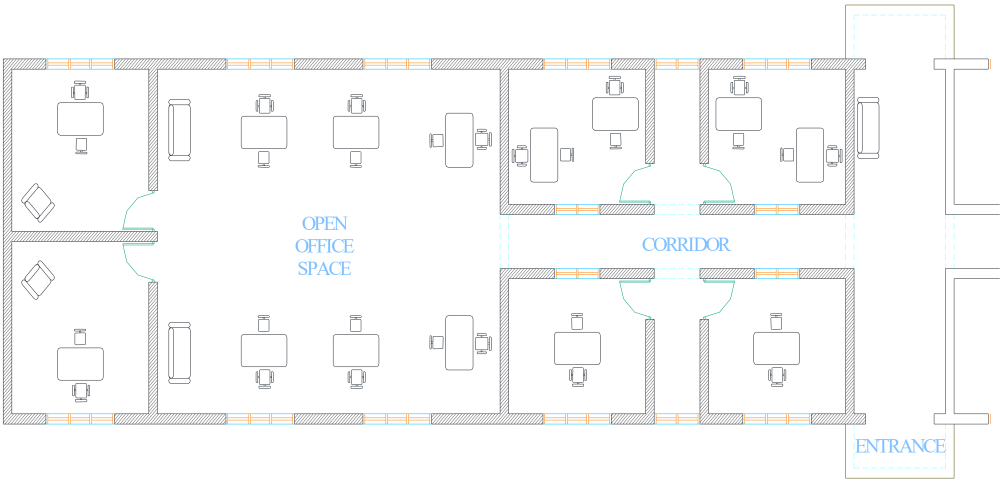


Figure 3.10: An example of office building combining Enclosed offices and an Open Plan office: Part of administrative block of Federal Road Safety Corps, Enugu, Nigeria

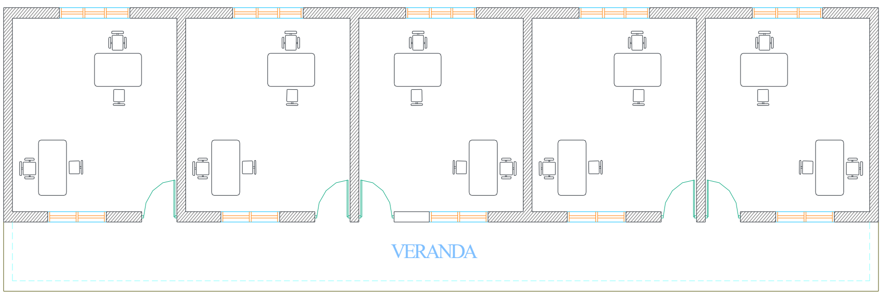


Figure 3.11: An example of Enclosed offices arranged along a veranda: Federal Radio Corporation of Nigeria, Enugu

3.3.2 Office Ventilation Systems

Ventilation is the process of exchanging or removing air from a space for the purpose of providing high indoor air quality, controlling humidity or temperature within the space (ASHRAE, 2013b). There are three main categories of ventilation system in buildings. These are:

- mechanically ventilated (MV) spaces,
- naturally ventilated (NV) spaces and
- mixed-mode ventilated (MM) spaces.

The Researcher's interaction with, and interviews with workers in the case study offices revealed that ventilation systems in offices were often determined by worker status and budget. The lower the status of the worker, the less the budget and also the less effective the ventilation in place.

Mechanically ventilated (MV) offices are those offices where the ventilation is completely controlled by powered equipment such as motor-driven fans and blowers (Schiavon, 2014). MV spaces do not have operable or openable windows. Occupants of such spaces have no control over the exchange of air between the outdoor and indoor environment. In the Enugu study area, offices with MV systems were found to be mostly financial institutions, such as the commercial banks.

Naturally ventilated (NV) offices rely on passive methods, such as windows opening, rather than mechanical means to achieve air exchange between the interior and exterior spaces. Office with this category of ventilation system are very common in the study area when compared to those with MV system.

Mixed-mode ventilated (MM) offices are also referred to as hybrid ventilated offices. These are offices were both MV and NV systems are employed in providing a comfortable internal environment. One major feature of the hybrid system is the intelligent control system that can switch automatically between natural and mechanical modes in order to minimize energy consumption (Heiselberg, 2002).

However, in the Nigerian context of this research, MM offices encountered had no intelligent control systems and therefore no automatic switching was taking place. Thus, rather than referring to such offices as hybrid ventilated offices, the researcher uses the term mixed-mode ventilation in describing these categories of offices.

MM offices, in this thesis are those with workspaces that utilise a combination of natural ventilation from operable windows and some form of air-conditioning cooling systems which are occupant control. The most common air-conditioning cooling systems encountered in the field research undertaken were wall-mounted air conditioners; comprising both the high wall split air conditioners and the floor standing (or package) air conditioners. The office workers were in complete control of their operation, in relation to their being switched on or off.

The focus of this thesis is on adaptive thermal comfort; hence the field research undertaken, surveyed workers' activities and comfort in offices with both NV and MM systems in place.

3.4 Building Fabric and Orientation

This section describes some common building materials that are used in the construction of buildings in Nigeria as well as the study location, Enugu. It also discusses building orientation and the main factor that influences the orientation of buildings.

3.4.1 Typical Building Fabric

The term building fabric refers to the walls, windows, doors, floor and ceiling of a building. With respect to thermal efficiency, the design of these building elements is very important in minimising cooling or heating requirement. Table 4.2 presents a summary of the different materials that were used in the construction of different components of the selected case study buildings used for this research work.

External Walls: The most common material used for the construction of building walls in Nigeria, including the study location, is sandcrete block (Oyekan & Kamiyo, 2011). Sandcrete blocks are made of a mixture of sand, cement and water (Oyekan & Kamiyo, 2008). They have low thermal mass (Amos-Abanyie, Akuffo, & Kutin-Sanwu, 2013); hence walls built with sandcrete blocks do not retain heat. The internal temperature condition without mechanical cooling or heating is usually a function of outdoor air temperature. As shown in Table 4.2, the walls of about 85 percent of the case study offices spaces used for this study are built with sancrete blocks. Apart from sancrete blocks, other materials which are used in the construction of walls in the study area include concrete, metal iron sheets with interior cladded with plyboard, glass and in rare cases wood.

The area weighted average U-value of the outside wall of all the case study office buildings satisfies the following inequality as discussed in section 2.2.3(A) of Chapter 2:

$$U_w < 50/(t_{d,i} - t_{d,e})$$

Windows of selected case study office buildings are fitted with single pane glazing. These are either clear, tinted or reflective glass. The most common type of window used in these case study buildings is the louvre window. When opened, it allows for natural ventilation and acts as a solar shading device (Datta, 2001). When other type of windows are installed; the design of the roof overhang (eave), which are usually up to 1.2 metres in most cases, prevent solar radiation from striking the window glazing directly (Offiong & Ukpoho, 2004). This is particularly applicable to buildings that are not high-rise, as it is with the case study office buildings used in this research study.

Doors: All exterior doors of the case study buildings were either made of hardwood or steel. They come in different designs and sizes. Most of the external doors are either shaded with the roof overhang or are located within an entrance porch were they are protected from direct solar radiation.

Floor of all office buildings were the survey was conducted are made with cast in situ concrete, which are either finished with ceramic floor tiles or mortal plaster. As discussed in section 2.2.2 (C); the floor finishing has no impact on the thermal comfort or sensation, since participants were putting on shoes. The thermal impact of the floor will only be significant in places where people are bare feet (Effting, Güths, & Alarcon, 2007).

Ceiling: The ceilings of the buildings were finished with either polyvinyl chloride (PVC) cladding or plyboard. About 85% of the office spaces surveyed were finished with pvc ceiling. PVC ceiling sheet has low density, low thermal conductivity and high thermal resistivity which help to reduce the thermal gain, thereby decreasing the energy consumption for cooling of the interior spaces in a building. (Onyeaju, Osarolube, Chukwuocha, Ekuma, & Omasheye, 2012).

3.4.2 Building Orientation

Proper building orientation can contribute significantly to a more acceptable indoor thermal comfort condition in tropical climates (Odim, 2008). Figure 4.2 shows the solar orientation of the selected case study office buildings where this research work was conducted. Generally, orientation of the buildings in Nigeria including the study location were dependent upon the layout of the access road (Adebamowo & Ilesanmi, 2012). While this is understandable in the case of residential buildings due to spatial constraint (Mu'azu, 2015); the large land allocation for most office complexes ought to take advantage of this potential in maximising solar orientation in improving natural ventilation. However, as shown in Figure 4.2, the orientation of the case study buildings studied did not take advantage of the prevailing wind condition to increase air flow across the buildings.

3.5 Office Clothing

This section presents a brief description of the different categories of office clothing worn by office workers in Enugu, the research subjects in the case study location. This clothing comprises four main categories:

- formal office wear,
- official uniforms,
- traditional 'native' office clothing and
- casual clothing.

3.5.1 Formal Office Wear

This category of office clothing is similar to the traditional British 'work' clothing. For males, it might comprise a shirt, a pair of trousers, a jacket and a tie. In offices where there is no strict clothing policy, some workers may choose not to put on a tie and at times the jacket.

For the females, there is a wide range of acceptable official or formal clothing, depending on each office's specific clothing policy. This may include different suit pieces such as matching skirts, trousers, jackets with co-ordinated blouses. When offices have no formal clothing policy, some females do not wear the full co-ordinated suit and instead have a formal blouse and skirt or trousers. Occasionally also an appropriate dress often called 'gown' was worn by females in the case study offices visited.

3.5.2 Official Uniforms

This is common to the armed forces and other semi military affiliated offices and parastatals. Under this category, the government or the employer will have a regulated uniform that all staff of the establishment are expected to wear at work at all times. This is strictly enforced, with disciplinary action taking place when staff fail to wear the appropriate uniform. The regulated uniform, is usually historic and bears little relation to contemporary clothing worn by staff. Often also the materials used are synthetic and affect the employee’s perception of comfort adversely.

Figure 3.12 and Figure 3.13 are illustrations of some uniform clothing categories discussed. The examples shown are the official uniforms worn by staff of the Federal Road Safety Corps (FRSC) and the Nigeria Security and Civil Defence Corps (NSCDC) respective. The equivalent clothing insulation values of the official uniforms of FRSC workers, who participated in this research study, are discussed and presented in Chapter 4 and Chapter 5.

Figure 3.12: Official uniform worn by staff of Federal Road Safety Corps (FRSC) of Nigeria

(Faces have been obscured for privacy and ethical reasons)

Figure 3.13: Official uniform worn by staff of Nigeria Security and Civil Defence Corps (NSCDC)

(Faces have been obscured for privacy and ethical reasons)

3.5.3 Traditional 'Ethnic' Office Clothing

This categorises locally tailored clothing which incorporates local fashion designs and also locally available textiles and fabrics (Figure 3.14). Some of the fabric is locally produced whilst more expensive locally tailored clothing is tailor made using imported fabric, mainly form Europe or the far East. Usually the textiles used are cotton based, although sometimes synthetic textiles are used. Commercial Banks, and other financial establishments often allow staff to wear ethnic or traditional clothing on Fridays, as a 'dress down' policy. The researcher found out that in offices with no strict uniform or regulated clothing policy, staff independently tended to 'dress down' or more informally in casual wear on Fridays.

Figure 3.14: Examples of some of the kinds of ethnic or traditional office clothing worn by office workers in Nigeria

3.5.4 Casual Wear

This is the last category of clothing worn by office workers in the study area as observed by the researcher. This category of office clothing is similar to what would be worn by Europeans whilst on holiday in warm countries. Casual clothing tends to have more cotton based material and short sleeves. As illustrated in Figure 3.15, this may include cloths such as polos, jeans, t-shirts etc. This is the least common of all the four categories of office clothing that the researcher observed workers wearing during work hours.

Figure 3.15: Some examples of casual office wears worn by office workers in Nigeria

3.6 Factors Influencing the Choice of Clothing

Several factors have been identified that affects the choice of clothing. Parsons (2014) mentioned *fashion* and *corporate image* as the most influential factors. Those who consider fashion in selecting clothing tend to perceive how they appear to themselves and to others as more important. With regard to corporate image, some organisations and establishments see their clothing or uniforms as their identity.

Goldman (2006) suggested four main factors which determine clothing comfort. These include *fashion, feel, fit* and *function;* known as the 4 Fs of clothing comfort. Loschek (2009), also, identified *fashion* as the major determinant of choice of clothing. He explains that to understand what fashion is all about, one has to look at the aesthetic premises, plurality of styles, performative impulses, social qualities and economic conditions of clothing.

In a research conducted in Ghana, West Africa, into the factors that influence the clothing choice, the most important factors identified include *colour, fashion, affordability, durability* and *religion* (Ofori, Adu, Nyame-Tawiah, Adu-Akwaboa, & Agbovie, 2014). Riungu (2009) categorise the factors to include physical characteristics of the clothes and psychological factors. Physical characteristics includes *construction and finishing*, *fabric quality*, *suitability for work*, *cleaning and care.* While the psychological factors include *smart look, style, personal beliefs and values (also describe as culture), latest style* and *uniqueness.* Another research work indicates that men were more influenced by *weather condition* while the most influential daily factor among women was *social activities* or *events* (Kwon & Drayton, 2007).

In Nigeria, including Enugu the study area, most of the factors discussed above also influence the dressing habits of local residents (Adaramaja, Adenubi, Alabi, Adeola, & Olanrewaju, 2010; Alooma & Lawan, 2013; Ejila, 2014; Lawan & Zanna, 2013; Okeh, 2009; Omoike, 2015; Pogoson, 2013). Generally, where there is no dress code, *fashion* seems to rank the highest among other factors that influence the selection of clothing especially among females (Ejila, 2014; Pogoson, 2013). People appear to be more concerned about how they will look or how others will see them in their clothing. According to a research conducted in South Eastern Nigeria by Okeh (2009), attracting attention to themselves, be it for positive or negative reason, is one of the dominant factors that influence the choice of clothing among younger female population.

For office workers, the dominant factors are *corporate image* and *fashion* (Komolafe, 2009; UBA, 2008). Most corporate organisation, especially the Banking, the Insurance and the Advertising sectors, consider the image of their establishment to be more important than the comfort of workers within the organisation. Hence, most of these establishment have a particular dress code that workers must adhere to (The Chartered Institute of Bankers of Nigeria, 2014). In United Bank for Africa, for example, the dress code stipulated not just the type of office clothing that must be worn but also the colour of shirt, skirt and pair of trousers that should be worn by staff. On Fridays, when the ‘dress down’ policy is allowed, the code also specify the categories and colours of clothing that workers must choose from. Failure to abide by the dress code could result to disciplinary action even dismissal (UBA, 2008).

Some government parastatals, like the Federal Road Safety Corps (FRSC) and the Nigeria Security and Civil Defence Corps (NSCDC), have a uniform policy (Figure 3.12 and Figure 3.13). Office workers in these establishments are expected to put on their uniform at all times during office working hours (FRSC, 2008). The strict enforcement of these uniform policies makes it difficult for workers to adjust their clothing to the thermal conditions surrounding their work places (Efeoma & Uduku, 2015). This in turn will affect the thermal satisfaction of office workers, since their ability to adapt their clothing is restricted by office clothing regulation.

In office establishments where strict dress code or uniform policy are not in place, *fashion* appears to be the most important determinant of clothing among office workers in the study area. Workers in such establishments have the flexibility of adapting their clothing when necessary.

3.7 Summary

This chapter clearly discussed the geographical and climatic conditions of the study area, Enugu. The key characteristics of the climate zone were illustrated in the composite climate graphical analysis presented at the end of the first part of the chapter. The analysis clearly shows that there is no strong diurnal swing in temperature all year round. With less than 4^0C difference between the maximum and minimum mean daily temperature, it is possible to passively design or modify buildings in the study location to ensure that occupants are thermally comfortable with minimal cooling all year round.

The chapter also attempted to establish a number of office classifications in relation to office workplace typologies, and the most crucial climatic element that influences thermal comfort in tropical region, ventilation system. The two key office workplace typologies considered for the field studies undertaken, were the enclosed office spaces (ES) and the open plan spaces (OP). Also, of the three categories of office ventilations systems discussed in this chapter, the field research work for this study focused on only two modes: naturally ventilated and mixed-mode ventilated offices. This choice was influenced by the scope of this research work, which is on adaptive thermal comfort.

In general, the building fabric were made of materials with low thermal mass. Hence, in most cases, the internal thermal environment of the selected offices were a function of the outdoor thermal condition. It was also noted that the case study buildings were oriented toward the access road leading into the site; the buildings did not optimise the potentials of building orientation. This poor orientation of the selected office buildings made it difficult to take advantage of the prevailing wind in ventilating the buildings.

The research into clothing found that office workers in the study area wore different categories of office clothing. While some offices operated a regulated office clothing or uniform policy, others allowed flexible clothing policy with no strict rules in place. The review of previous research work and analysis of clothing behaviour clearly shows that the most dominant factors affecting the choice of office workers clothing choice are corporate image and fashions. Thus, where the focus is on corporate image and in offices where uniform policy in place in the study location, it is difficult for workers to take advantage of the adaptive opportunity that clothing can provide.

CHAPTER 4

RESEARCH METHODOLOGY

4.1 Introduction

This chapter discusses the methodology applied in this thesis in order to accomplish the set aim and objectives. It presents the research methodology, design and analysis adopted in this thesis along with the justification for the selected methods.

4.2 Research Aim and Objectives

The main aim of this research work as discussed in Chapter 1 is 'to investigate the extent to which the wearing of regulated office clothing affects the perception and adaptation of office workers to work environments in the hot humid climate of Enugu, South Eastern Nigeria'. To set the context to the chapter, the specific objectives of the thesis as outlined in chapter 1 are restated as follow.

(i) To compare adaptive thermal comfort and its relationship to the thermal performances of office spaces in the hot humid climate of Enugu.

(ii) To explore office workers' thermal perception corresponding to office workplace typologies and ventilation systems.

(iii) To determine the neutral temperature and comfort range for office workers in the hot humid climate, focusing on adaptation.

(iv) To compare the thermal perception of office workers with strict uniform policy with those with flexible office clothing policy in the local climate of Enugu.

(v) To investigate the relationship between clothing insulation and the subjective thermal sensation of the local office workers in the hot-humid climate of Enugu.

4.3 Research Methodology Undertaken

Methodology refers to set of rules and procedures which guide any research study (Miller & Brewer, 2003). The success or failure of any research work depends on the research methodology (Johnston, 1980). Hence, the main research methodology adopted for this study is the conduct of field studies to determine thermal comfort in local office settings in Enugu. This method has been employed by international researchers in the field of adaptive thermal comfort studies (de Dear et al., 1997; Humphreys et al., 2007). The main feature of this research approach is the comparison of the objective indoor thermal conditions with the corresponding subjective thermal comfort responses of participants (Cândido et al., 2011). One advantage of this method is that it allows a researcher to study the participants in their familiar day to day environment, with their normal choice of clothing and activities (Nicol & Roaf, 2005).

However, rather than only using the quantitative method of data collection and analysis traditionally employed in the field of thermal comfort studies, this study adopted a mixed-method of data collection and analysis. It employed both the quantitative and qualitative methods of data collection and analysis. The decision to employ this approach is to draw on the strength of both quantitative and qualitative methods.

4.3.1 Mixed Methods Approach

Mixed methods research is defined by Johnson and Onwuegbuzie (2004), as the type of research that combines or mixes quantitative and qualitative research techniques, methods, approaches, concepts or language into a single study. The objective is not to replace either of these methods but to draw from the strengths and minimize the weaknesses of both approaches in single research studies and across studies (Onwuegbuzie & Leech, 2003). Mixed methods research, therefore, attempts to fit together the insights provided by quantitative and qualitative research into implementable solution.

According to Johnson and Turner (2003), the *fundamental principle of mixed research* is; researchers should collect multiple data using different approaches, methods and strategies in such a way that the resulting combination is likely to result in complementary strengths and 'non-overlapping' weaknesses. The main justification for mixed methods research is the effective use of this principle because the product will be superior to 'mono-method' studies (Johnson & Gray, 2010). The confidence held in the conclusion of the research study will be greater if findings are corroborated across different approaches; on the other hand, if the findings conflict then the researcher has a better understanding and can modify interpretations and conclusions accordingly (Johnson & Onwuegbuzie, 2004). In many cases the objective of combining both methods is not to search for corroboration but rather to expand one's understanding (Onwuegbuzie & Leech, 2004).

The rationale for the mixed methodology adopted in this research was informed by the *fundamental principle of mixed research* by Johnson and Turner (2003). The qualitative semi-structured interviews and observations, which will be discussed in subsequent sections, will provide a way to discuss directly the aim of this research and peer into participants' perception. It will also give explanation to some of the potential problems associated with the quantitative questionnaires. Overall, the corroboration of the findings from both methods will increase the confidence level of the conclusion that will be reached from this research study.

4.3.2 Quantitative Methods

Researchers in the field of thermal comfort studies, including the research studies that led to the development of the adaptive thermal comfort, have traditionally employed quantitative approaches in data collection and analysis (de Dear et al., 1997; Humphreys et al., 2007). According to Groat, quantitative methods are useful in dealing with precise and systematic measurement of verifiable quantities, such as climate data (Groat & Wang, 2013). Quantitative methods are useful for generalising (Creswell & Plano Clark, 2011). In order to achieve the objectives of this research work using the quantitative approach, this study adopted a three steps approach: field data acquisition, data analysis and interpretation of results, and conclusion. The specific methods for data collection and analysis are discussed in details in the subsequent sections.

A. Data collection

The quantitative data for the case studies were collected through the measurement of physical parameters, environmental quantities and subjective thermal comfort questionnaires. The quantities collected include physical characteristics of offices spaces, outdoor climatic conditions, indoor environmental conditions, and participants' subjective thermal perception.

B. Data composition

The quantitative data can be grouped into six categories: participants' non-thermal variables, office characteristics, outdoor thermal variables, indoor environmental conditions, participants' thermal factors and subjective thermal perception. A more detailed composition of each of these categories is given in Table 4.1.

Table 4.1: Summary of data collected

Categories	Variables
Participants' non-thermal variables	Age Gender Year in Enugu
Office characteristics	Office workplace typology Ventilation system
Outdoor thermal variables	Prevailing air temperature Relative humidity
Indoor thermal condition	Operative temperature Relative humidity Air velocity
Participants thermal factors	Metabolic rate/Activity level Clothing insulation
Subjective thermal perception	Thermal comfort vote Thermal sensation vote Thermal preference vote

C. Office spaces selection criteria

In order to fulfil research objectives (i), (iii), and (v); the following criteria, which are in compliance with the criteria of ASHRAE Standard 55 for occupants-controlled spaces (ASHRAE, 2013a), were used in choosing the office spaces used for the study:

(a) occupants of office spaces should have control over the ventilation system in place, it could either be mixed-mode or naturally ventilated but not mechanically ventilated;

(b) windows had to be easy to access and operate;

(c) participants had to be engaged in near sedentary activity ranging from 1.0 to 1.3 met.

For research objective (ii), the following criteria influenced the selection of office spaces used for the study:

(a) office spaces had to include open plan office (OP) spaces and enclosed office (ES) spaces and

(b) office spaces had to include spaces that were completely naturally ventilated and spaces with mixed-mode ventilation (a combination of natural ventilation and some form of air-conditioning cooling system which are occupant-controlled).

In order to achieve objective (iv), spaces had to be selected from two different establishments. One with an enforced uniform policy and the other with a flexible work clothing policy. The two different establishments selected for this research work were:

(1) the Federal Radio Corporation of Nigeria (FRCN), Enugu—with flexible work clothing policy; and

(2) the Federal Road Safety Corps (FRSC), Enugu—with strict uniform policy.

The office spaces selected from the above mentioned establishments satisfied all the criteria stated above. The specific characteristics of selected office spaces are discussed in the next section.

D. Selected office spaces and their characteristics

In all, six office spaces were selected. Three from FRCN and three from FRSC. The three office spaces selected from FRCN were selected from three different buildings within the complex. While the three office spaces selected from FRSC were all located within the administrative building in the complex. Figure 4.1 shows the location of the complexes of FRCN and FRSC on google map. The distance between the two establishments is less than a kilometres.

Figure 4.2 shows sketches of the floor plans of the selected office spaces showing the various sitting arrangement as at the time of the field survey. While Table 4.2 gives a summary of office spaces selected showing their location and their characteristics. These include the GPS coordinates of each office space, ventilation system in place, office workplace typology, square area, occupation density, construction materials, number of windows and number of doors.

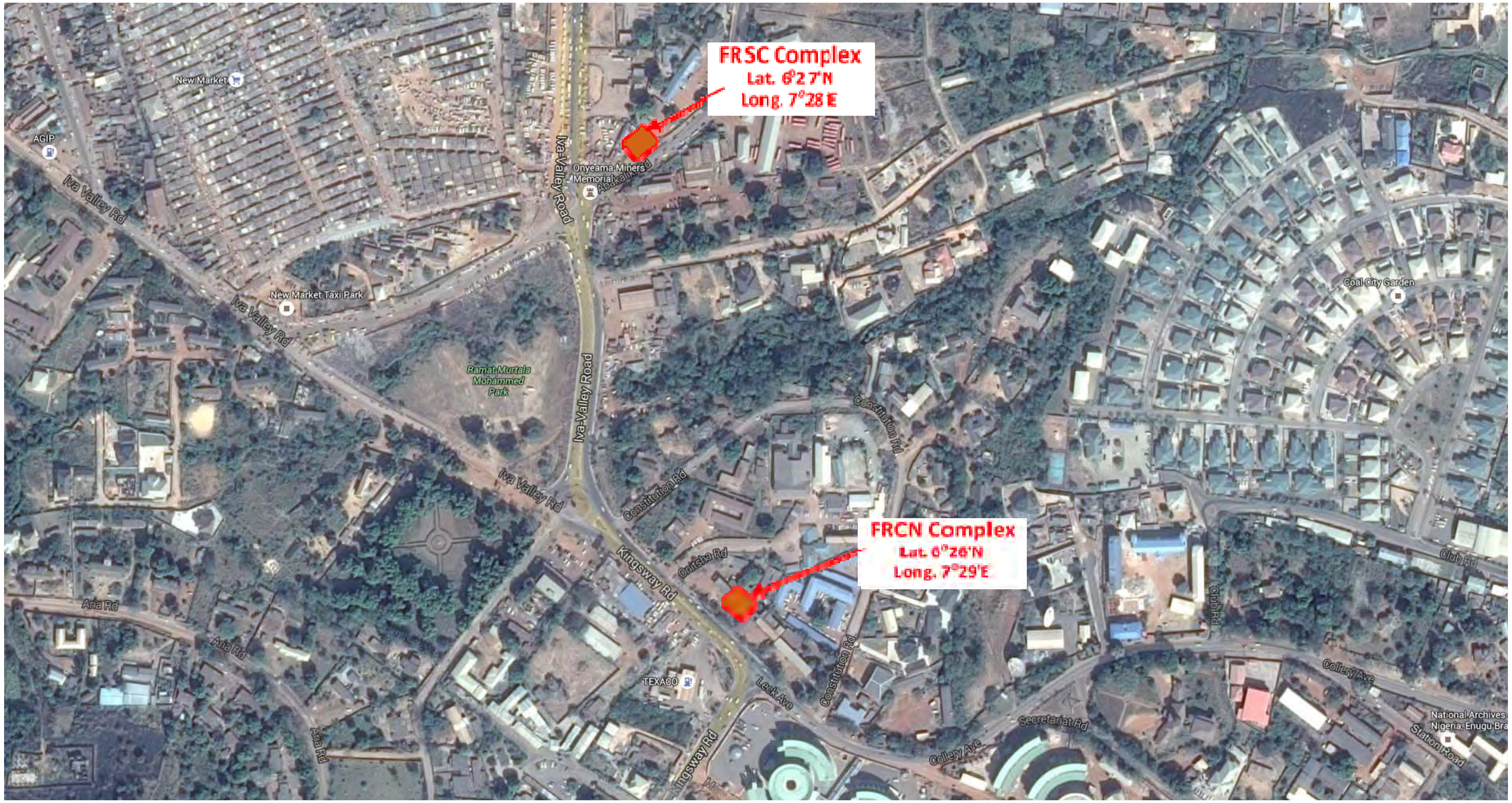


Figure 4.1: Location map of FRCN and FRSC office complexes, Enugu, Nigeria (Source: Google Map, accessed 27 January 2016)

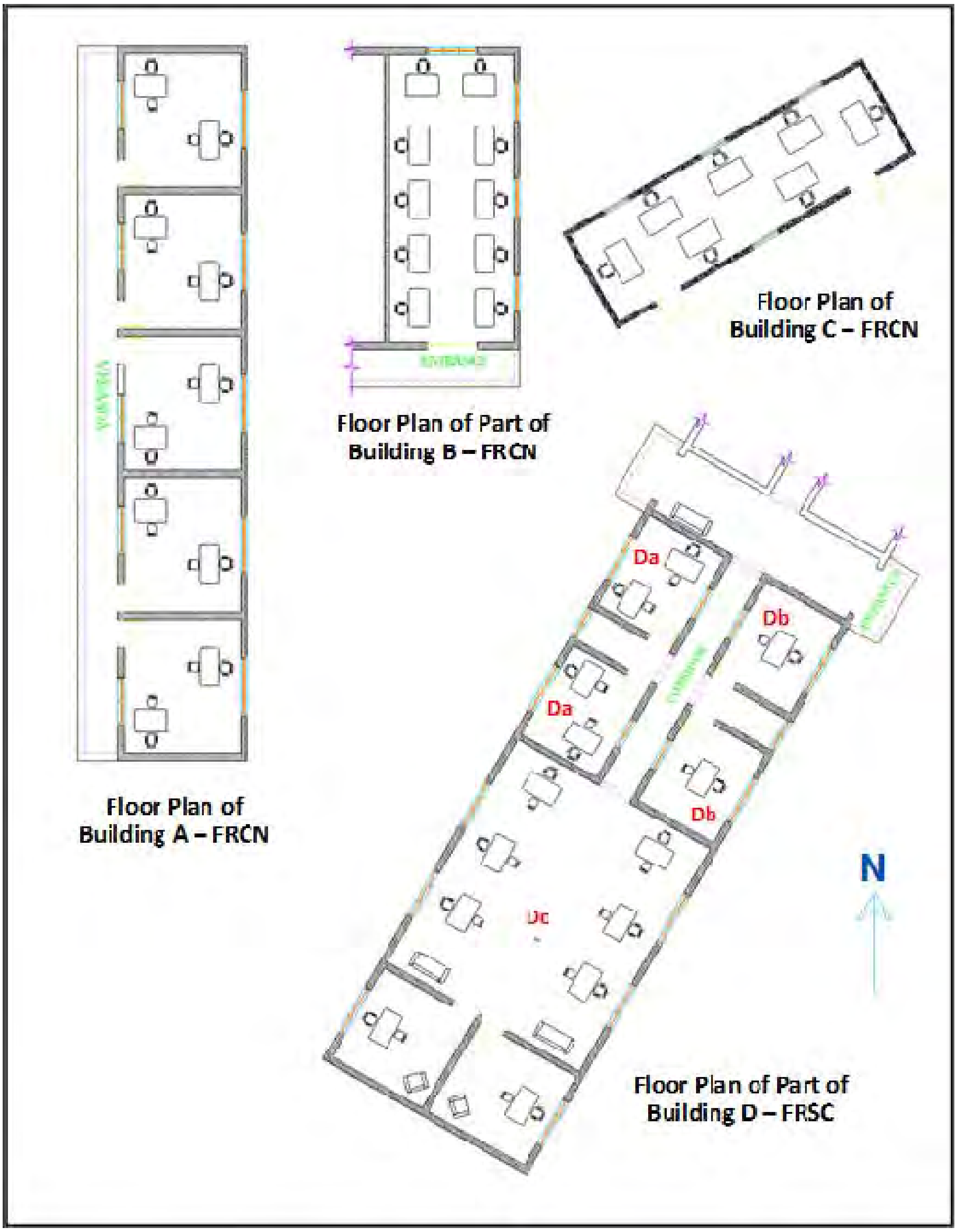


Figure 4.2: Sketches of floor plans of selected office spaces used for the survey in FRCN and FRSC

Table 4.2: Summary of analysis of selected office

	A	B	C	Da	Db	Dc
Location	FRCN	FRCN	FRCN	FRSC	FRSC	FRSC
GPS Coordinates	$6^0$26'46.9''N $7^0$29'02.8''E	$6^0$26'43.4''N $7^0$29'04.1''E	$6^0$26'46.9''N $7^0$29'02.8''E	$6^0$27'06.8''N $7^0$28'54.0''E	$6^0$27'06.8''N $7^0$28'54.0''E	$6^0$27'06.8''N $7^0$28'54.0''E
Ventilation system	MM	MM	MM	MM	NV	NV
Workplace typology	ES	OP	OP	ES	ES	OP
Square area (m^2)	14.40	40.50	24.48	10.80	10.80	54.00
Occupation density (m^2/person)	4.80	4.05	3.50	3.6	5.4	6.75
Construction materials	**Walls:** Sandcrete blocks **Roof:** Longspan aluminium roofing sheets **Ceiling:** Pvc ceiling cladding **Floor:** Tiles	**Walls:** Sandcrete blocks **Roof:** Corrugated iron roofing sheets **Ceiling:** Pvc ceiling cladding **Floor:** Tiles	**Walls:** External walls made of metal iron sheets while internal wall finished with plyboard **Roof:** Asbestos roofing sheets **Ceiling:** Plywood **Floor:** Concrete floor	**Walls:** Sandcrete blocks **Roof:** Longspan aluminium roofing sheets **Ceiling:** Pvc ceiling cladding **Floor:** Tiles	**Walls:** Sandcrete blocks **Roof:** Longspan aluminium roofing sheets **Ceiling:** Pvc ceiling cladding **Floor:** Tiles	**Walls:** Sandcrete blocks **Roof:** Longspan aluminium roofing sheets **Ceiling:** Pvc ceiling cladding **Floor:** Tiles
No. of windows	Ext: 2	Ext: 4	Ext: 4	Ext: 1 Int: 1		Ext: 4
No. of doors	Ext: 1	Ext: 1 (2-in-1)	Ext: 2	Int: 1	Int: 1	Int: 1

Notes: *Ext (External), Int (Internal), Pvc (Polyvinyl Chloride)*

E. Equipment

In order to measure the air temperature and relative humidity of the office spaces surveyed, Tinytag Ultra 2 (TGU-4500[6]) Gemini loggers (Figure 4.3) were placed in each of the spaces surveyed. The corresponding outdoor air temperature and relative humidity were recorded with the aid of Tinytag Plus 2 (TGP-4500[7]) Gemini loggers (Figure 4.4), which were placed in the immediate outdoor environment of the indoor spaces being monitored.

Figure 4.3: Tinytag Ultra 2 Temperature/Relative Humidity Logger (-25 to +85^{0}C/0 to 95% RH) Gemini Data Loggers

[6] http://www.geminidataloggers.com/data-loggers/tinytag-ultra-2/tgu-4500 (accessed on 28 September 2015)

[7] http://www.geminidataloggers.com/data-loggers/tinytag-plus-2/tgp-4500 (accessed on 28 September 2015)

Figure 4.4: Tinytag Plus 2 Dual Channel Temperature/Relative Humidity (-25 to +85^{0}C/0 to 100% RH) Gemini Data Loggers

TGU-4500 and TGP-4500 are capable of recording readings up to 32,000 each, with high reading resolution. The temperature reading resolution of both loggers is ±0.01^{o}C or better. While the reading resolution of the relative humidity is ±0.3%.

The TGU-4500 data loggers were placed in all the office spaces being surveyed to record indoor air temperature and humidity at 15 minutes interval throughout the study period. The loggers were located within 1 meter of the participants' workstation to record the actual thermal conditions being experienced by participants during normal working hours. The TGP-4500 data loggers were also placed outside the buildings to automatically record both the corresponding temperature and humidity of the immediate outdoor environment at the same time intervals as the data loggers placed indoors.

In this research, the average indoor air temperature recorded by with the data loggers were assumed to be equal to operative temperature. This assumption was based on the fact that all the office spaces surveyed satisfied all three conditions specified in ASHRAE Standard 55, and as discussed in section 2.2.4(A) of Chapter 2.

A handheld device, the Kestrel 3000 Pocket Wind Meter (Figure 4.5), was used in monitoring the air velocity of the different office spaces used for the survey at different instances. Due to unavailability of instrument for logging the air velocity continuously at the same time as the air temperature and relative humidity, the Kestrel 3000 Pocket Wind Meter was used for monitoring the air velocity at different instances during the field work. It is capable of measuring airspeed range from 0.30 to 40.0m/s with ±1.66% accuracy[8].

Figure 4.5: Kestrel 3000 Pocket Wind Meter

[8] http://kestrelmeters.com/products/kestrel-3000-wind-meter (accessed on 28 September 2015)

Apart from measuring wind speed, Kestrel 3000 is also used for measuring temperature and Relative Humidity. It is designed to measure air, water and snow temperature.

All of the instruments used for this survey are ISO certified.

F. Questionnaire design

The questionnaire used for this study had two parts. Part 1 was designed to obtain general information about the office space conditions of participants. Personal information requested for in Part 1 of the questionnaire included participants' gender, age, number of years participants had lived in Enugu. While the information requested regarding the office spaces included office workplace typologies, ventilation systems in place, number of persons occupying office space, number of openable external windows in the space, position of participant's desk in relation to external window(s). Table 4.3 shows the questions used in acquiring information for the various category. The questionnaire is shown in Appendix A.1.

Table 4.3: Design of Part 1 of questionnaire

<table>
<tr><th>Concept</th><th>Abbreviation</th><th>Questions</th></tr>
<tr><td rowspan="3">Personal Information</td><td>Gender</td><td>Please indicate your gender</td></tr>
<tr><td>Age</td><td>Please indicate your age range</td></tr>
<tr><td>Years in Enugu</td><td>How long have you lived in the hot-humid climate of Enugu?</td></tr>
<tr><td rowspan="4">Office Space Condition</td><td>Office Workplace Typology</td><td>How would you describe your office space?</td></tr>
<tr><td>Ventilation System</td><td>How would you describe the ventilation system of this office space?</td></tr>
<tr><td>Occupation Density</td><td>How many persons usually work in this office space?</td></tr>
<tr><td>Openable Windows</td><td>How many external openable windows are there in this office space?

Is your desk close to a window?</td></tr>
</table>

Part 2 of the questionnaire was designed to obtain information relating to participants' subjective thermal comfort perception, which is a classic 'right-here-right-now' survey. Three variables relating to participants' thermal comfort perception were collected by means of the Part 2 of the questionnaire at the same time. These variables include:

- thermal comfort,
- thermal sensation and
- thermal preference.

This study adopted a six-point scales

- very uncomfortable,
- uncomfortable,
- somewhat uncomfortable,
- somewhat comfortable,
- comfortable and
- very comfortable

of thermal comfort to obtain participants' direct evaluation of their corresponding thermal environments. The purpose of employing thermal comfort scale was to allow the participants to make their own judgement about whether the physical thermal condition are acceptable. This helped to determine whether the prevailing thermal conditions within the office spaces are acceptable. This determination was done in conformity with ASHRAE Standard 55, which defines acceptable thermal environment as the thermal environment were 80% or more of occupants find to be thermally acceptable (ASHRAE, 2013a).

The ASHRAE Standard 55 seven-point scale

- cold,
- cool,
- slightly cool,
- neutral,
- slightly warm,
- warm and
- hot

was adopted to measure participants' subjective thermal sensation (TSENS). As shown in Table 4.4, this seven-point scale was also used in measuring participants' thermal preference (TPREF). In order to carry out statistical analysis on participants' subjective thermal perception votes, as shown in Table 4.5, real numbers were given to all the subjective scales.

Table 4.4: Design of Part 2 questionnaire questions for thermal perception

Variable	Questions
Thermal Comfort (COMF)	How comfortable is the thermal environment in your office RIGHT NOW? ( ) Very Uncomfortable ( ) Uncomfortable ( ) Slightly Uncomfortable ( ) Slightly Comfortable ( ) Comfortable ( ) Very Comfortable
Thermal Sensation (TSENS)	HOW DO YOU ACTUALLY FEEL RIGHT NOW in your office? (Please select a single option) ( ) Cold ( ) Cool ( ) Slightly cool ( )Neutral ( ) Slightly warm ( )Warm ( ) Hot
Thermal Preference (TPREF)	Which single temperature sensation DO YOU MOST PREFER RIGHT NOW in your office? (Please select a single option) ( ) Cold ( ) Cool ( ) Slightly cool ( )Neutral ( ) Slightly warm ( )Warm ( ) Hot

Table 4.5: Thermal scales and given real numbers

Variable	Scale and Given Real Number
Thermal Comfort (COMF)	(1) Very Uncomfortable (2) Uncomfortable (3) Slightly Uncomfortable (4) Slightly Comfortable (5) Comfortable (6) Very Comfortable
Thermal Sensation (TSENS)	(-3) Cold (-2) Cool (-1) Slightly cool (0)Neutral (+1) Slightly warm (+2) Warm (+3) Hot
Thermal Preference (TPREF)	(-3) Cold (-2) Cool (-1) Slightly cool (0)Neutral (+1) Slightly warm (+2) Warm (+3) Hot

The ASHRAE thermal sensation scale is a widely recognised and accepted tool, used in the field of thermal comfort studies in both laboratory and field studies, and adopting it makes it easy for the comparison of the results from the hot-humid climate of Enugu with others that have adopted similar scale (Humphreys, 2008). There are some conventional assumptions that are made with regards to the scale: (1) “neutral” thermal sensation vote corresponds to optimal conditions as perceived by the occupants, and (2) the three central categories of the thermal scale (slightly cool, neutral, and slightly warm) are regarded as acceptable or comfortable (de Dear & Brager, 1998).

Other information collected through the administration of the Part 2 of the thermal comfort questionnaire include participants’ activity levels and clothing insulation. A detailed Part 2 of the thermal comfort questionnaire is presented in Appendix A.2.

These questionnaires, both Part 1 and Part 2, used in this study were tested in pilot study conducted in the Enugu before the start of the first stage of the survey during the dry season in January 2014. The pilot study was conducted in December 2013 using both online and paper-based methods of administration. For all questionnaires administered online, none of them were returned. This was, most likely, as a result of the poor or unstable internet access available to participants. On the other hand, about 90% of the paper copies of questionnaires administered were completed and returned. Hence, the decision was taken to administer paper copies of questionnaires during the actual survey. The specific methods used in administering these are discussed in details in the following section.

The pilot study also highlighted the need to refine some sections of the questionnaires and to cut down the time participants spent in completing each questionnaire. For example, the thermal perception component of the initial questionnaire used for the pilot study had questions on thermal comfort vote, thermal sensation vote, thermal preference vote and thermal acceptance vote. However, all completed paper copies of questionnaires that were returned indicated that there was no difference in the thermal conditions preferred and accepted by participants during the pilot study. About 100% of the returned questionnaires had the same comfort vote for both thermal preference and thermal acceptance. Hence, the decision was taken to eliminate the thermal acceptance question and retain only the thermal preference question, as participants were having the same comfort vote in both.

During the course of the pilot study, it was also discovered that some participants were more willing to talk about things than to put them down in writing. Despite being assured that all their answers to the questionnaire questions are anonymous, some of them remained sceptical. Some were having the feelings that any information written down might be linked to them and used against them by their management. However, they were willing and happy to talk freely. This discovery further reinforced the decision to include a qualitative semi-structured interviews and observations as part of the research method adopted for this study.

G. Administration of the questionnaires

The field research work was conducted in two stages. During the dry season (January to March 2014) and during the rainy season (May to June 2014). The Part 1 of the questionnaire was used for the recruitment of participants on a voluntary basis. Paper copies of the first part of the questionnaires were distributed to a self-selected group of participants who are office workers in both offices of FRCN and FRSC. For the purpose of anonymity, codes were assigned to each participants that completed the first part of the questionnaires. Part 1 of the questionnaire was only administered during the first stage of the field research work since the information collected from that part of the questionnaire remains unchanged throughout the course of the survey.

Part 2 of the questionnaire was administered in both stage of the field research work using a longitudinal approach. In contrast with a one-off 'point-in-time' assessment, a longitudinal approach that studies the same subject repeatedly over time can yield more comprehensive results (Langevin, Wen, & Gurian, 2013). Hence, this study adopted the longitudinal approach in administering Part 2 of the thermal comfort questionnaires during both stages of the survey. For each day of the survey, three thermal comfort questionnaires were administered to each participant; one in the morning (before 11am), another one at mid-day (between 11am and 1pm), and the last one in the afternoon (after 1pm). This process was repeated for different days throughout the period of the two stages of the survey.

H. Data analysis

The analysis of the quantitative data collected in this study began with compilation, coding and the computing of the different raw data obtained from different sources such as from data loggers, measurements and questionnaires. The data were then sorted and summarised into a dataset suitable for computer analysis. These were first computed with Microsoft Excel and transferred to Statistical Package for Social Sciences (SPSS) software for analysis.

Raw data from the data loggers, which measured both the indoor and outdoor thermal conditions, were downloaded into an Excel spreadsheet. Data from both the Part 1 and Part 2 of the questionnaires; which included participants' personal information, office spaces, subjective thermal perception votes, metabolic rate, clothing insulation; were coded into Excel spreadsheet. The data from the loggers were then matched with the data obtained from the questionnaires using the time indicated by the participants in the questionnaires. These were then compiled into another Excel spreadsheet. After eliminating data-errors, the completed Excel data were converted into SPSS file for analysis. The final data were then analysed using both descriptive and inferential statistical techniques as explained below.

Descriptive statistical analysis

This statistical analysis method is useful for the collection, description, summary and analysis of a known set of variables. In this research, it is applied in describing, displaying and summarising of data obtained from the data loggers and questionnaires. The purpose is to describe the characteristics of analysis units, such as measure of central of tendency, measures of variation or dispersion, and measures of position and location for a given characteristic.

This study employed the following descriptive statistical techniques in data analysis: mean, median, frequency, percentage, standard deviation, variance and graphical comparison. "Percentage" and "Frequency" were employed in describing the characteristics of participants' gender, age, years lived in Enugu etc. The central of tendency of the measured air temperature, relative humidity, metabolic rate, clothing insulation and subjective thermal perception votes were described using "Mean" and "Median". The variability of the measure data and units of all the objective thermal variables and the subjective thermal perception votes were described using "Standard Deviation" and "Coefficient of Variation". "Graphical Comparison" was employed in describing the relationship among variables including comparing the collected thermal variables with existing Standards.

Inferential statistical analysis

Inferential statistics, also referred to as inductive statistics, are techniques employed for the purpose of making generalizations or inference about populations based on a sample drawn from the population. The main inferential statistical techniques used in this study included Pearson's Correlation Coefficient and Linear Regression Analysis. These methods have been widely used by researchers in the field of adaptive thermal comfort studies to investigate the interrelationship among subjective thermal perception and thermal indices (de Dear et al., 1997; Humphreys et al., 2007).

4.3.3 Qualitative Methods

According to Groat, the strength of qualitative methodological approach include the capacity to take into account the rich and holistic qualities of circumstances, flexibility in design and procedure process, and sensitivity to meanings and processes of people's activities (Groat & Wang, 2013). The desire to seek to understand the participants' perspective is another reason for the choosing the qualitative method (Bryman, 1988). These advantages of qualitative methods can complement the weaknesses of quantitative methods, vice visa, in the field of thermal comfort studies which involves people and their environment.

Shahzad, Brennan, & Theodossopoulos (2013) demonstrated in their work on the neutral thermal sensation and thermal environmental intention that there is risk of misjudgement associated with quantitative appraisal. Hence, qualitative methodology such as the use of interviews was suggested as a way of reducing the risk of misjudgement of information.

Another value of qualitative research in the field of thermal comfort was highlighted by Healey & Webster-Mannison (2011); qualitative research methods, such as semi-structured interviews employed in this research, are better suited to identifying hidden issues which affect occupants' thermal comfort and satisfaction. These methods also add depth to known issues, details which could be overlooked using measurement and survey instruments alone normally employed in the field of thermal comfort.

Hence, this study combined the qualitative methods with the quantitative approach in order to draw on the strength of both methods. The main choice of data collection employed was the face-to-face interview using semi-structured interviews. The semi-structured interviews were complemented with observations of workers in their work environment.

A. Semi-Structured Interviews

Semi-structured interviews provide a structure and direction to the researcher without taking the rigid approach of the quantitative interview (Harding, 2013). Employing this approach as the main mode of data collection for the qualitative method makes it easy for participants to comment freely on a number of questions prepared by the researcher as a guide.

In semi-structured interviews, the questions only serve as a guide and the researcher might raise the questions in different order. The quality of this interview is a function of how good the listening skills of the researcher is (Roulston, 2010). Hennink et al. (2011), also highlighted a range of settings were interviews are particularly relevant, these include: when examining people's belief and perceptions, when identifying motives for behaviour, when determining the meanings people attach to their experiences, when examining feelings and emotions, when examining the context surrounding people's lives.

In the field of thermal comfort, the use of semi-structured interviews is at it's early stage of application. Healey and Webster-Mannison (2012) tried this approach in their pilot study of thermal comfort of office workers in the warm humid climate of Brisbane, Australia. The findings from the study highlighted the quality of contextual information that can be obtained using this approach. For example, the use of semi-structured interviews were successful in all; allowing themes to emerge unprompted from the responses. The findings that emerged thus provided directions for the research study.

The focus of the semi-structured interviews employed in this study was to find out how the selected participants interviewed feel about how their clothing, and in this case their official clothing, affects their perception of thermal comfort. The questions were also designed to see to what extent they adapt their clothing during working hours to the thermal conditions surrounding their work environment. The following questions guided the interviews administered during the course of the studies.

(i) What do you do when you feel too hot/cold?
(ii) Do you think your clothing affects how hot or cold you feel?
(iii) What usually influences what you wear to work?
(iv) What kind of clothing do you usually put on during working hours for most part of the week?
(v) Do you usually alter your clothing when you feel too hot or too cold?
(vi) Do you support a strict office clothing policy?

For the purpose of comparison with the results of the thermal comfort vote from the thermal comfort questionnaires, the selected participants were asked to describe their thermal feelings at some point during the interview. Using the six-point scale

- very uncomfortable,
- uncomfortable,
- slightly uncomfortable,
- slightly comfortable,
- comfortable or
- very comfortable

adopted in the subjective thermal comfort questionnaire, participants in the semi-structured interviews were asked to rate their thermal feelings.

In selecting participants to be interviewed from among those recruited for this research, consideration was given to having a representation across board. The researcher considered having a representation from each of the six office spaces used for the research. The selection was done so as to have an equal sample of male and female participants. Since each interview section lasted for about 10 to 15 minutes; in selecting the participants, consideration was also given to those participants who will be willing to talk freely for that duration of time. In the end, 18 participants (9 from FRCN and 9 from FRSC) were selected to participate in the interviews section of this research.

The thematic method was the primary approach adopted for the analysis of the results obtained from the interviews. This approach was selected in order to identify the similarity and differences in participants' perception (Harding, 2013).

B. Observations

A non-participant unstructured set of observation were used to complement the semi-structured interviews. The researcher recorded relevant thermal behaviours of the participants in their work setting without taking part in it. The main purpose of the observation was to look for explanation to some of the participants' responses in both the thermal comfort questionnaires and the interviews. This was done at random focusing on different persons at different time throughout the period of this research.

4.3.4 Ethics

The most important ethical factor that guided this research work was confidentiality. It was designed in such a way that participants' anonymity were maintained. In order to achieve this, the same code assigned to participants of the thermal comfort survey were also used in the semi-structured interviews. Using this code, instead of participants' names or different codes, also made it possible to link their thermal comfort vote from the thermal comfort questionnaires with those of the interviews without revealing their identities.

4.4 Summary

The materials, methods, measuring techniques, and data treatments used in this research originally come from those recently employed in the field of adaptive thermal comfort studies in the built environments by the international research communities. One innovative approach that was adopted for this study was the administration of the subjective thermal comfort questionnaires using the longitudinal approach to investigate the local participants' adaptive thermal comfort as opposed to the more typically used one-off 'point-in-time' assessments. Another exploratory method employed was the use of a mixed-methodological approach, a combination of quantitative and qualitative methods in order to understand the local office workers thermal comfort perception and adaptation.

CHAPTER 5

ANALYSIS AND RESULTS

5.1 Introduction

This chapter presents an analysis of the field study research results in five sections. The first covers the general characteristics of samples and office spaces surveyed. This is followed by the analysis of the thermal performance of the office spaces used for the survey. The third section presents the results of the subjective thermal perception votes. It then presents the results of the semi-structured interviews. The final section is the comparison of the results from the participants' subjective thermal comfort vote, obtained from the questionnaires with those of the semi-structured interviews.

5.2 General Characteristics of Samples and Buildings Surveyed

The field surveys were carried out at two different time periods in 2014; in the "dry season" from late January to March and in the "rainy season" from late May to June. The participants of the survey were selected from among office staff of both the Federal Radio Corporation of Nigeria (FRCN) and Federal Road Safety Corps (FRSC) both in Enugu, Nigeria. As discussed in Chapter 4, four buildings (3 from FRCN and 1 from FRSC) were used for the survey. In all, participants were chosen from six typical office spaces (3 from FRCN and 3 from FRSC).

5.2.1 Sample Size and Characteristics

At the initial stage of the survey, 47 staff from both FRCN and FRSC were recruited on a voluntary basis for the survey. However, only 38 (about 80%) of the initial participants completed the longitudinal survey, for both the dry and rainy seasons. A total of 201 valid responses were obtained from 37 participants during the first stage of the survey from late January to March 2014, representing the dry season. From late May to June 2014, representing the rainy season, a total number of 249 valid responses were obtained from 28 participants (27 who took part in during the first stage of the survey and 1 who only took part during the second stage of the survey) during the survey. In all, 450 valid[9] responses were obtained from the field research work. It should be noted that equal number of responses where not obtained from each participants.

Table 5.1 gives a summary of participants' background information on gender, age and the duration of years they have lived in the hot-humid climate conditions of Enugu.

During both stages of the survey, there were slightly more female participants (56.7% during the dry season and 54.2% during the rainy season). Majority of the participants (more than 89%) were below 39 year of age. While about half of the participants had lived in the hot humid climate of Enugu for more than 1 year but less than 5 years.

[9] A total number of 564 questionnaires were administered during the survey periods. About 20% of the administered questionnaires, which is 114, were either invalid or not returned by participants. For any day a participants fails to complete the 3 set of questionnaires for the day, any responses from the participants for that day were rejected.

Table 5.1: Summary of respondents' background information

		Total (n=450)		Dry season (n=201)		Rainy season (n=249)	
		Sample size	Percentage	Sample size	Percentage	Sample size	Percentage
Gender	Male	201	44.7	87	43.3%	114	45.8%
	Female	249	55.3	114	56.7%	135	54.2%
Age (years)	19-29	192	42.7	102	50.7%	90	36.1%
	30-39	210	46.7	78	38.8%	132	53.0%
	40-49	24	5.3	15	7.5%	9	3.6%
	50-59	24	5.3	6	3.0%	18	7.2%
Years in Enugu	<1	36	8.0	18	9.0%	18	7.2%
	1-5	207	46.0	99	49.3%	108	43.4%
	6-10	75	16.7	30	14.9%	45	18.1%
	11-15	12	2.7	3	1.5%	9	3.6%
	>15	90	20.0	39	19.4%	51	20.5%
	Missing	30	6.7	12	6.0%	18	7.2%

5.2.2 Office Spaces and Their Characteristics

A total of six typical office spaces (3 in FRCN and 3 in FRSC) where used for the survey in both seasons. Table 5.2 gives a summary of the spaces surveyed. More than a third of the responses (37.3%) from both survey are from Office Space B located within the FRCN complex. While the number of responses from the three office spaces in FRSC complex where less than ten percent each during the dry season, the responses obtained from those office spaces during the rainy season were higher than ten percent for each space (14.5%, 10.8% and 18.1% for office spaces Da, Db and Dc respectively).

Figure 5.1 to Figure 5.3 represent the comparison of participants' gender, age and years lived in Enugu respectively. With the exception of Office Spaces C and Db, the number of responses received from female participants were higher than those received from male participants. Office Space B has the concentration of those age 29 and below, while those who are age 50 and above are all located in Office Space Da.

Table 5.2: Summary of office spaces used for the survey

	A	B	C	D		
				A	b	C
Location	FRCN	FRCN	FRCN	FRSC	FRSC	FRSC
Office Workplace Typology	ES	OP	OP	ES	ES	OP
Ventilation System	MM	MM	MM	MM	NV	NV
Sample Size (n=450)	72	168	57	51	39	63
Percentage	16.0%	37.3%	12.7%	11.3%	8.7%	14.0%
Dry Season (201)	39	87	30	15	12	18
Percentage	19.4%	43.3%	14.9%	7.5%	6.0%	9.0%
Rainy Season (249)	33	81	27	36	27	45
Percentage	13.3%	32.5%	10.8%	14.5%	10.8%	18.1%

Note: *FRCN (Federal Radio Corporation of Nigeria), FRSC (Federal Road Safety Corps),*
ES (Enclosed Office Space), OP (Open Plan Office Space), MM (Mixed-Mode Ventilated),

NV (Naturally Ventilated)

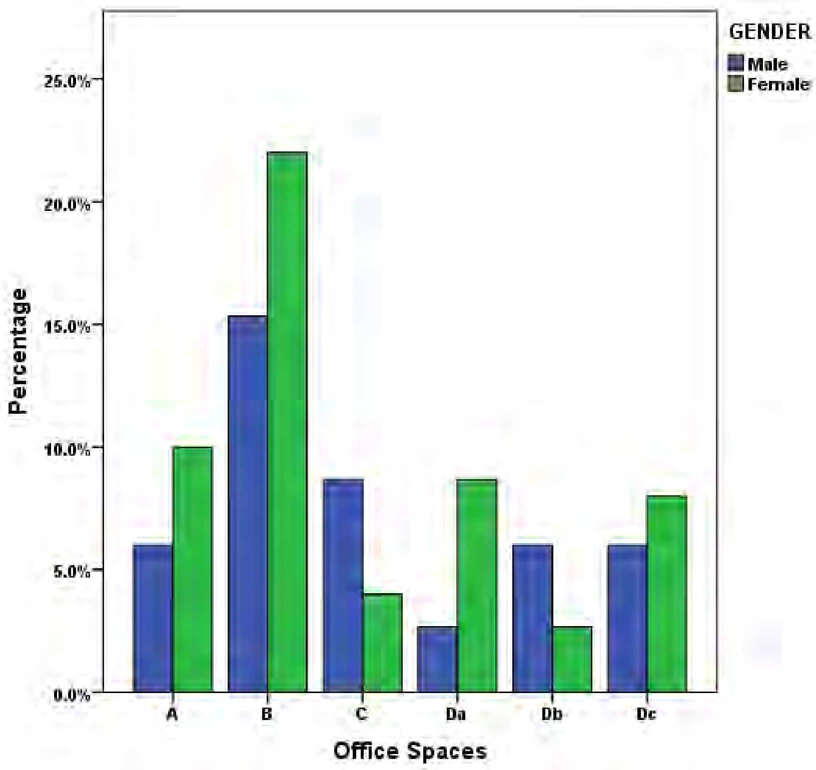


Figure 5.1: Distribution of participants' gender among the office spaces

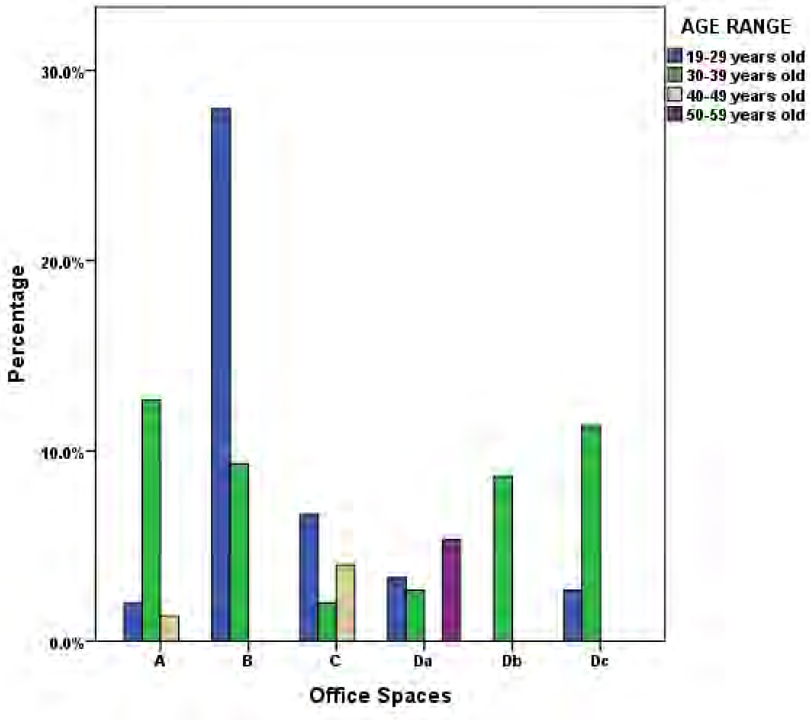


Figure 5.2: Distribution of age of participants among the office spaces

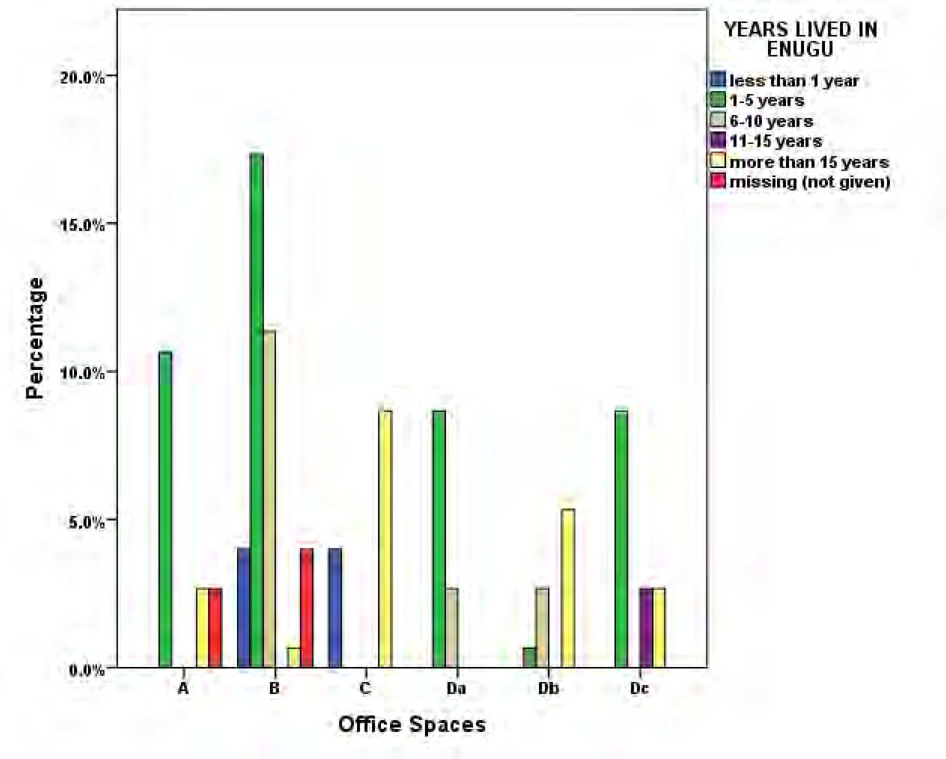


Figure 5.3: Distribution of participants' years lived in Enugu among the office spaces

5.2.3 Metabolic Rates of Participants

During the survey, participants were asked to record their activity level for the past 15 minutes or less (MET_1), for the past 15 to 30 minutes (MET_2) and for the past 30 minutes or more (MET_3). Using Table 2.1 presented in Chapter 2, the corresponding MET units were determined and computed. The statistical summary of the participants' metabolic rate is given in Table 5.3. In each case, the maximum and minimum metabolic rates were 2.1 and 1.0 respectively.

Table 5.3: Summary of participants' metabolic rate

	MET_1	MET_2	MET_3	Average MET
Maximum	2.1	2.1	2.1	2.0
Minimum	1.0	1.0	1.0	1.0
Mean	1.13	1.14	1.15	1.14
Std. Deviation	0.154	0.180	0.193	0.149

As represented in the Figure 5.4, the overall average metabolic rate is 1.14, while the most occurring metabolic rate is 1.1. These complies with the metabolic rates range for ASHRAE Standard 55 adaptive comfort. The ASHRAE adaptive comfort is applicable to spaces where the occupants are engaged near sedentary physical activities with metabolic rates ranges from 1.0 to 1.3 (ASHRAE, 2013a).

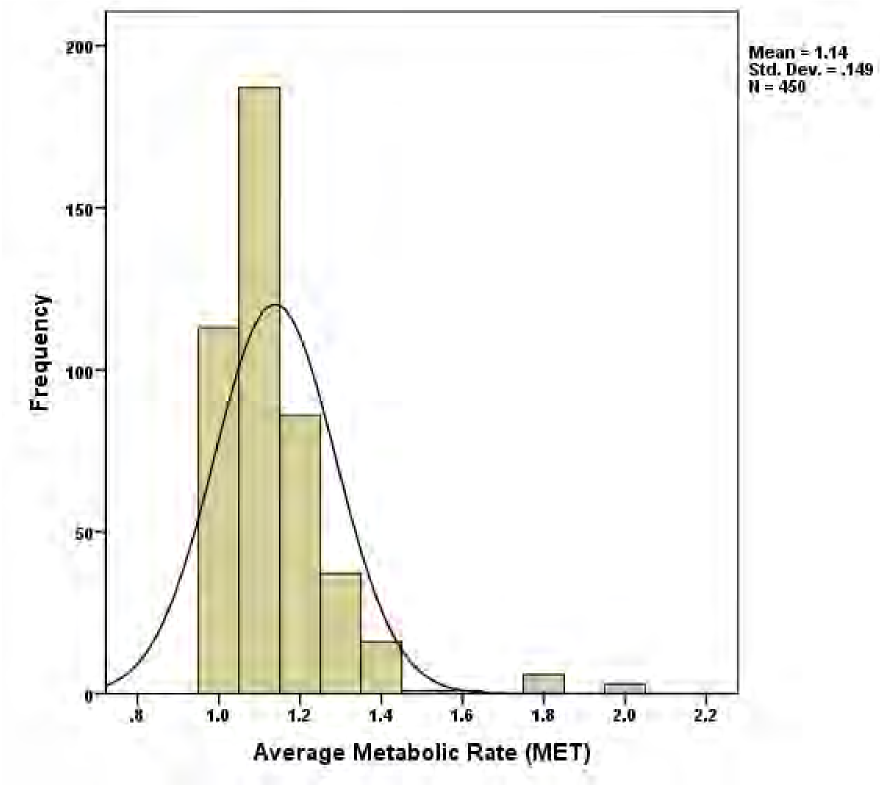


Figure 5.4: Participants' average metabolic rate

5.3.4 Clothing Insulation of Participants

The corresponding clothing insulation values for participants clothing were worked out using the values presented in Table 2.2 as presented in Chapter 2. While the clothing insulation value from participants non-Western clothing were worked out from ASHRAE RP-1504 (Havenith et al., 2013, 2015). Table 5.4 is a statistical summary of participants' clothing insulation and a breakdown according to office clothing policy. The combined average clo for all participants is 0.73. A breakdown of this according to office clothing policy shows that; in FRCN offices where workers have flexible office clothing policy, the average clo is 0.60 with a coefficient of variation of 8.5%. Whereas, for workers in FRSC where staff are expected to put on a specified uniform the average clo is 0.99 with a coefficient of variation of 23.3%.

Table 5.4: Summary of participants clothing insulation (clo)

	Combined clothing insulation (clo)	Clothing insulation for staff of FRCN (Flexible Clothing)	Clothing insulation for staff of FRSC (Strict Uniform)
Number of cases	450	297	153
Maximum	1.14	0.67	1.14
Minimum	0.51	0.51	0.67
Mean	0.73	0.60	0.99
Standard Deviation	0.235	0.051	0.231
Coefficient of variation	0.322	0.085	0.233

A further analysis of the clothing insulation according to the time of the day: morning (before 11am), mid-day (between 11am and 1pm) and afternoon (after 1pm), as shown in Figure 5.5, explains the large variation existing among the clothing insulation values of staff of FRSC. For staff of FRCN, with no strict office clothing policy, the average clo for morning, mid-day and afternoon is the same. However, for staff of FRSC, with a specific office uniform requirement, the average clo for the morning hours is less than 1.0 (0.75). For mid-day and afternoon, the average clo is more than 1.0 (1.12).

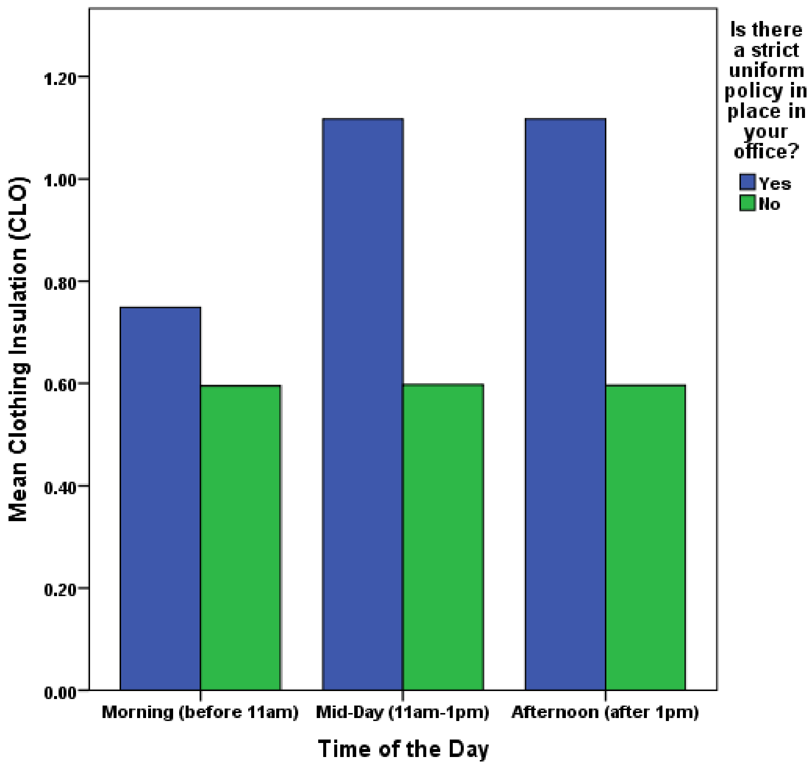


Figure 5.5: Comparison of clothing insulation of staff of FRCN and FRSC according to the time of the day

A. Participants dressing habits as observed

Figure 5.6 shows the samples of clothing that is worn by both staff of FRCN and FRSC. For staff of FRCN, with no specified uniform clothing, there is a wide arrays of clothing choice that allows them to adapt their clothing to suit their comfort. For staff of FRSC, the official uniform clothing does not allow the staff to adapt their clothing during a typical work day.

However, it was observed that the majority of the participants from FRSC go to work in personal clothing and only later change to the official uniform before the late morning hours or mid-day. The change to official uniform happens before senior officers appear in the office and check that uniforms are being worn by junior staff. Due to ethical reasons, there are no detailed photographs to show this as participants did not wish to be photographed. However, Figure 5.7 gives an example of what they use in bringing different cloths to work.

Figure 5.6: Typical examples of clothing worn by staff of FRCN (left) and FRSC (right)

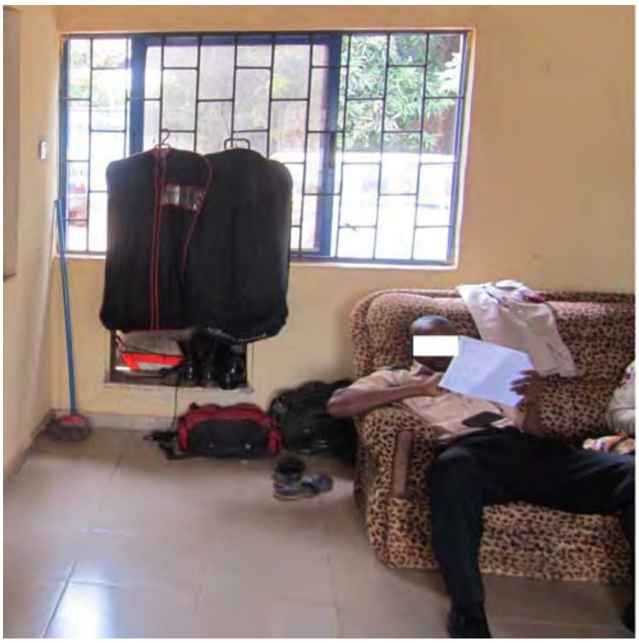


Figure 5.7: Typical example of what staff of FRSC use in bringing different cloths to the office

5.3 Thermal Performance of Office Spaces

5.3.1 Measured Indoor Thermal Variables

During the course of the field work, the indoor air temperature and the relative humidity were measured in the office spaces used for the survey. The data loggers were placed within 1 meter away from the participants' workstation, away from direct sunlight, to record both the indoor operative temperature and relative humidity at every 15 minutes interval. Table 5.5 and 5.6 are statistical summary of the measured indoor operative temperature and relative humidity during the period of the survey. While Figure 5.8 and Figure 5.9 are samples of graphical comparison of data from loggers for temperature and relative humidity respectively.

The overall mean operative temperature for the periods of the survey is 28.5^{0}C with a standard deviation of 1.75K. For the dry season, the mean temperature was 29.4^{0}C and the standard deviation was 1.75K. While during the rainy season, the mean temperature and the standard deviation are 27.7^{0}C and 1.36K respectively.

The combined difference in the mean operative temperature for all the office spaces surveyed during the dry and rainy season is 1.7^{0}C. A comparison of the coefficient of variation of operative temperature for all the spaces surveyed shows a close similarity in temperature variation in all the spaces. The range of the coefficient of variation of operative temperature for all the office spaces is 1.8%.

The mean relative humidity for the dry season was 50.7% with a coefficient of variation of 1.56%. While that of the mean relative humidity and coefficient of variation of the rainy season is 66.6% and 1.38% respectively.

A hand-held instrument, Kestrel 3000 Pocket Wind Meter, was used to measure air velocity at different instances during the field work. The maximum air velocity recorded for all the office spaces surveyed did not exceed 0.3m/s.

Table 5.5: Statistical summary of indoor operative temperature

Office Space	Season	Max (^{0}C)	Min (^{0}C)	Mean (^{0}C)	Std. Dev (^{0}C)	Coefficient of variation
A	Dry	30.8	26.1	28.4	1.31	0.046
	Rainy	29.1	24.8	27.1	1.20	0.044
	Combined	30.8	24.8	27.8	1.42	0.051
B	Dry	31.2	25.8	28.8	1.70	0.059
	Rainy	30.9	25.7	27.0	0.94	0.035
	Combined	31.2	25.7	28.0	1.64	0.059
C	Dry	31.9	28.7	30.4	0.98	0.032
	Rainy	31.3	24.4	28.5	1.68	0.059
	Combined	31.9	24.4	29.5	1.64	0.056
Da	Dry	31.8	28.0	30.1	1.64	0.054
	Rainy	30.7	26.9	28.4	0.89	0.031
	Combined	31.8	26.9	28.9	1.40	0.048
Db	Dry	32.4	27.6	31.1	1.47	0.047
	Rainy	30.6	26.1	28.6	1.51	0.053
	Combined	32.4	26.1	29.4	1.88	0.064
Dc	Dry	32.0	28.4	30.8	1.38	0.045
	Rainy	30.7	25.7	27.9	1.36	0.049
	Combined	32.0	25.7	28.7	1.90	0.066
Total	Dry	32.4	25.8	29.4	1.75	0.060
	Rainy	31.3	24.4	27.7	1.36	0.049
	Combined	32.4	24.4	28.5	1.75	0.061

Table 5.6: Statistical summary of indoor relative humidity

Office Space	Season	Max (%)	Min (%)	Mean (%)	Std. Dev (%)	Coefficient of variation
A	Dry	55.8	47.2	51.9	2.05	0.039
	Rainy	79.7	52.2	64.8	9.22	0.142
	Combined	79.7	47.2	57.8	9.09	0.157
B	Dry	53.6	41.9	45.4	3.73	0.082
	Rainy	82.7	52.2	62.5	6.95	0.111
	Combined	82.7	41.9	53.7	10.17	0.189
C	Dry	73.5	46.2	60.2	7.10	0.118
	Rainy	83.7	49.2	63.0	10.16	0.161
	Combined	83.7	46.2	61.5	8.73	0.142
Da	Dry	59.4	40.4	47.2	8.95	0.190
	Rainy	82.5	67.3	76.0	3.40	0.045
	Combined	82.5	40.4	67.5	14.37	0.213
Db	Dry	64.2	57.9	61.2	2.57	0.042
	Rainy	76.8	44.4	66.1	6.96	0.105
	Combined	76.8	44.4	64.6	6.35	0.098
Dc	Dry	64.2	40.2	54.0	9.77	0.181
	Rainy	82.0	45.9	70.3	9.85	0.140
	Combined	82.0	40.2	65.6	12.25	0.187
Total	Dry	73.5	40.2	50.7	7.91	0.156
	Rainy	83.7	44.4	66.6	9.16	0.138
	Combined	83.7	40.2	59.5	11.69	0.196

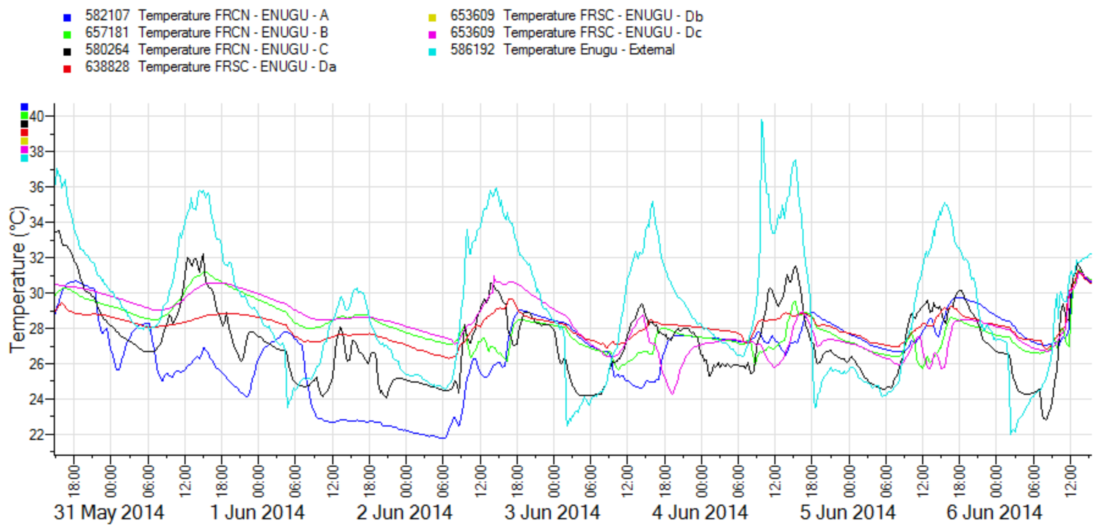


Figure 5.8: Sample of graphical presentation of temperature data from loggers

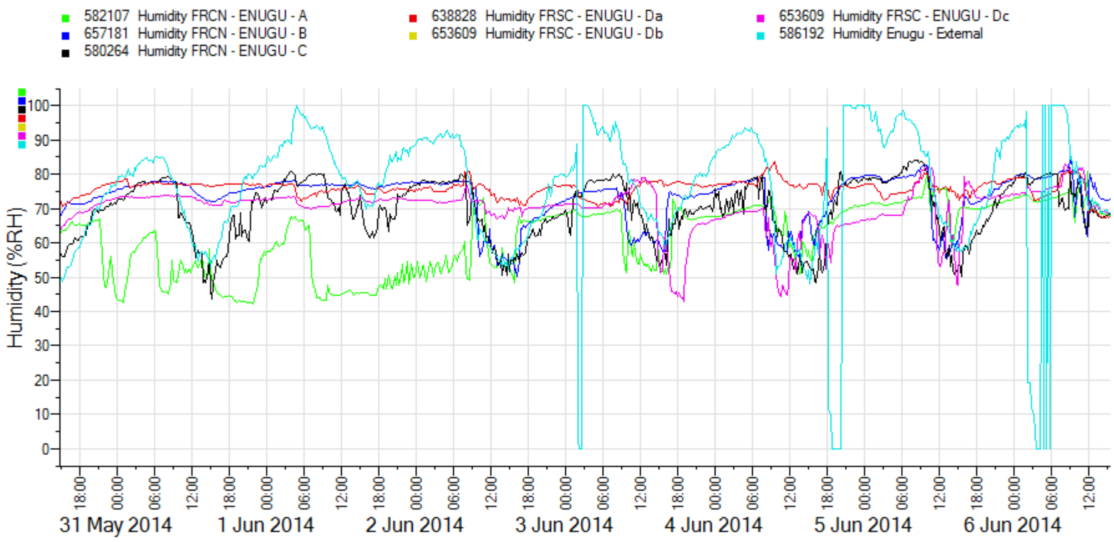


Figure 5.9: Sample of graphical presentation of humidity data from loggers

5.3.2 Environmental Comparison Between Indoor and Outdoor Measured Thermal Variable

Table 5.7 and Table 5.8 show the result of Paired-Samples T Test and Bivariate Correlation testing of the indoor and outdoor temperature and absolute humidity for all the spaces surveyed. The combined out door mean air temperature is 4.7K higher than the indoor operative temperature. While the difference between the combined outdoor absolute humidity and the indoor absolute humidity is 5.4g/m^3. For all the office spaces surveyed, the indoor operative temperature were lower than the corresponding outdoor temperature. However, with the exception of Office Spaces A and B, the indoor relative humidity were slightly higher than the corresponding outdoor relative humidity.

The comparisons of measured indoor and outdoor thermal variables show that the indoor environment were correlated with the outdoor thermal environments. With exception of the naturally ventilated office spaces where the significant of the correlation between indoor and outdoor air temperature were 0.05, all the mixed-mode ventilated spaces have a correlation significant of 0.01. The correlation significant for the absolute humidity for all the surveyed office spaces, with the exception of Office Spaces Da and Db, were also 0.01.

Table 5.7: Paired-Samples T Test and Bivariate Correlations testing between indoor operative temperature and outdoor temperature

	Office Spaces						
	Combined	**A**	**B**	**C**	**Da**	**Db**	**Dc**
Sample Size	450	72	168	57	51	39	63
Mean Indoor Temperature (^{0}C)	28.5	27.8	28.0	29.5	28.9	29.4	28.7
Mean Outdoor Temperature (^{0}C)	33.2	33.3	33.1	33.3	33.0	33.4	33.1
Differences in Mean	-4.7	-5.5	-5.1	-3.8	-4.1	-4.0	-4.4
Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pearson Correlations	0.520	0.502	0.680	0.774	0.577	0.397	0.253
Correlations Sig.	0.000	0.000	0.000	0.000	0.000	0.012	0.046

Table 5.8: Paired-Samples T Test and Bivariate Correlations testing between indoor absolute humidity and outdoor absolute humidity

	Office Spaces						
	Combined	**A**	**B**	**C**	**Da**	**Db**	**Dc**
Sample Size	450	72	168	57	51	39	63
Mean Indoor Absolute Humidity (g/m^3)	16.6	15.5	14.6	18.2	19.3	19.0	18.6
Mean Outdoor Absolute Humidity (g/m^3)	22.0	21.9	21.5	21.8	22.6	22.0	22.6
Differences in Mean	-5.4	-6.4	-6.9	-3.6	-3.3	-3.0	-4.0
Sig. (2-tailed)	0.008	0.068	0.000	0.219	0.053	0.016	0.081
Pearson Correlations	0.496	0.508	0.593	0.782	0.349	0.359	0.468
Correlations Sig.	0.000	0.000	0.000	0.000	0.012	0.025	0.000

5.3.3 Comparison With ASHRAE Standard 55 Adaptive Comfort

In order to compare the buildings' thermal performances with ASHRAE Standard 55 adaptive comfort, the prevailing weekly mean outdoor temperature from the loggers were plotted against the corresponding daily mean indoor operative temperature for office spaces used for the survey in FRCN and FRSC complexes. As shown in Figure 5.10 and Figure 5.11, these were compared with the 80% and 90% acceptable comfort ranges of the ASHRAE Standard 55-2013 adaptive comfort model (ASHRAE, 2013a). The results from the comparisons show that all the office spaces surveyed comply with the ASHRAE Standard 55 adaptive comfort standard.

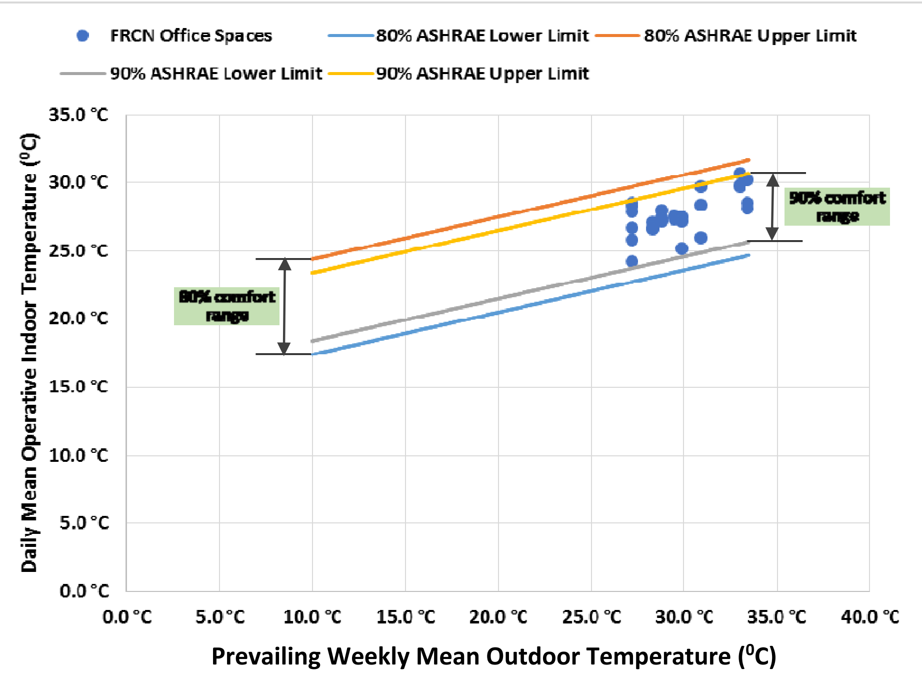


Figure 5.10: Daily mean indoor operative temperature for Office Spaces in FRCN Complex plotted against the prevailing weekly mean outdoor temperature and overlaid with the adaptive model of ASHRAE Standard 55-2013

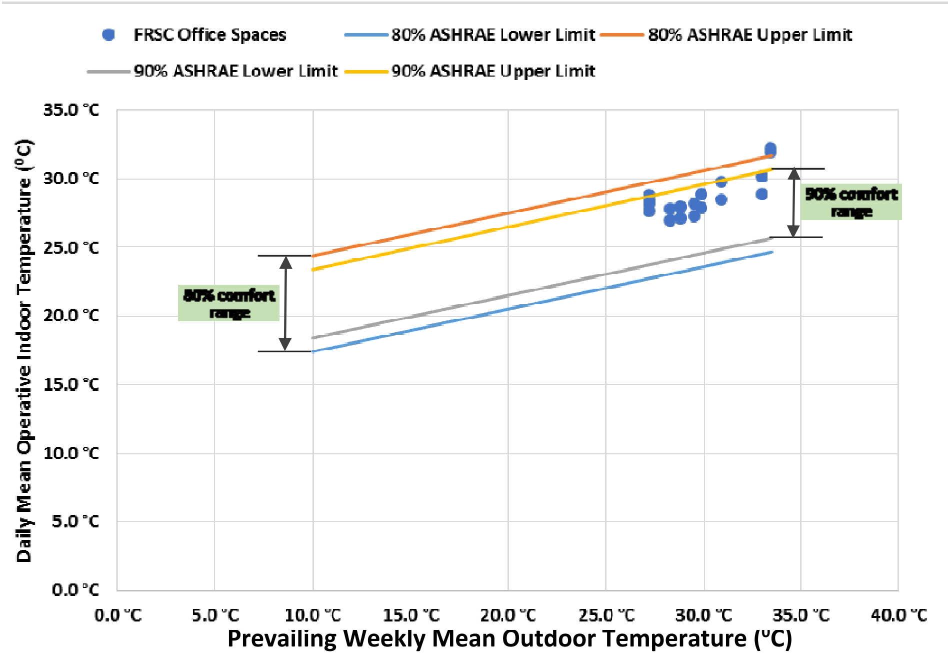


Figure 5.11: Daily mean indoor operative temperature for Office Spaces in FRSC complex plotted against the prevailing weekly mean outdoor temperature and overlaid with the adaptive model of ASHRAE Standard 55-2013

As shown in Figure 5.12 and Figure 5.13, the few points in Figure 5.11 that were outside the 80% adaptive comfort ranges of ASHRAE Standard 55-2013 were further analysed using the Center for the Built Environment Thermal Comfort Tool, an online thermal comfort analysis tool for ASHRAE Standard 55 (Hoyt, Schiavon, Piccioli, Moon, & Steinfeld, 2013). The results indicated that with an air velocity of 0.6m/s, all the office spaces in FRSC complex will comply with the ASHRAE Standard 55 adaptive comfort standard.

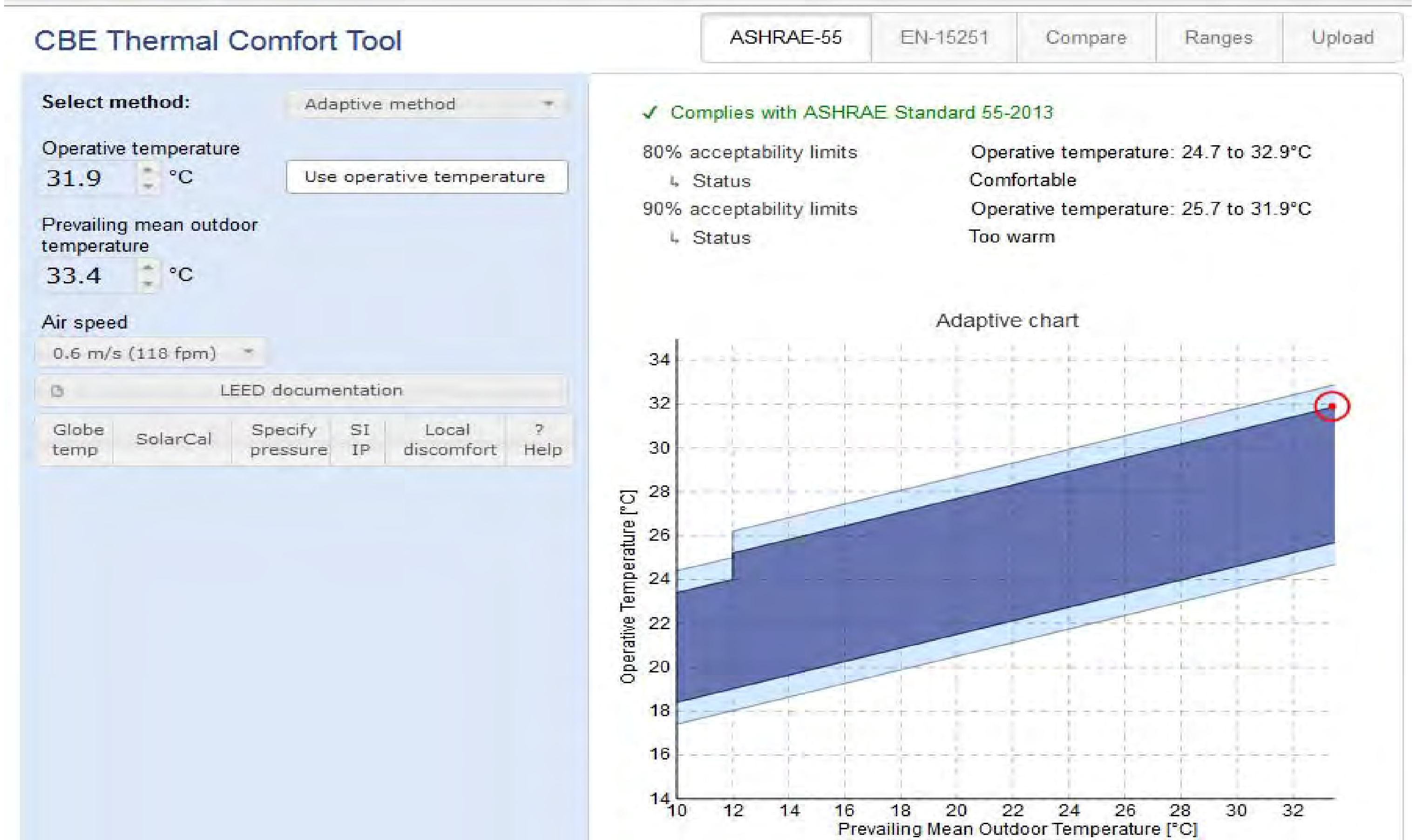


Figure 5.12: Analysis of extreme points from Office Spaces in FRSC Complex with CBE Thermal Comfort Tool at an air velocity of 0.6m/s

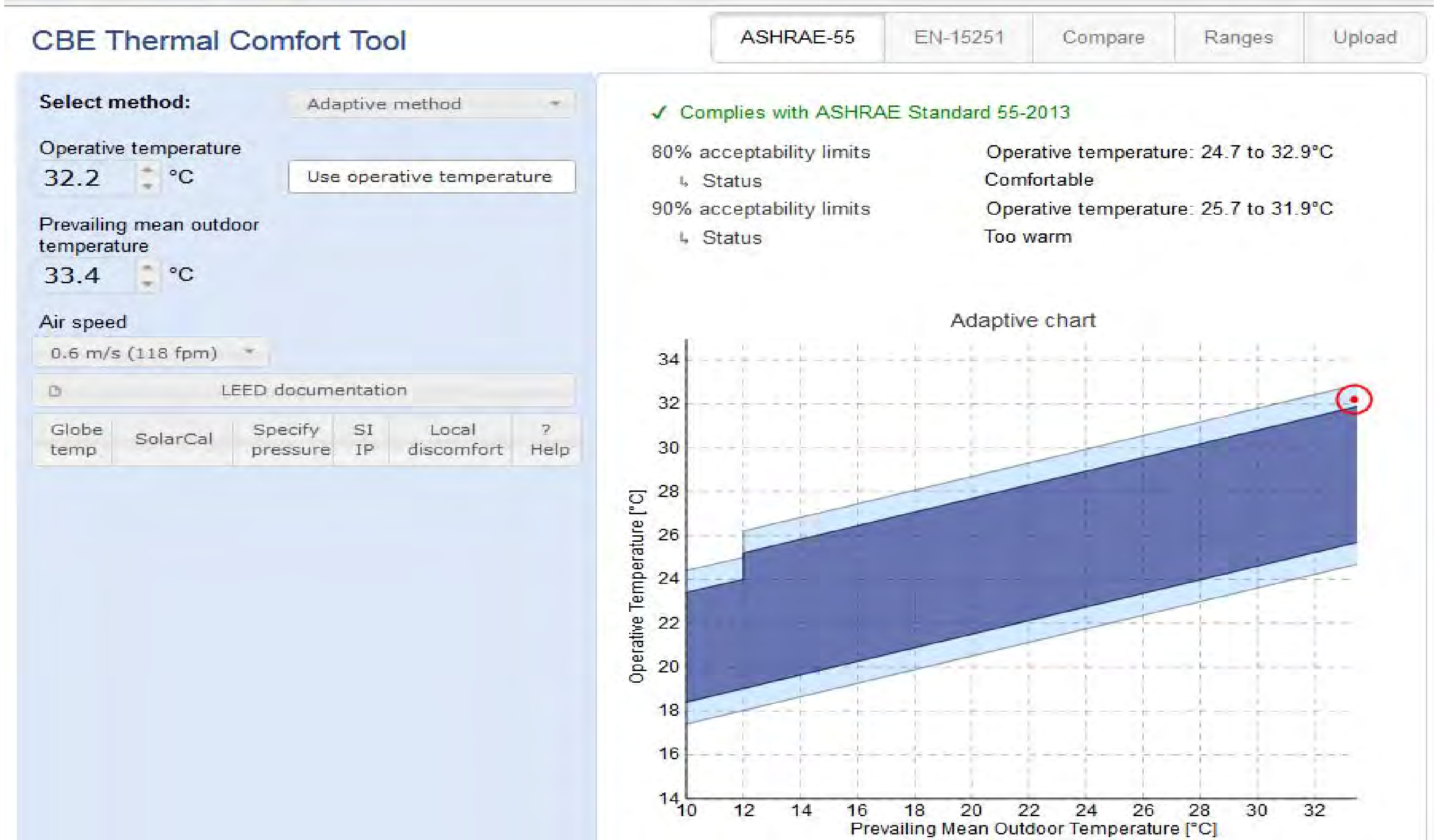


Figure 5.13: Analysis of extreme points from Office Spaces in FRSC Complex with CBE Thermal Comfort Tool at an air velocity of 0.6m/s

5.3.4 Comparison With CEN/EN-15251 Adaptive Comfort

In order to compare the buildings' thermal performances with EN-15251 adaptive comfort standard, the prevailing weekly mean outdoor temperature from the loggers were plotted against the corresponding daily mean indoor operative temperature for office spaces in FRCN and FRSC complexes that were used for the survey. These were compared with Class II and Class III acceptable comfort ranges of CEN/EN-15251-2007 adaptive comfort model (CEN, 2007).

As shown in Figure 5.14 and Figure 5.15, about half of the points were outside the Class II and Class III acceptable comfort limits of CEN/EN-15251 adaptive comfort.

This results indicated that the office spaces surveyed did not comply with CEN/EN-15251 adaptive comfort standard.

Prevailing Weekly Mean Outdoor Temperature (^{0}C)

Figure 5.14: Daily mean indoor operative temperature for Office Spaces in FRCN Complex plotted against the prevailing weekly mean outdoor temperature and overlaid with the adaptive model of CEN/EN-15251-2007

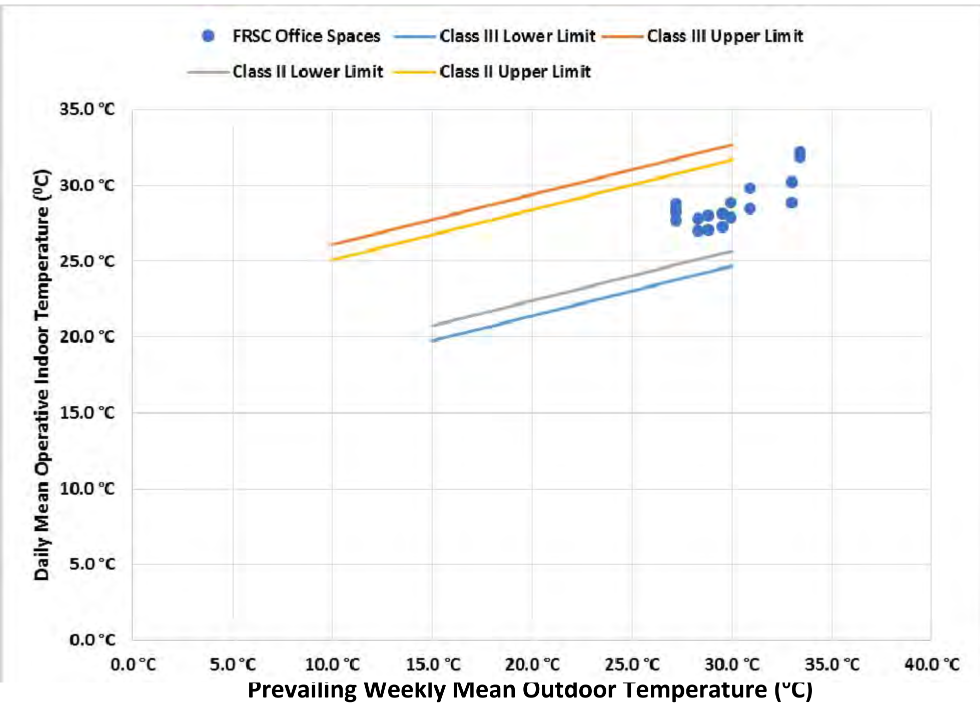


Figure 5.15: Daily mean indoor operative temperature for Office Spaces in FRSC Complex plotted against the prevailing weekly mean outdoor temperature and overlaid with the adaptive model of CEN/EN-15251-2007

5.4 Subjective Thermal Perception and Thermal Discomfort

The administered questionnaire measured three components of the participants' subjective thermal perception. These include thermal comfort (COMF), thermal sensation (TSENS) and thermal preference (TPREF). Table 5.9 contains a statistical summary of the combined participants' subjective thermal perception votes for all the buildings surveyed. Additionally, the part of the body where participants experience the most discomfort were also recorded.

Table 5.9: Summary of participants' thermal perception votes

	N	Min	Max	Mean	Std. Deviation
COMF	450	1.0	6.0	4.26	1.384
TSENS	450	-3.0	3.0	-0.08	1.793
TPREF	450	-3.0	2.0	-1.44	0.886

5.4.1 Thermal Comfort (COMF)

In order to distinguish the overall comfort satisfaction of participants from their thermal sensation, a six-point thermal comfort scale (1=very uncomfortable, 2=uncomfortable, 3=somewhat uncomfortable, 4=somewhat comfortable, 5=comfortable, and 6=very comfortable) question was used to get a broader picture of the subjective thermal condition of the participants.

As can be seen in Table 5.9, the statistical summary of thermal comfort votes indicated that the mean general comfort was between "somewhat comfortable" and "comfortable" with a mean value of 4.26 for all office spaces surveyed. A breakdown of the percentage distribution of the thermal comfort vote for each of the office spaces surveyed can be seen in Figure 5.16. Except for office spaces Db and Dc, the percentage of participants who voted "somewhat comfortable" and "comfortable" were more than 50% in each case (51.4% in A, 66.1% in B, 68.4% in C, 84.3% in Da, 38.4% in Db and 36.5% in Dc).

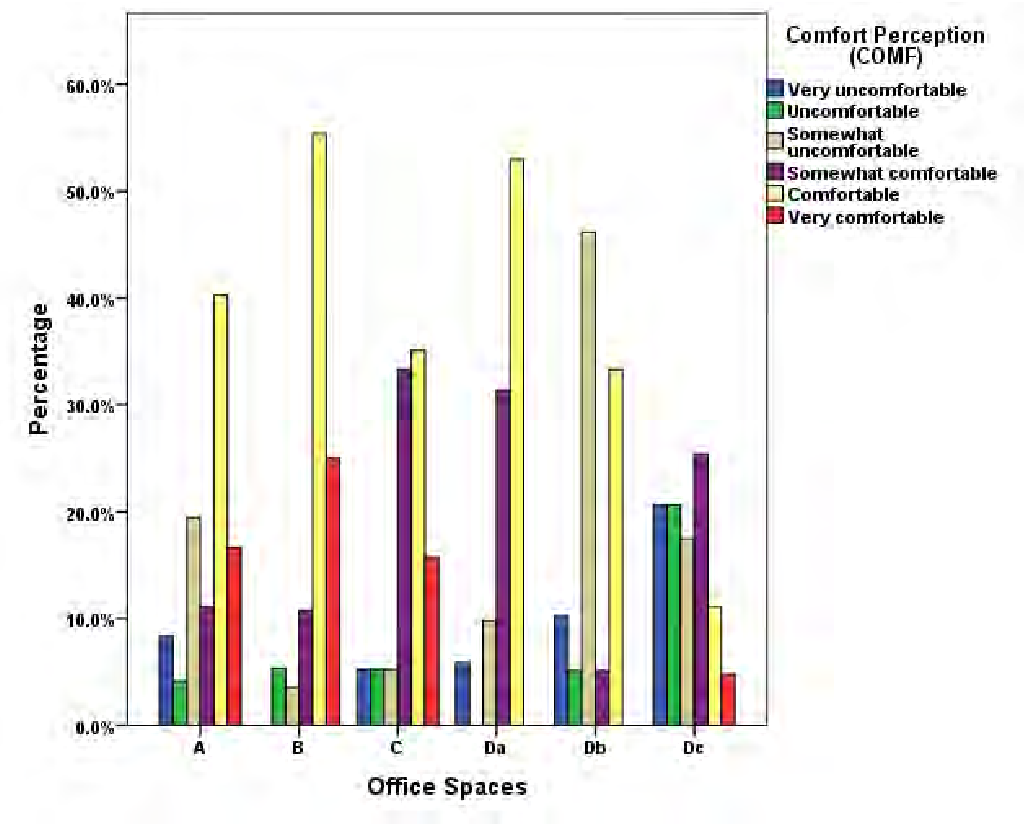


Figure 5.16: Percentage distribution of thermal comfort votes for each of the office spaces

A. *Distribution of thermal comfort according to time of the day*

Figure 5.17 categorised the thermal comfort responses according to time of the day. Three categories, corresponding to the three different time of the day the thermal comfort questionnaires were administered to each participants, were adopted for this analysis: morning (before 11am), mid-day (between 11am and 1pm) and afternoon (after 1pm). About 88% of the participants voted either "somewhat comfortable", "comfortable" or "very comfortable". For mid-day and afternoon, the percentages were less than 80% but more than 70%.

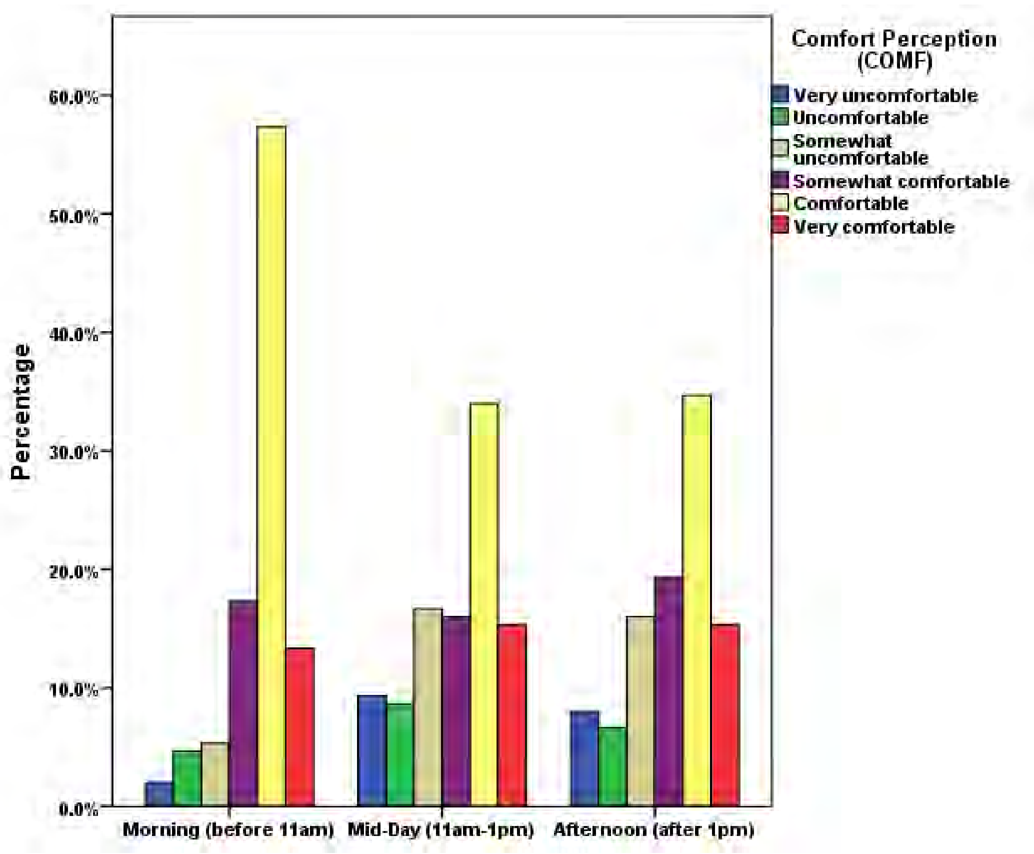


Figure 5.17: Percentage distribution of thermal comfort perception votes according to time of the day

B. Distribution of thermal comfort according to office workplace typologies

The thermal comfort votes were further categorised according to the office workplace typologies. Two categories of office spaces, enclosed space (ES) and open plan (OP), were used for the survey. As shown in Figure 5.18, while more than two-third of the participants voted either “somewhat comfortable”, “comfortable” or “very comfortable” in both enclosed office spaces and open plan office spaces, the percentage was higher for participants in open plan office spaces (66.05% for ES and 78.82% for OP)

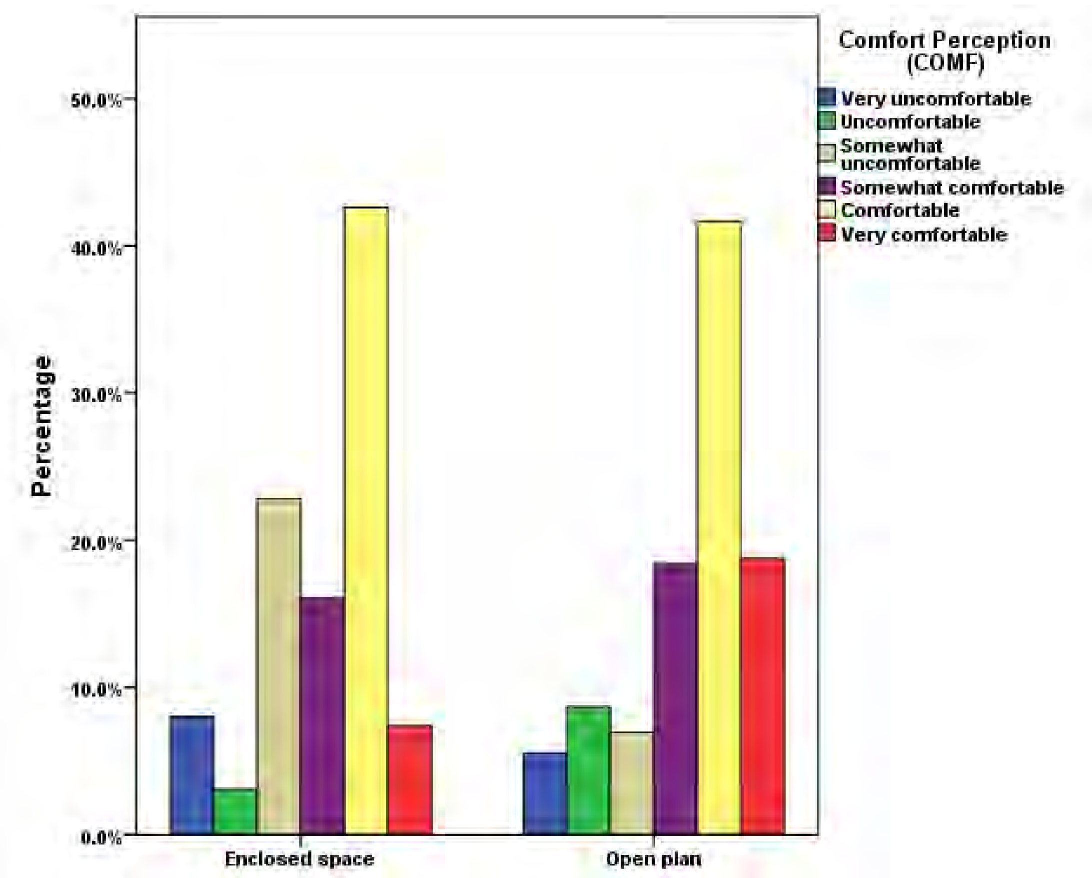


Figure 5.18: Percentage distribution of thermal comfort perception votes according to office workplace typologies

C. Distribution of thermal comfort according to office ventilation systems

The subjective thermal comfort votes were also categorised according to office ventilation systems. As discussed in Chapters 3 and 4, the office spaces surveyed fall into two categories: either mixed-mode ventilation (MM) or naturally ventilated (NV) office spaces. As illustrated in Figure 5.19, less than 50% of the participants in naturally ventilated office spaces voted either "somewhat comfortable", "comfortable" or "very comfortable" in naturally ventilated office spaces. The percentage for mixed-mode office spaces was about 85%. It should also be noted that of the six office spaces used for the survey, all but office space Db and Dc, were operating in mixed-mode ventilation system.

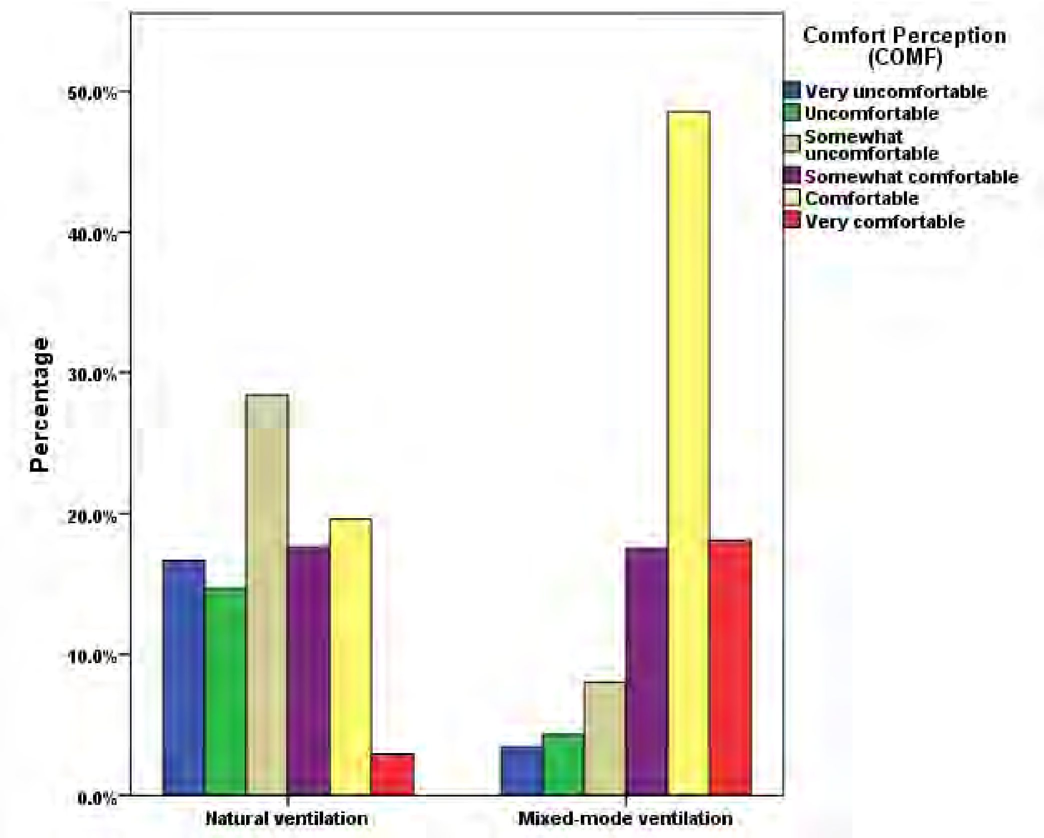


Figure 5.19: Percentage distribution of thermal comfort perception votes according to office ventilation systems

D. Distribution of thermal comfort according to office clothing policy

Figure 5.20 shows the distribution of participants thermal comfort votes with respect to the clothing policies. Participants were categorised into two different categories: workers with strict office clothing or uniform policy and workers with flexible office clothing policy. The analysis shows that only about 55% of participants with strict clothing or uniform policy voted either "somewhat comfortable", "comfortable" or "very comfortable". However, the percentage was about 85% for participants with flexible clothing policy.

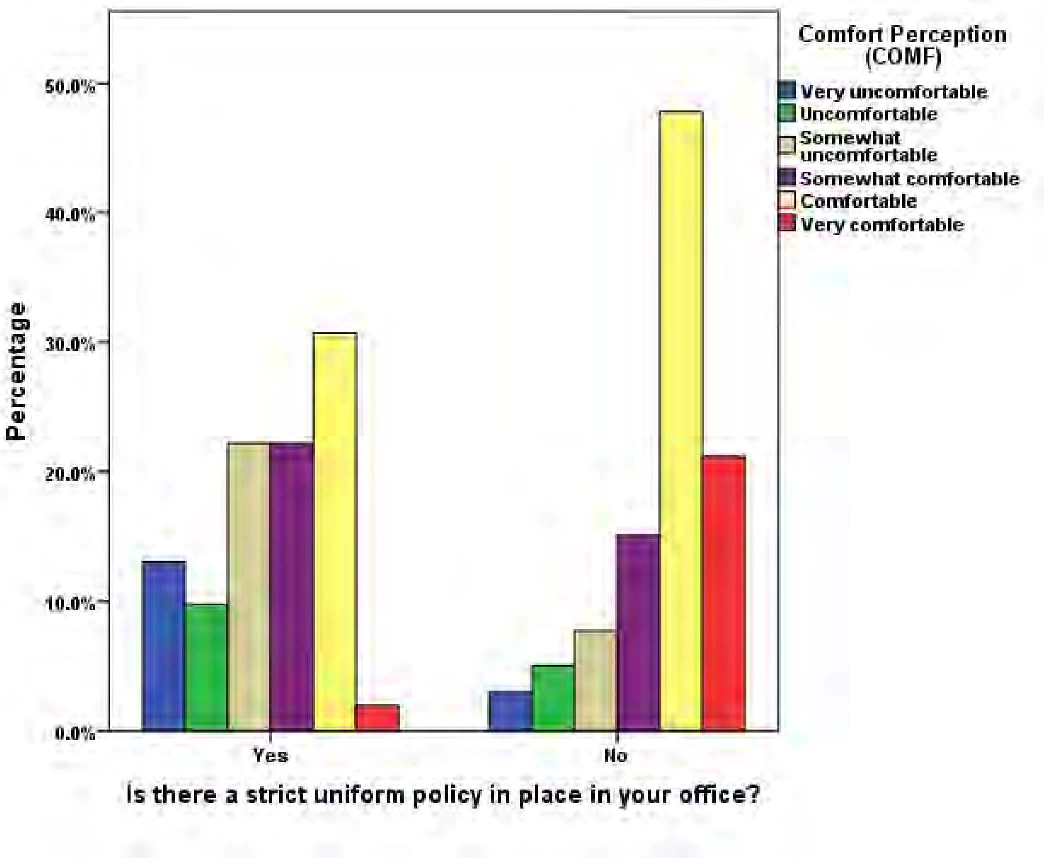


Figure 5.20: Percentage distribution of thermal comfort perception votes according to clothing policy

The thermal comfort perception votes were further analysed according to time of the day (morning, mid-day and afternoon) for workers with strict clothing policy and for workers with flexible clothing policy.

Figure 5.21 shows the result of the further analysis of the thermal comfort votes of participants with strict clothing policy according to time of the day. The result shows that more than 90% of participants voted either "somewhat comfortable", "comfortable" or "very comfortable" during the morning hours. This is in sharp contrast with the less than 40% (37.26) who voted same during mid-day and afternoon hours. It was also noted that none of the participant voted "very comfortable" at mid-day and afternoon hours.

Whereas, as shown in Figure 5.22, the percentage of participants who voted "somewhat comfortable", "comfortable" or "very comfortable" for offices with flexible clothing policy were almost the same throughout the day. The percentage was 86.87% for morning hours, 79.79% for mid-day and 85.85% for afternoon.

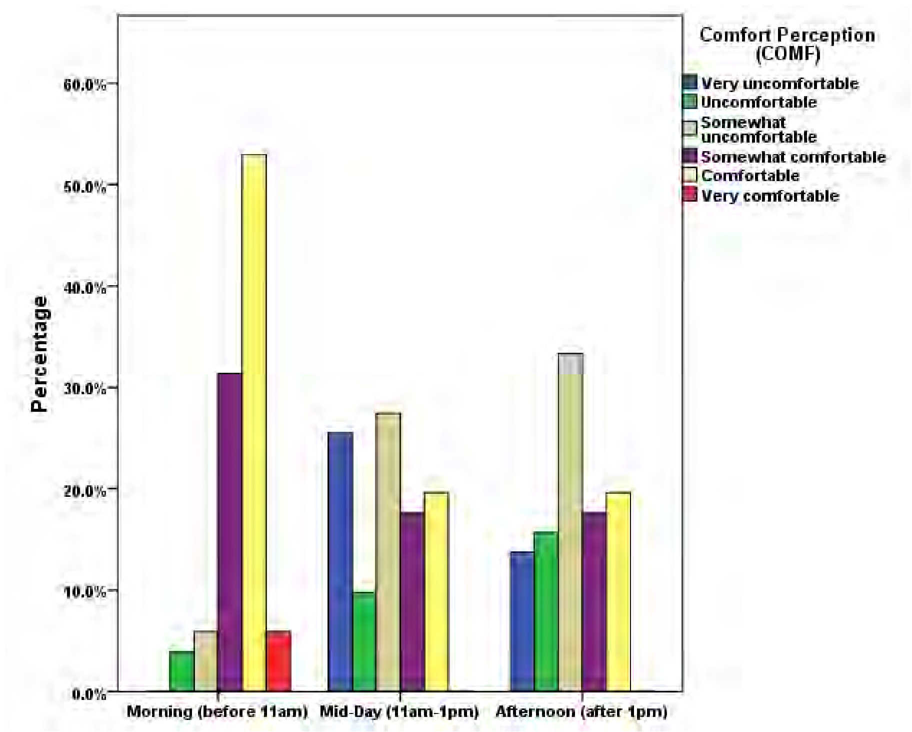


Figure 5.21: Percentage distribution of thermal comfort perception votes according to the time of the day for offices with strict clothing policy

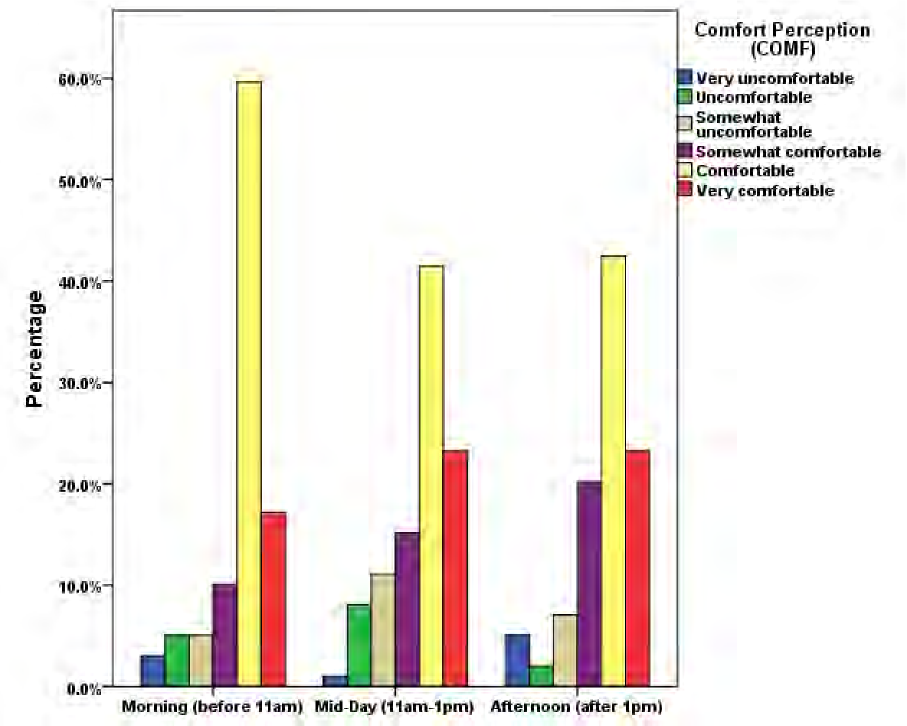


Figure 5.22: Percentage distribution of thermal comfort perception votes according to the time of the day for offices with flexible clothing policy

E. Summary of percentage of thermal comfort votes

Table 5.10 shows a summary of percentage of participants who voted that they were comfortable and uncomfortable. Where 'comfortable' is define as "somewhat comfortable", "comfortable" and "very comfortable". On the other hand, 'uncomfortable' corresponds to "somewhat uncomfortable", "uncomfortable" and "very uncomfortable".

More than 75% of participants in mixed mode, open plan offices and offices with flexible clothing policy voted that they were comfortable with the thermal conditions surrounding their work environment. Whereas, more than 50% in naturally ventilated office spaces and more than 40% in office spaces with strict uniform policy voted that they were uncomfortable. A detailed discussion of the implication of this thermal comfort vote is presented in Chapter 6.

Table 5.10: Summary of percentage of comfortable votes

<table>
<tr><th colspan="2"></th><th>% Comfortable</th><th>% Uncomfortable</th></tr>
<tr><td colspan="2">Combined votes for all participants</td><td>74.23</td><td>25.77</td></tr>
<tr><td rowspan="2">According to ventilation systems</td><td>Naturally ventilated</td><td>40.20</td><td>59.80</td></tr>
<tr><td>Mixed-mode ventilation</td><td>84.19</td><td>15.81</td></tr>
<tr><td rowspan="2">According to office workplace typologies</td><td>Enclosed space</td><td>66.05</td><td>33.95</td></tr>
<tr><td>Open plan</td><td>78.82</td><td>21.18</td></tr>
<tr><td rowspan="2">According to office clothing policy</td><td>Strict dress code</td><td>54.90</td><td>45.10</td></tr>
<tr><td>Flexible clothing</td><td>84.17</td><td>15.83</td></tr>
</table>

5.4.2 Thermal Sensation (TSENS)

In order to determine the subjective thermal sensation (TSENS) of the participants, the questionnaire adopted the ASHRAE seven-point thermal sensation scale (-3=Cold, -2=Cool, -1=Slightly cool, 0=Neutral, 1=Slightly warm, 2=Warm, 3=Hot). Participants were allowed to select all the options that apply and the resulting mean from options selected was used to determine the participants vote. This same method was applied to thermal preference (TPREF) vote.

As shown in Table 5.9, the mean TSENS vote for all participants in the survey was slightly below “Neutral”, between “Slightly cool” and “Neutral” with a value of -0.08. Figure 5.23 to Figure 5.26 show the distribution of mean TSENS according to time of the day, office workplace typology, office ventilation system, and office clothing policy accordingly. In each case, the mean TSENS vote as well as the 80% upper and lower limits of acceptable comfort range of ASHRAE Standard 55 were shown with reference lines.

The breakdown of the mean TSENS votes show that the median votes during mid-day, afternoon hours, of participants in enclosed office spaces fall within the 80% comfort range. The median votes during the morning hours, of participants in mixed-mode ventilated office spaces and that of participants with flexible clothing policy were slightly below the lower limit, participants having cooler sensation with a median vote of 1.0 on the ASHRAE thermal sensation scale. With a median vote of 2.0 on the ASHRAE thermal sensation scale, participants in naturally ventilated spaces and those with strict clothing policy voted that they were much warmer compared to the group mean TSENS vote.

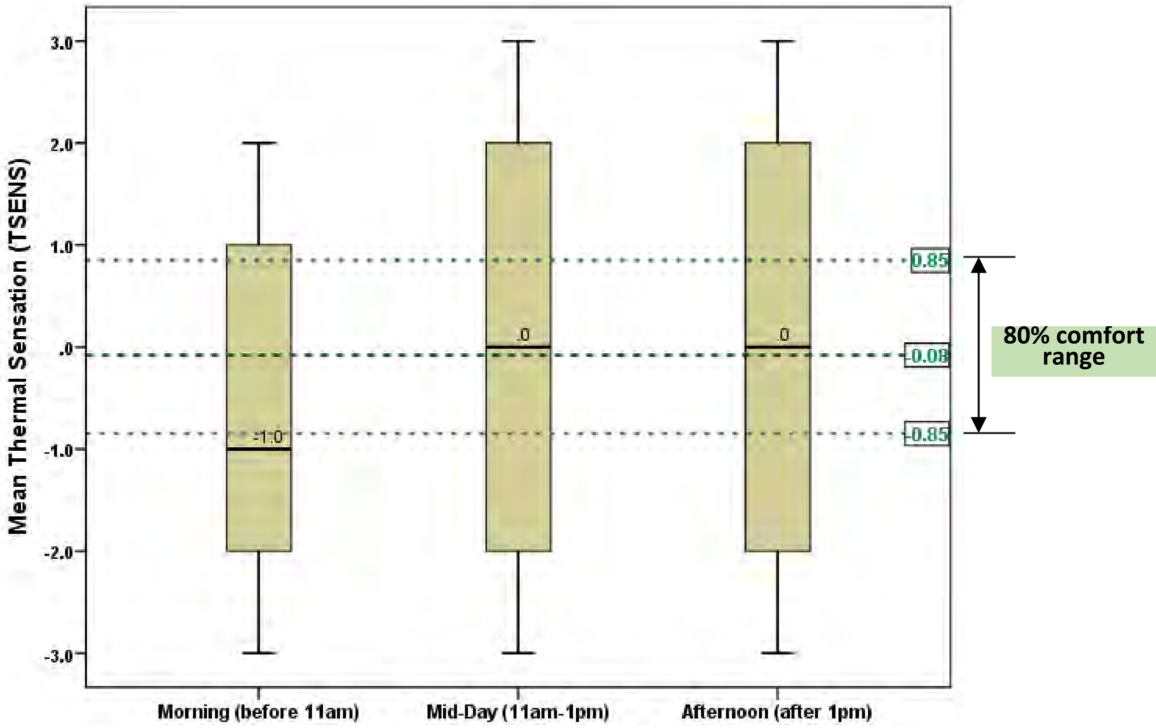


Figure 5.23: Distribution of mean TSENS according to time of the day

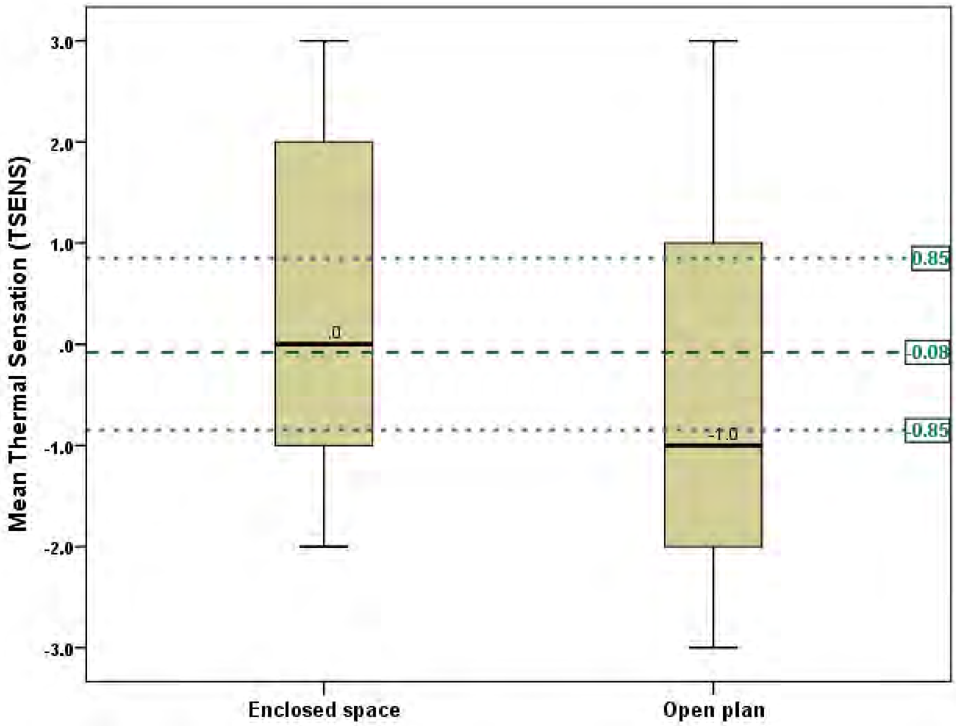


Figure 5.24: Distribution of mean TSENS according to office workplace typologies

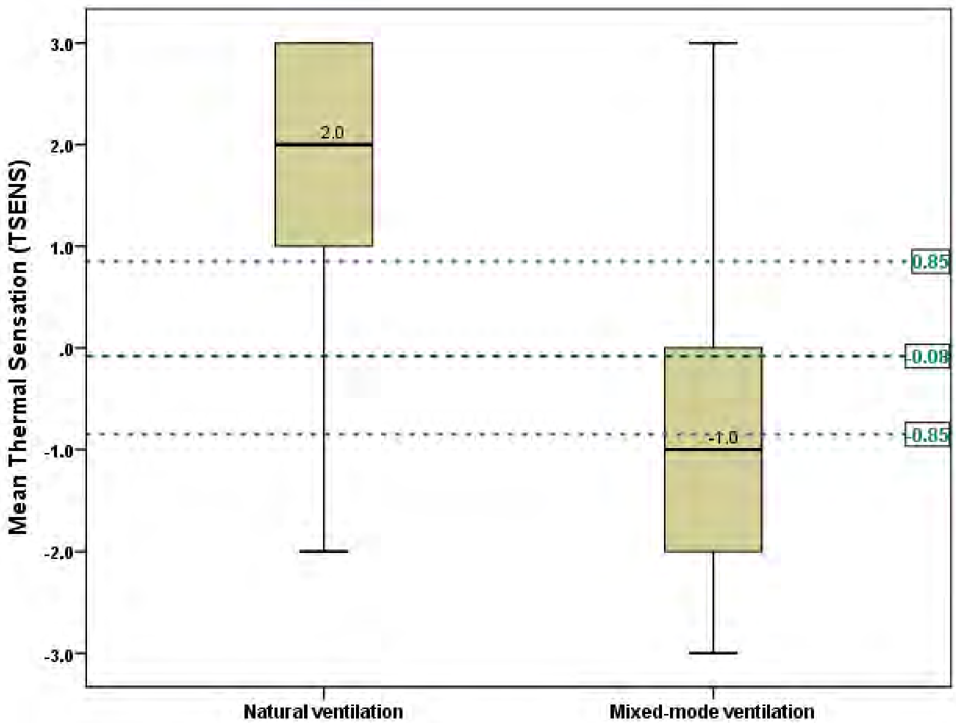


Figure 5.25: Distribution of mean TSENS according to office ventilation systems

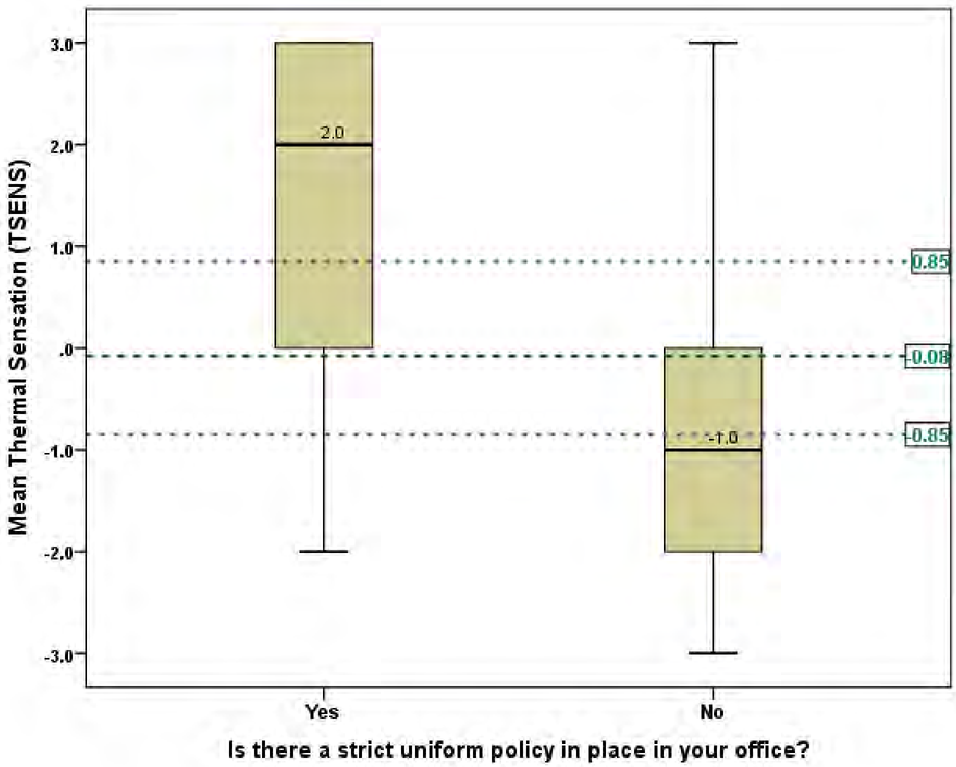


Figure 5.26: Distribution of mean TSENS according to office clothing policy

A. Correlation of Thermal Sensation to Other Variables

Figure 5.27 shows the correlation matrix of the mean thermal sensation (TSENS) to the following variables: operative temperature, clothing insulation, outdoor air temperature, relative humidity and average metabolic rate. The bivariate scatter plots and the fitted lines are shown on both the left and right parts; Pearson's correlation values, their significance values and the corresponding R^2 values are shown on both the upper and lower part. The results show that thermal sensation is strongly correlated to clothing insulation (r=0.516) and operative temperature (r=0.236). It is also slightly correlated with outdoor air temperature (r=0131) and relative humidity (r=0.115). It has a weak correlation to metabolic rate (r=0.020).

The 2-tailed correlation is significant at the 0.01 level for clothing insulation, operative temperature and outdoor air temperature. While the correlation between the mean thermal sensation and relative humidity is significant at the 0.05 level. With a correlation significant of 0.678, there is no statistical significant correlation between mean thermal sensation and metabolic rate. This implies that, changes in the activities of participants of the survey did not affect their thermal sensation.

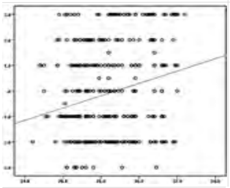
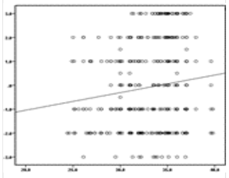
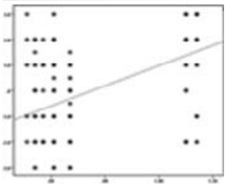
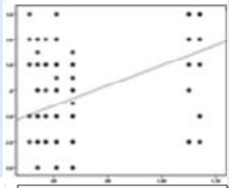
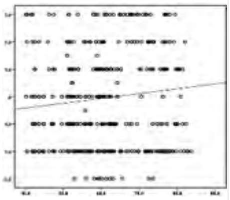
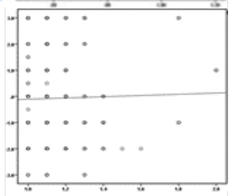
TSENS	**0.236 (0.000) R^2=0.056**	**0.516 (0.000) R^2=0.266**	**0.131 (0.005) R^2=0.017**	**TSENS**
	**Operative temperature (^{0}C)**		**Outdoor air temperature (^{0}C)**	
		**Clothing insulation (clo)**		
	**Relative humidity (%)**		**Metabolic Rate (met)**	
TSENS	**0.115 (0.014) R^2=0.013**	**0.516 (0.000) R^2=0.266**	**0.020 (0.678) R^2=3.841E-4**	**TSENS**

Figure 5.27: Correlation matrix showing the relationship between the mean thermal sensation (TSENS) and the following variables: operative temperature, clothing insulation, outdoor air temperature, relative humidity and metabolic rate. Bivariate scatter plots and the fitted lines are shown in both the left and right parts; Pearson's correlation values, their significance values and the corresponding R^2 values are shown in both the upper and lower parts

B. Neutral temperature and comfort range

In order to determine the neutral temperature and comfort range, a linear regression analysis of thermal sensation was carried out with respect to weighted indoor operative temperature using SPSS software package. The resulting linear regression models was fitted according to the format as shown in (Equation 5.1). Table 5.11 is the summary of the linear regression analysis of thermal sensation on weighted operative temperature showing result for total votes.

$$Y = m*X + b \qquad (5.1)$$

Where,

m is coefficient or gradient

b is constant

***Y** is mean thermal sensation*

***X** is operative temperature*

The approach employed in ASHRAE adaptive comfort standard was used to define the indoor operative comfort range, it defines the 80% operative comfort range as -0.85≤TSENS≤+0.85 (de Dear & Brager, 1998). This corresponds to approximately 80% thermal satisfaction, where Predicted Percentages Dissatisfied (PPD) is less than 20%. The neutral temperature corresponding to TSENS value equalling “0” was also calculated.

As shown in Table 5.11, the linear regression for the mean TSENS on weighted indoor operative temperature resulted to the equation: Y = 0.250*X – 7.197 with a correlation coefficient of 0.245 and a p-value of 0.000 (less than 0.05). This equation yielded a subject neutral temperature of 28.8^{0}C and comfort range (TSENS between -0.85 and +0.85) of between 25.4^{0}C and 32.2^{0}C. The gradient of the linear regression which is represented as "m" in Equation 5.1 indicates how much the thermal sensation (TSENS) changes with each operative temperature unit.

Table 5.11: Summary of thermal sensation votes responding on weighted indoor operative temperature

Sample size (n)	Comfort Range -0.85≤TSENS≤+0.85 (^{0}C)	Regression Equation	Pearson correlations	P-value
450	25.4 – 32.2	Y = 0.250*X-7.197	0.245	0.000

As illustrated in Figure 5.28, the resulting the linear regression model as shown in Table 5.11, can only explains 6 percent of the relationship between total TSENS votes and indoor operative temperature. However, with a p-value of less than 0.05, the relationship is statistically significant. Hence, the model is a good predictor. The low R-squared value only help to highlights how difficult it is to predict subjective human behaviours, responses or perception. Chapter 6 will discuss this relationship in further detail.

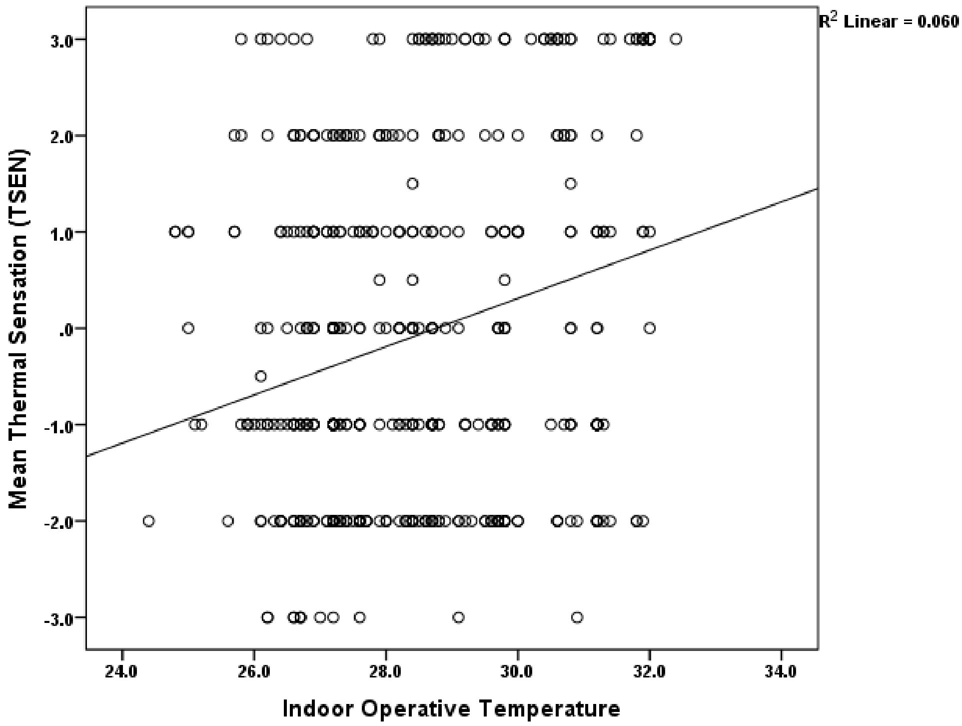


Figure 5.28: Bivariate scatter plot of mean TSENS votes against the weighted indoor operative temperature

C. Relationship between clothing insulation and subjective thermal sensation (TSENS)

A regression analysis was also carried out to establish the relationship between clothing insulation and the subjective thermal sensation (TSENS) of the local office workers in the hot-humid climate of Enugu. Using the SPSS software, a linear regression analysis on the TSENS was carried out with respect to clothing insulation. The result of the relationship is summarised in Table 5.12.

The linear regression equation for the relationship between the participants' clothing insulation and the subjective TSENS votes is Y = 3.960*X – 2.961 with a correlation coefficient of 0.521 and a p-value that is statistically significant at 0.01. This yielded a subject clothing insulation comfort range (TSENS between -0.85 and +0.85) of between 0.53 clo and 0.96 clo. This is in compliance with the adaptive comfort standard of ASHRAE Standard 55-2013, which specifies a clothing insulation range of 0.5 to 1.0 clo.

Table 5.12: Summary of thermal sensation votes responding on clothing insulation

Sample size (n)	Comfort Range $-0.85 \leq TSENS \leq +0.85$ (clo)	Regression Equation	Pearson correlations	P-value
450	0.53 – 0.96	Y = 3.960*X-2.961	0.521	0.000

The bivariate scatter plot as illustrated in Figure 5.29 shows that the regression equation is able to explain more than 27% of relationship between the total TSENS and the clothing insulation of the participants. Also, with a p-value of less than 0.05, the relationship is statistically significant.

This analysis also indicates that clothing insulation is a better predictor of participants' thermal sensation when compared with indoor operative temperature.

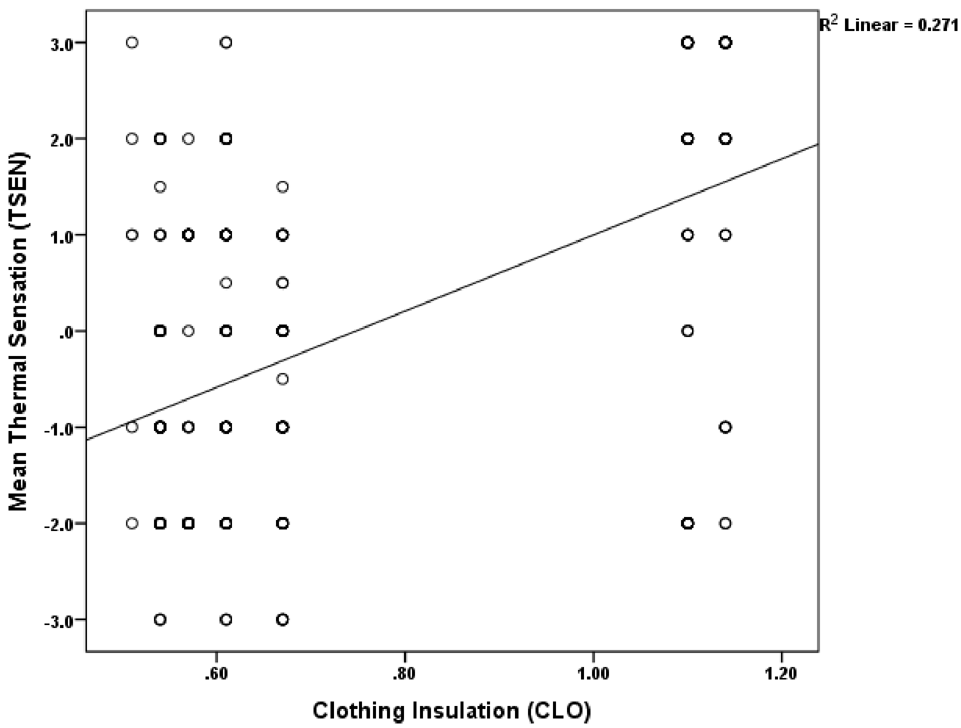


Figure 5.29: Bivariate scatter plot of mean TSENS votes against clothing insulation of participants

5.4.3 Thermal Preference (TPREF)

As shown in Table 5.9, the mean thermal preference (TPREF) votes for all participants in the survey was between “Cool” and “Slightly cool” with a value of -1.44. This value was lower that the TSENS votes, which was -0.08. If the mean TPREF is taken as the neutral TSENS for the participants, then the regression equation (Y = 0.250*X – 7.197) discussed in section 5.4.2(B) will give a preferred temperature of 23.0^{0}C. The resulting preferred temperature of 23.0^{0}C, is below the lower limit of the 80% comfort range derived from the mean TSENS votes of participants during the survey. It thus indicates that many of the participants would have preferred the thermal conditions surrounding them to be much cooler than it was during the survey.

Figure 5.30 to Figure 5.33 show the distribution of the mean TPREF votes according to time of the day, office workplace typology, office ventilation system and office clothing policy accordingly. In each case, the total mean TPREF vote as well as the 80% upper and lower limits of acceptable comfort range of ASHRAE Standard 55 were shown with reference lines. A comparison of each of these distributions show that the total mean TPREF vote and the median of each of the distribution are outside the 80% acceptable comfort range, below the lower limit. Participants’ subjective thermal preference votes were similar, with the majority preferring a little cooler working environment when compared with the total mean TPREF vote.

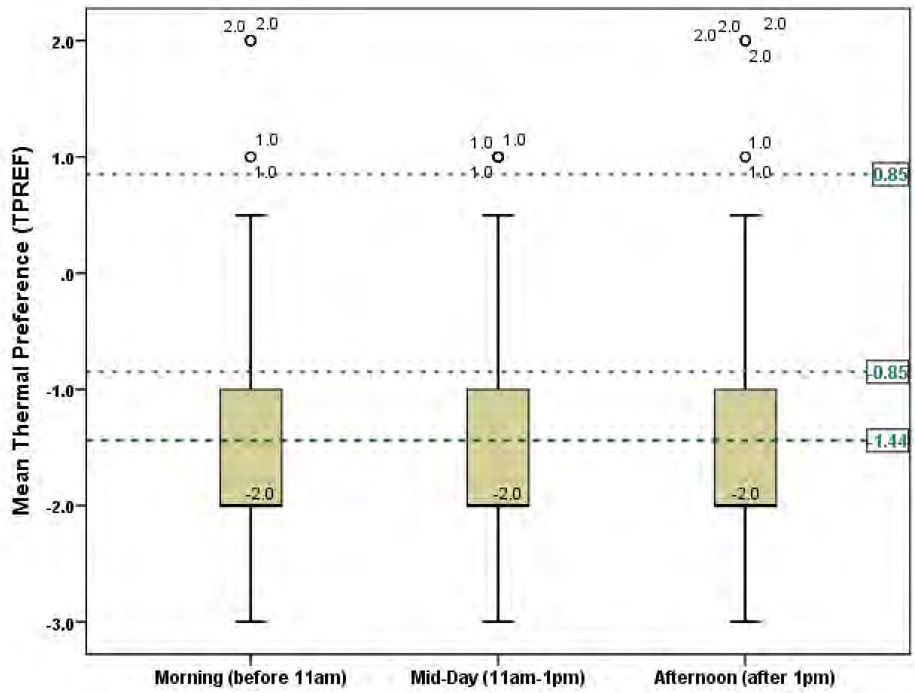


Figure 5.30: Distribution of mean TPREF according to time of the day

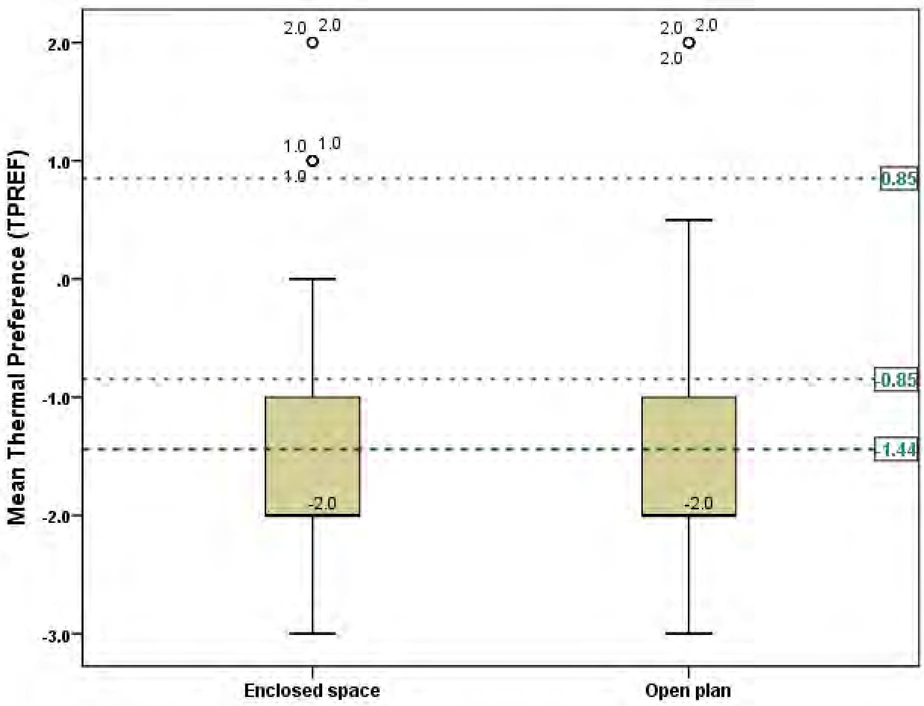


Figure 5.31: Distribution of mean TPREF according to office workplace typologies

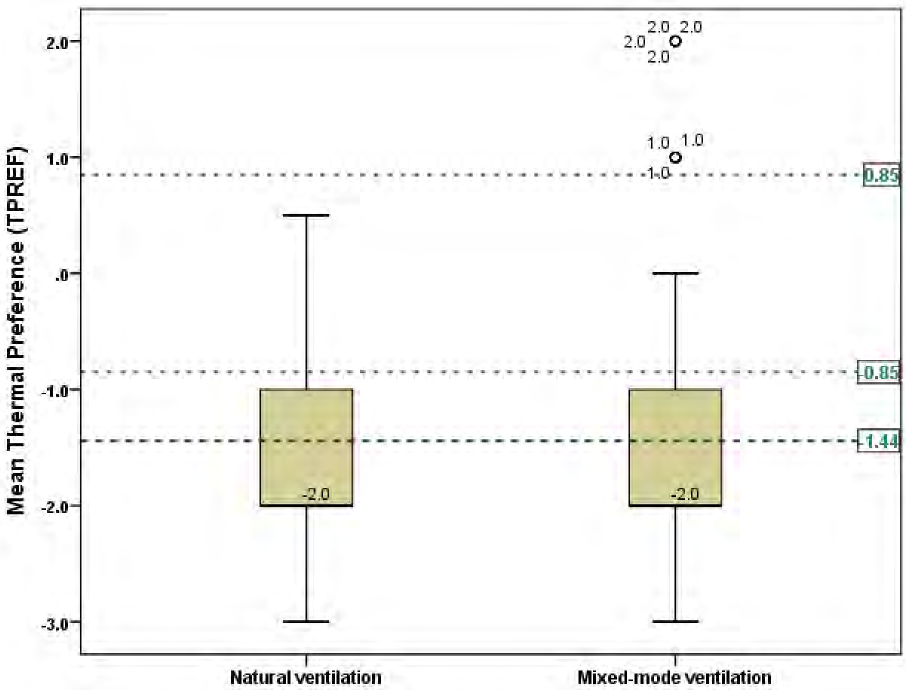


Figure 5.32: Distribution of mean TPREF according to office ventilation systems

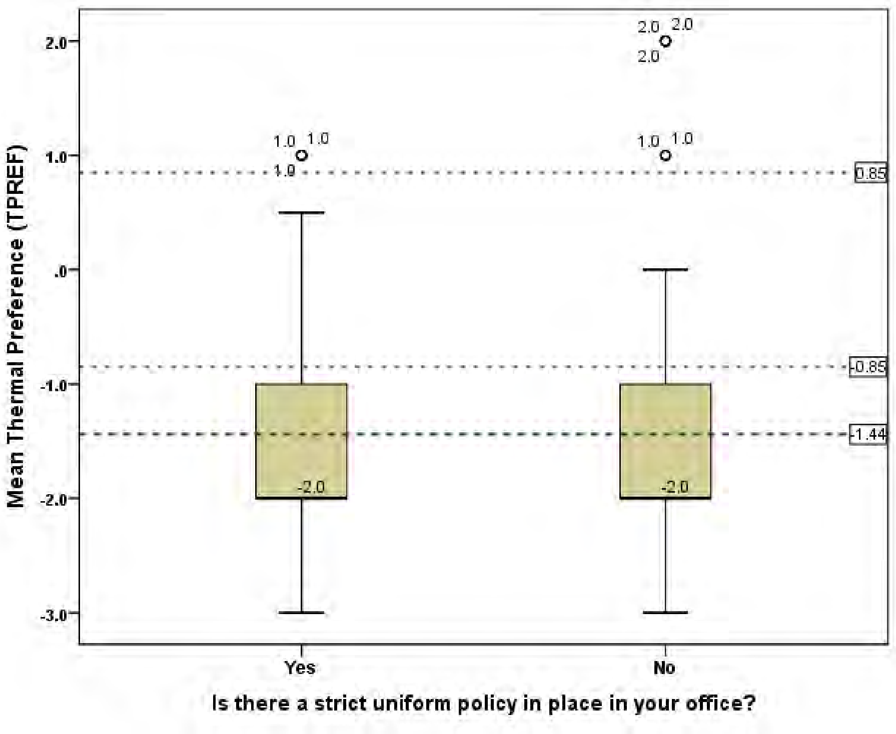


Figure 5.33: Distribution of mean TPREF according to dress code policy

5.4.4 Comparison of Mean Thermal Sensation (TSENS) Votes With Mean Thermal Preference (TPREF) Votes

In order to show the comparison between the TSENS and TPREF, the total mean values of the subjective votes where plotted in into a clustered bar chart to make for easy comparison. These were also compared with the 90% and 80% comfort zone of ASHRAE Standard 55-2013, $-0.5 \leq TSENS \leq +0.5$ and $-0.85 \leq TSENS \leq +0.85$ respectively. The result of the comparisons are illustrated in Figure 5.34 to Figure 5.37. These show comparison according to time of the day, office workplace typology, office ventilation system and office clothing policy.

The mean TSENS votes of the participants, except for participants in naturally ventilated spaces and those with strict clothing policy, were all within the acceptable comfort zone of ASHRAE Standard 55. As shown in Figure 5.36 and Figure 5.37, the mean TSENS votes of participants in naturally ventilated spaces and those with strict clothing policy were between “slightly warm” and “warm”. Whereas, the median TPREF votes for all the cases analysed shows that participants prefer a thermal condition that is between “slightly cool” and “cool”. A further discussion of these comparison is presented in Chapter 6 of this thesis.

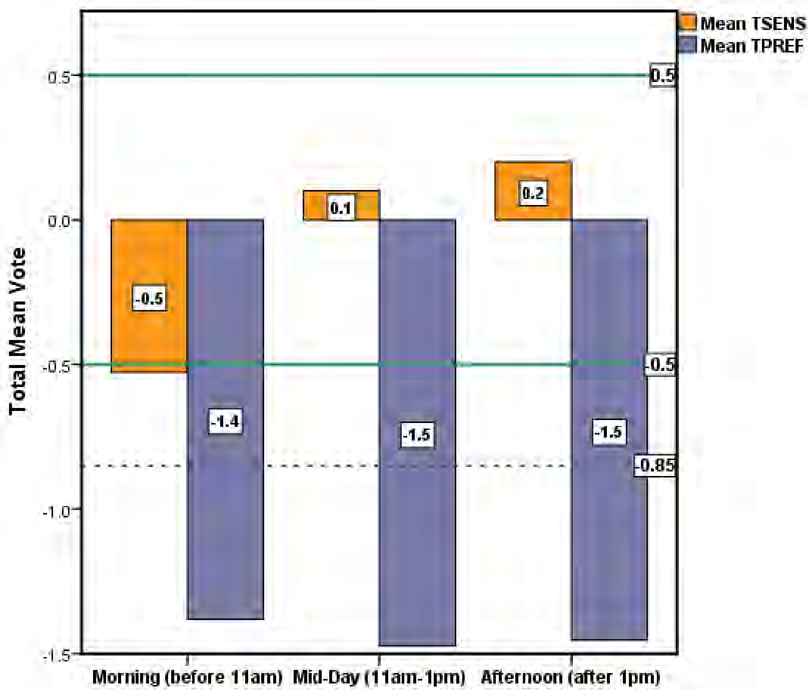


Figure 5.34: Mean comparison of TSENS and TPREF according to time of the day

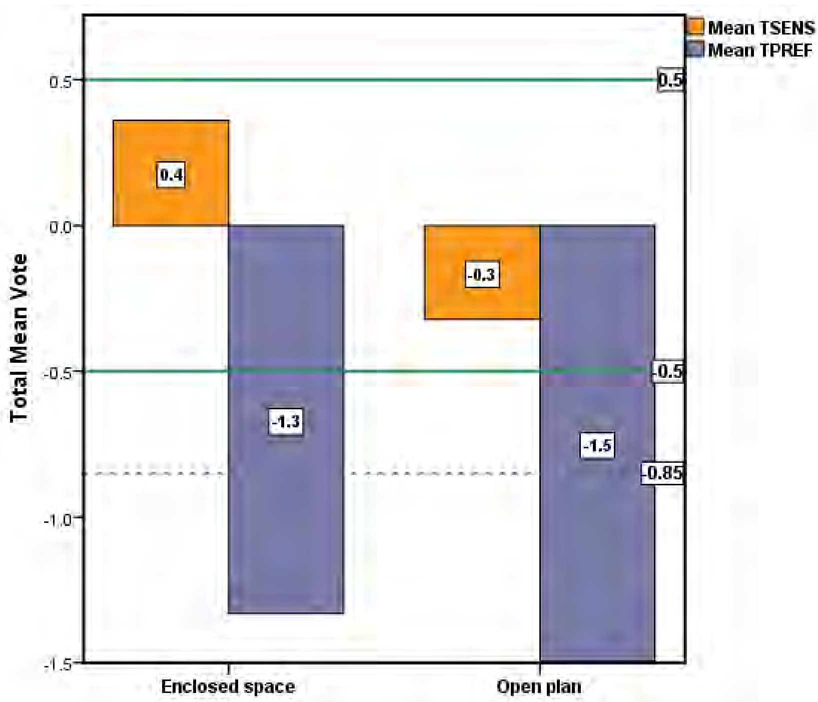


Figure 5.35: Mean comparison of TSENS and TPREF according to office workplace typologies

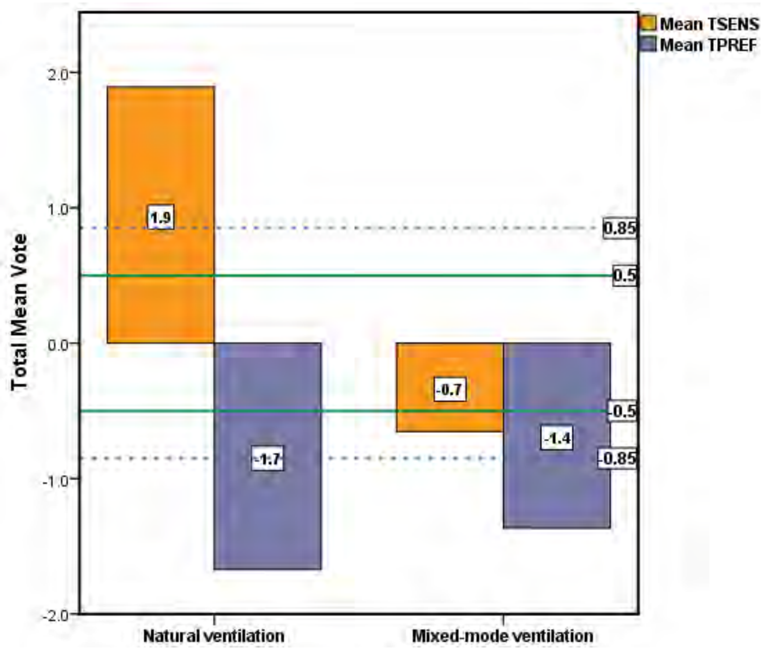


Figure 5.36: Mean comparison of TSENS and TPREF according to office ventilation systems

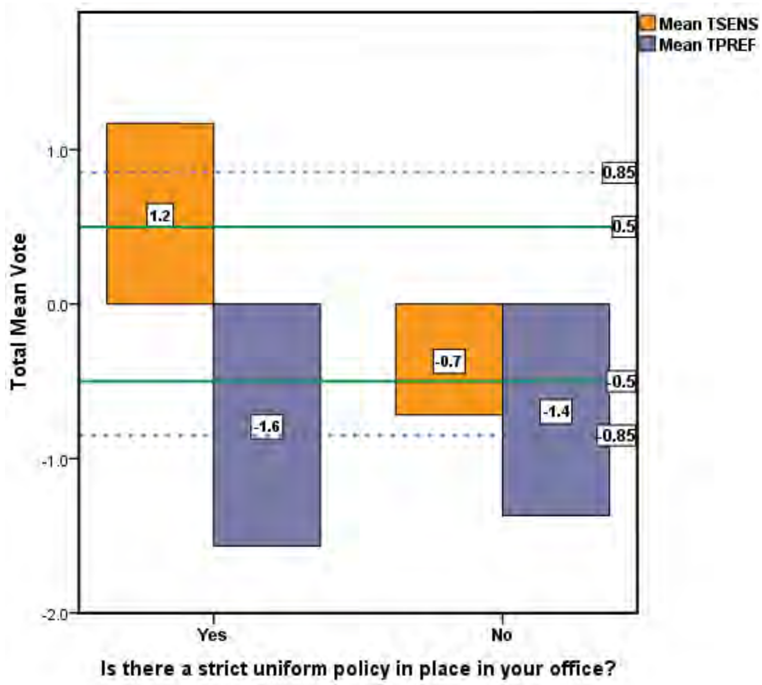


Figure 5.37: Mean comparison of TSENS and TPREF according to office clothing policy

5.4.5 Thermal Discomfort Location

The thermal comfort questionnaire also asked participants to indicate the area where they feel thermal discomfort. The following options were given to the participants to choose from: head, chest, back, pelvis, arms, hands, legs, feet or all over. The summary of the result is presented in Figure 5.38. The results shows that more than 75% (75.80%) of participants in the survey feel discomfort all over their body.

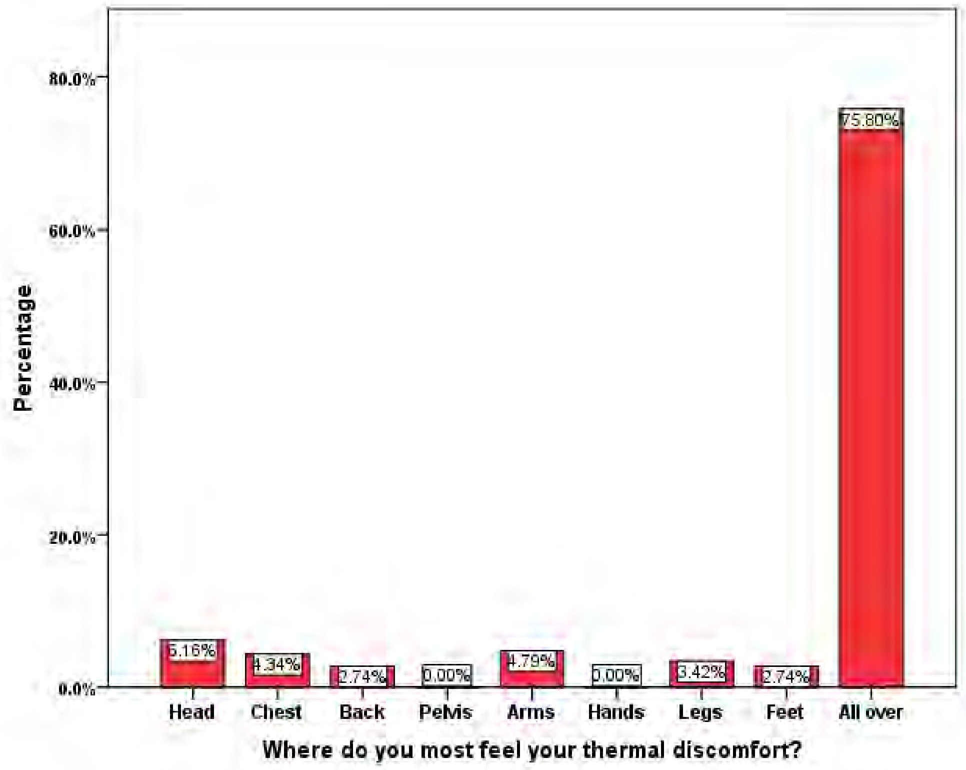


Figure 5.38: Summary of participants' thermal discomfort location

5.5 Semi-Structured Interviews

In addition to the thermal comfort measurements and thermal comfort questionnaires administered to all participants of the survey, a cross-section of the participants were also interviewed using a semi-structured interviews. Those interviewed were selected at random to include different sexes and from different office spaces. A total number of 18 persons were interviewed across the 6 office spaces used for the survey. The selection was done in such a way that we have equal numbers of male and female participants. Half of them were from FRCN and the other half were from FRSC.

As discussed in chapter 4, the choice of the semi-structured interviews was to provide some structure and guidance without taking the rigid approach of quantitative interview. The focus of the interview was to determine from the participants to what extent they feel that office clothing or dress code policy influence their perception or adaptation to the thermal conditions surrounding their work places. In other to guide the interview, the following semi-structured questions were adopted:

(i) What do you do when you feel too hot/cold?

(ii) Do you think your clothing affects how hot or cold you feel?

(iii) What usually influences what you wear to work?

(iv) What kind of clothing do you usually put on during working hours for most part of the week?

(v) Do you usually alter your clothing when you feel too hot or too cold?

(vi) Do you support a strict office clothing policy?

5.5.1 *What do you do when you feel too hot/cold?*

This question was included to determine if any of those being interviewed will mention any action related to office clothing or dress. However, none of the 18 participants interviewed mentioned anything related to clothing adjustment. Their responses can be summarised as follow:

(i) five of the 18 persons interviewed said they either open or close windows or doors as the case me be,

(ii) four out of the 18 said they will leave the office or go out of the environment,

(iii) another four said they usually turn on or turn off the fan,

(iv) three person of the 18 persons interviewed said they either switch on or switch off the air conditional,

(v) the other 2 persons said they usually take a walk.

5.5.2 Do you think your clothing affects how hot or cold you feel?

This question was a follow-up question to the previous one. The expected response was either a ‘Yes’ or ‘No’. Of all those interviewed, only 3 answered ‘Yes’, that their office clothing affects their perception of thermal comfort. The other 15 participants said they think that their clothing has nothing to do with their thermal comfort conditions.

The 3 persons who said their clothing affects how hot or cold they feel are all from naturally ventilated offices spaces and are based in FRSC, where there is a strict uniform policy in place. Further probing as to why the 15 persons believe that their clothing does not affects how hot or cold they feel reveals that as long as there are some forms of mechanical cooling in place to complement the natural ventilation, their clothing has nothing to do with their perception of thermal comfort.

5.5.3 What usually influences what you wear to work?

All participants from FRSC said, it is the office uniform or clothing policy that influences how they dress to work. Participants from FRCN, where there is no formal uniform policy in place, mentioned things such as: weather condition, what is available, colour of cloths, culture and fashion.

5.5.4 What kind of clothing do you usually put on during working hour for most part of the week?

The response of FRSC participants was: official uniform (Figure 5.39). However, it was observed that most of the FRSC workers usually put on unofficial clothing besides their uniform before and after the official working hours. Some of them were noticed still having their unofficial clothing on during working hours, especially if they were not being observed by their senior officers. Due to ethical reasons, detailed photographs to show this action are not included in this thesis. However, Figure 5.7 shows a typical example of what workers of FRSC use in bringing different clothing besides their official uniforms to the office. When asked the reason behind this action, most of them responded that the uniform makes them feel too uncomfortable. This response was then followed by the question of section 5.5.2: Do you think your clothing affects how hot or cold you feel? Seven of the 9 participants from FRSC, including some who had initially answered 'No' to the question responded that their office clothing affects how hot or cold they feel.

The responses from workers of FRCN can be summarised as follow:

(i) five of the 9 participants said they usually put on corporate English clothing,

(ii) three of them said they usually put on traditional ethnic clothing especially on Fridays,

(iii) one said casual (mostly polo and jeans).

Further probing reveals that those who wear traditional or casual clothing feel more comfortable with their thermal environment than those who put on corporate English clothing.

Figure 5.39: Representations of the official uniform of FRSC workers

5.5.5 Do you usually alter your clothing when you feel too hot or too cold?

This question requires a 'Yes' or 'No' response. Thirteen out of the 18 persons interviewed responded 'Yes'. The remaining 5 persons said it depends on what they are putting on at that particular point in time.

Surprisingly, more than half of the 15 persons who said 'No' to the question on section 5.5.2 agreed here that they usually alter their clothing when they feel either too hot or too cold. Further probing reveals that alteration usually carried out include: folding of long sleeves, opening of shirt buttons for males, taking off outer layer of cloths where necessary, removing shoes and wearing slippers, removing tie if they are putting on one and so on.

5.5.6 Do you support a strict office clothing policy?

All the 18 persons interviewed answered 'No' to this question. Their comments indicates that they prefer a flexible clothing policy. The major reason given by them is that restricting their choice of clothing will make them uncomfortable, which in turn make them not be able to adjust or adapt to the thermal conditions surrounding their work places. Few among them said they can only support a strict clothing or uniform policy if it comes with 'increased salary'.

5.6 Quantitative Versus Qualitative Comparison of Thermal Comfort Perception

This section compares the participants' subjective thermal comfort votes obtained from the questionnaires with those obtained from the semi-structured interviews. The 18 participants selected for the interviews were asked at some point during the interviews to rate their comfort condition using the same 6-point scale used in the questionnaire that was administered during the period of the survey. The 6-point scale include: very uncomfortable, uncomfortable, somewhat uncomfortable, somewhat comfortable, comfortable and very comfortable. For the purpose of comparing their interview responses with the responses from the questionnaire, the interviews were conducted at a time participants were completing one of the series of questionnaires that was administered to them during the period of the survey.

Table 5.13 shows the summary of the comparison between the results of the thermal comfort vote obtained from the questionnaires with those of the interviews. The results from the comparison show a consistency of more than 70% between the results from questionnaires and semi-structured interviews. This shows that while thermal comfort questionnaires remain a suitable method of obtaining participants subjective thermal comfort perception, there is need to compliment it with other forms of qualitative data collection such as interviews.

Table 5.13: Comparison of results of thermal comfort votes from questionnaires with those of semi-structured interviews

Participants/	Response Source	Office	Date/ Time	1	2	3	4	5	6	Remarks
002	Questionnaire	FRCN	02/06/14							√
	Interview		1532							
006	Questionnaire	FRCN	14/02/14							√
	Interview		1157							
013	Questionnaire	FRCN	14/02/14							×
	Interview		0915							
015	Questionnaire	FRCN	24/02/14							√
	Interview		1010							
017	Questionnaire	FRCN	02/06/14							√
	Interview		1249							
026	Questionnaire	FRCN	03/06/14							×
	Interview		1455							
007	Questionnaire	FRCN	24/02/14				Δ			√
	Interview		1152							
008	Questionnaire	FRCN	03/06/14							√
	Interview		1002							
010	Questionnaire	FRCN	14/02/14							√
	Interview		1517							
033	Questionnaire	FRSC	26/02/14				Δ			×
	Interview		0920							
039	Questionnaire	FRSC	26/02/14				Δ			√
	Interview		1255							
042	Questionnaire	FRSC	04/06/14				Δ			√
	Interview		1655							
030	Questionnaire	FRSC	25/02/14							×
	Interview		1530							
031	Questionnaire	FRSC	02/06/14							√
	Interview		1325							
032	Questionnaire	FRSC	30/02/14							√
	Interview		1325							
034	Questionnaire	FRSC	03/06/14							√
	Interview		0847							
037	Questionnaire	FRSC	26/02/14							×
	Interview		1430							
047	Questionnaire	FRSC	04/06/14							√
	Interview		1145							

NB: 1-very uncomfortable, 2-uncomfortable, 3-somewhat uncomfortable, 4-somewhat comfortable, 5-comfortable, 6-very comfortable

5.7 Summary

The results presented in this chapter have demonstrated that where participants are given the opportunity to adjust their office clothing, they easily adapt to the thermal conditions surrounding their work environment in the city of Enugu, located in a hot-humid climate zone of Nigeria.

Analysis of the measured indoor and outdoor climatic variables showed that there was a significant correlation between indoor and outdoor thermal variables measured during the survey period. When these thermal conditions were compared with the adaptive comfort of ASHRAE Standard 55-2013, it was shown that office spaces surveyed were in compliance with the adaptive thermal comfort. Of all the thermal variables recorded, clothing insulation had the strongest correlation to participants' subjective thermal sensation.

The observation and semi-structured interviews components of the survey helped to highlight the different actions that participants took in order to adapt to the thermal conditions surrounding their work places. These included: clothing adjustment, the opening of doors and windows, taking a walk, turning fans, air conditioners and other mechanical cooling devices on or off depending on the weather condition.

CHAPTER 6

DISCUSSION

6.1 Introduction

This chapter discusses the relationship between the research objectives and the results obtained from the research and its associated field survey. The analysis of how the results helped in achieving the five research objective of this thesis were discuss in five sections.

6.2 Comparison With Adaptive Thermal Comfort

One of the objectives of this study is to compare the thermal performances in the case study office spaces with the adaptive thermal comfort model. In order to be able to make the comparison, both the outdoors and the indoors environmental variables where measured. In this study, the internal and external air temperature and relative humidity were logged at 15 minutes interval throughout the period of the survey. The results and analysis from these measurements are presented in section 5.3 of Chapter 5.

6.2.1 Outdoor Temperature Versus Indoor Temperature

The adaptive model relates the indoor neutral temperature to the monthly outdoor mean temperature. The results of the comparison between indoor and outdoor measured temperature, as presented in Table 5.7, shows a strong correlations between the indoor and outdoor temperature. The Pearson correlation for the combined indoor temperature to the immediate outdoor temperature is 52%, and this relationship is statistically significant at 0.01 (less than 0.05). A breakdown of each of the office spaces surveyed show that all mixed-mode office spaces have a correlations of more than 50%, while the two naturally ventilated office spaces (Db and Dc) are 39.7% and 25.3%. With a 2-tailed correlation that is significant at 0.01 level for all the office spaces surveyed in this study, as summarised in Table 6.1, an increase in outdoor temperature resulted in the increase of the operative temperature for each of the office spaces.

These measured indoor and outdoor temperature, thus, exhibited the tendency to conform with the adaptive model that relates the monthly mean outdoor air temperature to the indoor neutral temperature.

Table 6.1: Summary of statistical significant correlations between indoor and outdoor temperature

Office Spaces	2-tailed Significant	Remark
A	0.000 (<0.05)	√
B	0.000 (<0.05)	√
C	0.000 (<0.05)	√
Da	0.000 (<0.05)	√
Db	0.000 (<0.05)	√
Dc	0.000 (<0.05)	√

√ *There is a statistically significant correlations*

6.2.2 Outdoor Absolute Humidity versus Indoor Absolute Humidity

While the adaptive model did not show the relationship between the indoor and outdoor relative humidity, this study has shown the statistical comparison between the indoor and outdoor absolute humidity of all office spaces necessary. As presented in Table 5.8, the indoor absolute humidity of all spaces surveyed have a Pearson correlation value of 49.6% to the outdoor relative humidity, at a 2-tailed statistical significant at 0.05. However, a breakdown of the 2-tailed significant for each of the office spaces as summarised in Table 6.2 shows that there was no statistical significant correlations between the outdoor and indoor absolute humidity for all case study office spaces.

So increase in outdoor absolute humidity did not always result in increase in indoor absolute humidity for all the cases studied.

Table 6.2: Summary of statistical significant correlations between indoor and outdoor absolute humidity

Office Spaces	2-tailed Significant	Remark
A	0.068 (>0.05)	✕
B	0.000 (<0.05)	√
C	0.219 (>0.05)	✕
Da	0.053 (>0.05)	✕
Db	0.016 (<0.05)	√
Dc	0.081 (>0.05)	✕

√-There is a statistically significant correlations ✕*-There is no statistically significant correlations*

6.2.3 Comparison With ASHRAE Adaptive Comfort Model

As presented in section 5.3.3, in order to show the comparison of the measured indoor operative temperature and the outdoor air temperature with the ASHRAE adaptive comfort model; the daily mean indoor operative temperature were plotted against the corresponding prevailing weekly mean outdoor air temperature and overlaid with the adaptive model of ASHRAE Standard 55-2013. The results as shown in Figure 5.10 and Figure 5.11, showed that almost all the collected data fit into the 80% comfort range of the adaptive comfort model of ASHRAE Standard 55-2013.

The two extreme points in Figure 5.11, were further analysed using the Center for the Built Environment Thermal Comfort Tool, an online thermal comfort analysis tool for ASHRAE Standard 55 (Hoyt et al., 2013). The results from these analysis as presented Figure 5.12 and Figure 5.13, indicated that with an increase in air flow or movement, these extreme points will fit-in within the 80% acceptability limits of the adaptive model of ASHRAE Standard 55-2013.

During the field research work, the air velocity of the office spaces surveyed were not logged continuously as did temperature and relative humidity. This is due to non-availability of equipment to log the air velocity of the spaces on a continuous basis. The only instrument available for measuring air movement was a hand-held instrument, Kestrel 3000 Pocket Wind Meter. This was used in measuring the air speed at different instances. The maximum air speed recorded during those instances as stated in section 5.3.1 was 0.3m/s.

Since it was not possible to record the air speed on a continuous basis at the same time as the operative temperature, it is not possible to conclude if any of the spaces surveyed experienced air speed that exceeded the 0.3m/s that was recorded. However, the analysis of the comparison between the outdoor air temperature and the indoor operative temperature, using the Centre for the Built Environment Thermal Comfort Tool; shows that when the operative temperature exceeds 31.7^{0}C for any given space, the space will requires air speed that exceeds 0.3m/s (Efeoma & Uduku, 2014). For this study, the maximum operative temperature recorded for Office Spaces C, Da, Db and Dc exceeded the 31.7^{0}C (31.9^{0}C, 31.8^{0}C, 32.4^{0}C and 32.0^{0}C respectively). However, the mean operative temperature used for the analysis did not exceed the maximum operative temperature the instance when an increased air speed of 0.3m/s will be required.

In summary, the analysis of the results from this study clearly shows that the ASHRAE Standard 55 adaptive comfort model is very applicable to the case study office spaces. As this study used Nigerian case studies, there is a clear indication that the model will be applicable to mixed-mode and naturally ventilated buildings in the hot humid climate zones of Nigeria. Also, if buildings are properly designed to take advantage of the prevailing wind to ventilate the interior spaces, there is the possibility that occupants will be comfortable without the use of air-conditioning cooling systems. In extreme cases, fans could be installed to increase the air movement across the spaces and the body.

6.2.4 Comparison With CEN/EN-15251 Adaptive Comfort Model

As illustrated in Figure 5.14 and Figure 5.15, the daily mean operative indoor temperature were also plotted against the corresponding prevailing weekly mean outdoor air temperature and overlaid with the adaptive model of CEN/EN-15251-2007. As shown, about 50% of the measured data were outside the acceptable comfort limits of Class II and Class III comfort limits of CEN/EN-15251-2007. This shows that the case study office spaces did not comply with the adaptive comfort standard of CEN/EN-15251-2007.

This non-compliance with CEN/EN-15251, can be explained from the information presented in section 2.3.6 and Table 2.5. The data that form the basis for the development of the adaptive component of CEN/EN-15251, were obtained from five Western European countries whose climate is completely different from the tropical climate of Nigeria and the hot humid climate zone of the study location (Efeoma & Uduku, 2014; Humphreys et al., 2016; Nicol et al., 2012). The adaptive comfort standard of CEN/EN-15251, therefore, is not suitable for the analysis and estimation of thermal comfort in mixed-mode and naturally ventilated buildings in the hot humid climate zone of Nigeria.

6.2.5 Summary of Comparison With Adaptive Thermal Comfort

The analysis of results and associated research from this study therefore clearly shows that all the case study office spaces (be they mixed-mode or naturally ventilated spaces, open plan and enclosed office spaces) comply with the adaptive thermal comfort component of the ASHRAE Standard 55-

2013. They were, however, not in compliance with the adaptive component of CEN/EN-15251. Hence, the adaptive thermal comfort standard of ASHRAE Standard 55-2013 is a suitable standard for the design, analysis and estimation of thermal comfort in the mixed-mode and naturally ventilated office spaces in the hot humid climate zone of Nigeria, and by extension in other climate zones of Nigeria and West Africa.

6.3 Thermal Perception of Office Workers

The second objective of this study was to explore office workers' thermal perception corresponding to office workplace typologies and ventilation systems. This objective was achieved through the analysis of participants' subjective thermal perception votes. The variables analysed in this respect are participants' subjective:

- thermal comfort votes,
- thermal sensation votes and
- thermal preference votes

A discussion of the analysis of each of the above variables with respect to office workplace typologies and ventilation systems are presented as follow.

6.3.1 Office Workers Thermal Comfort (COMF) Perception

The combined analysis of the subjective thermal comfort votes of all participants as summarised in Table 5.10, indicated that about 3 out of every 4 (about 75%) of the participants voted that they were comfortable with the thermal conditions within their work places. A breakdown of these results according to office workplace typologies and ventilation systems are discussed in the following sub-sections.

A. COMF Perception According to Office Workplace Typologies

As discussed in Chapters 3 and 4, the two categories of office workplace typologies covered in the research are enclosed space (ES) and open plan (OP). The results as presented in Figure 5.18 and summarised in Table 5.10, showed that workers in OP office spaces were more comfortable with the thermal condition surrounding their office when compared with those working in ES. About 4 out of every 5 (about 80%) of the participants voted that they were comfortable in OP offices. Whereas in ES, it was 2 out of every 3 (approximately 66%) of the participants that perceived their thermal environment to be comfortable.

As discussed in section 6.2, the measured thermal variables from all office spaces surveyed during the field research work showed that they were in compliance with 80% comfort range of the adaptive comfort of ASHRAE Standard 55-2013. The thermal comfort votes obtained from the occupants of those spaces indicated that; while the ASHRAE Standard 55 accurately predicted the thermal comfort of participants in OP office spaces, it did not accurately predict the thermal comfort of workers in ES as only 66% voted that were comfortable.

B. COMF Perception According to Office Ventilation Systems

Both mixed-mode ventilated (MM) and naturally ventilated (NV) office spaces were used for this study. As illustrated in Figure 5.19 and summarised in Table 5.10, ASHRAE Standard 55 was able to estimate the thermal comfort of office workers in MM office spaces correctly; as about 85% of participants in MM offices spaces voted that they were comfortable with the thermal conditions surrounding their work spaces. However, ASHRAE Standard 55 did not estimate the thermal comfort perception of participants in NV office spaces correctly; as only 2 out of every 5 (about 40%) of the participants voted that they were comfortable.

While the measure thermal variables showed that the NV spaces were in compliance with the adaptive comfort of ASHRAE Standard 55-2013, the thermal comfort votes of participants indicated otherwise. Among other factors, office clothing of workers was discovered to be the major contributing factor to this discrepancy between measure data and their perception of comfort. Section 6.5 discusses this factor in details.

6.3.2 Office Workers Thermal Sensation (TSENS) and Thermal Preference (TPREF)

As summarised in Table 5.9, the overall mean TSENS vote for all participants during the survey was -0.08, between “Slightly cool” and “Neutral” point on the ASHRAE TSENS scale. This mean vote is within the 90% comfort limits of the ASHRAE Standard 55 TSENS scale, where less than 10% of occupants are said to be dissatisfied with the thermal conditions surrounding them. However, the overall TPREF vote of -1.44, between “Cool” and “Slightly cool” on the ASHRAE scale, indicated that workers in the hot humid region of Enugu would prefer thermal conditions that were much cooler that those suggested in the ASHRAE Standard 55-2013. The breakdown of these TSENS and TPREF votes are discussed in the following sub-sections.

A. TSENS and TPREF According to Office Workplace Typologies

As shown in Figure 5.35, the mean TSENS votes of ES and OP offices space were 0.4 and -0.3 respective on the ASHRAE scale. As it is with the overall mean TSENS for all participants of the survey, these mean votes were within 90% comfort limits of the ASHRAE scale, where only less 10% of occupants are said to be dissatisfied with their thermal environment. However, when compared with the mean TPREF votes of -1.3 and -1.5 for ES and OP office spaces, participants prefer thermal conditions that were below the 80% lower limits of the ASHRAE thermal sensation scale.

The median of the distribution of the mean TSENS votes as illustrated in Figure 5.24, shows that more than 75% of workers in both ES and OP office spaces will be comfortable with their thermal environment according to the ASHRAE Standard 55 estimation. This is consistent with the overall thermal comfort perception votes as discussed in section 6.3.1.

B. TSENS and TPREF According to Office Ventilation Systems

The mean TSENS votes for NV and MM ventilated office spaces, as shown in Figure 5.36, were 1.9 and -0.7 on the ASHRAE scale respectively. This shows that workers in NV spaces of the case study buildings sensed that the thermal conditions surrounding their work places were warmer that the comfort limits estimated by ASHRAE Standard 55. Here again, as highlighted in section 6.3.1(B), a major factor contributing to this warmer sensation was office clothing.

The thermal conditions preferred by workers in both NV and MM ventilated office spaces were consistent. Workers in both office spaces preferred conditions that were cooler than those estimated by adaptive comfort of ASHRAE Standard 55-2015

6.3.3 Summary of Office Workers' Thermal Perception

In terms of thermal comfort votes, ASHRAE Standard 55-2013 was able to estimate office workers thermal perception in OP and MM ventilated office spaces accurately in the cases studied. This was slightly different with ES office spaces, where only 66% voted to be comfortable whereas the adaptive comfort model of ASHRAE Standard 55-2013 had estimated that more than 80% would be comfortable with their thermal environment. In the case of NV ventilated spaces, while the spaces were in compliance with the 80% comfort limits of ASHRAE Standard 55 adaptive comfort, only 40% of the participants from those spaces voted that they were comfortable with the thermal conditions within their work environment.

With respect to thermal sensation, ASHRAE Standard 55-2013 was consistent in its estimation of the votes of participants in ES, OP and MM office spaces; as the mean TSENS votes of participants in those spaces were within the 80% comfort limits of the ASHRAE thermal sensation scale. However, the mean TSENS votes of participants in NV office spaces were above the 80% upper limits. All NV office spaces selected for this study are located with the office complex of FRSC, offices with strict clothing regulation. As will be discussed in section 6.5, office clothing is a major factor accounting for the inconsistency with the estimation of the adaptive model of ASHRAE Standard 55-2013.

Overall, the thermal preference of office workers in ES, OP, NV and MM ventilated office spaces were consistent. They all preferred conditions that were cooler that those predicted by the adaptive model of ASHRAE Standard 55-2013.

6.4 Office Workers Neutral Temperature and Comfort Ranges

The third objective of this study was to determine the neutral temperature and comfort range for office workers in the hot humid climate of Enugu. In order to achieve this objective, as discussed in section 5.4.2(B) and summarised in Table 5.11, a linear regression analysis of the mean TSENS was carried out on the weighted indoor operative temperature (TOP). This analysis yielded a subject neutral temperature of 28.8^{0}C and 80% comfort limits (TSENS between -0.85 and +0.85) of between 25.4^{0}C and 32.2^{0}C. These results from this study were compared with the results of previous works carried out in Nigeria as well as those carried out in hot humid climate zones by researchers in other countries, as discussed and presented in Chapter 2.

6.4.1 Comparison With Previous Thermal Comfort Research Performed in Hot Humid Climates

As summarised in Table 6.3, the neutral temperature from this study is comparable to those of previous studies carried out in Singapore by Wong et al. (2003), in classrooms buildings and the one done by de Dear et al (1991), in naturally ventilated residential buildings. The comfort zone from this studies is also close to the previous works done in hot humid climates:

by Hwang et al. (2006), in classrooms buildings in Taiwan; by Karyono (2000), in office buildings in Jakarta, Indonesia; and by Kwok (1998), in classrooms buildings in Hawaii. This thus indicated that office workers in the hot humid climate zone of Enugu can adapt to a much higher temperature than those predicted by international Standards such as ISO 7730.

Table 6.3: Summary of comparison with selected research findings conducted in hot humid climates

Year	Researcher	Location	Building	Key Research Findings
2014 ~ 2016	This study	Enugu, Nigeria	Offices	1. Neutral temp. = 28.8^{0}C TOP* 2. Acceptable comfort zone = 25.4–32.2^{0}C TOP* (-0.85 ≤ TSENS ≤ +0.85)
2006	Hwang et al.	Taiwan	Classrooms	1. Neutral temp. = 26.3^{0}C ET* 2. Preferred temp. = 24.7^{0}C ET* 3. Acceptable comfort zone = 21.1–29.8^{0}C ET*
2003	Wong et al.	Singapore	Classrooms	1. Neutral temp. = 28.8^{0}C TOP* 2. Acceptable comfort zone = 27.1–29.3^{0}C TOP*
2000	Karyono, T. H.	Jakarta, Indonesia	Offices	1. Neutral temp. = 26.4^{0}C TA* 2. Neutral temp. = 26.7^{0}C TOP*
1998	Kwok, A. G.	Hawaii	Classrooms	1. Neutral temp. = 26.8^{0}C ET* (naturally ventilated buildings) 2. Neutral temp. = 27.4^{0}C ET* (air conditioned buildings) 3. Acceptable comfort range = 22.0–29.5^{0}C
1991	de Dear et al.	Singapore	Residential	1. Neutral temp. = 28.5^{0}C TOP* (naturally ventilated buildings)
			Offices	2. Neutral temp. = 24.2^{0}C TOP* (air conditioned buildings)

Note: *ET* (Effective Temperature), TOP* (Operative Temperature), TA* (Air Temperature)*

6.4.2 Comparison With Previous Thermal Comfort Research Done in Nigeria

Table 6.4 summarised the comparison of key research findings from this study with previous thermal comfort research that were carried out in the tropical climate of Nigeria. The key findings from this study are consistent with most of the recent thermal comfort research that have been carried out in Nigeria. The neutral temperature of 28.8^{0}C obtained from this study is consistent with that of Akande and Adebamowo (2010) in the hot dry region, northern Nigeria city of Bauchi which was 28.44^{0}C. It is also comparable to the 29.09^{0}C obtained by Adebamowo (2007) in the southern city of Lagos in the warm humid climate zone.

The neutral temperature and comfort range from this studies were, however, slightly higher than those of the work carried out by Ogbonna and Harris (2008), which was done in the city of Jos in the temperate dry zone. The neutral point obtained in their work was 26.7^{0}C, with a 90% comfort range ($-0.5 \leq TSENS \leq +0.5$) of 24.88^{0}C to 27.66^{0}C. Comparing the characteristic of the hot humid climate zone of Enugu city, where this study was carried out, with the temperate dry zone where Ogbonna and Harris carried out their studies, as discussed in Chapter 3; one can understand the reason for the little disparity in the thermal neutralities obtained. The city of Jos where their work was done is situated on a plateau, which is cooler all year round when compared to other part of the country.

Apart from the climate zone of study location, other factors that might account for the little disparity in thermal neutrality of this study with some of the selected previous works done in Nigeria might be time and duration of study, methodology used or accuracy of reading of equipment used. For example, the result obtained from work carried out in another hot humid climate zone of Ibadan by Adunola (2012), yielded a thermal neutrality of 32.3^{0}C. This result is much higher than the 28.8^{0}C obtained from this study. The neutral temperature is also outside the 80% comfort limits (-0.85≤TSENS≤+0.85) of 25.4^{0}C – 32.2^{0}C obtained from this study. Several factors might account for this disparity. Compared with this study which was carried out in office buildings, the work of Adunola was done in residential buildings. Also, in contrast with this work that was done in both the rainy and dry seasons, Adunola's work was carried out during the month of April only. Another important factor to highlight is that, this study also adopted a longitudinal approach instead of the traditional one-off 'point-in-time' assessment.

The 28.8^{0}C neutral temperature from this study is also higher than the historic work carried out by Ojosu et al (1988), which predicted a PMV comfort range of 21-26^{0}C for the hot humid climate zone. This comparison also shows that people are comfortable with temperature range that are higher than those predicted by the PMV model.

A comparison with another historic research work carried out by Ambler (1955) in office buildings in the warm humid climate zone of Port Harcourt; shows that as people get acclimatise with the higher temperature as a results of climate change, they get more and more comfortable with higher temperature range. The work of Ambler yielded a neutral temperature of 23.13^{0}C. This is much lower than the minimum comfort limit of 25.4^{0}C achieved in this study.

In summary, the comparison of the results obtained from this study with other similar works carried out in the different climate zones in Nigeria suggest that occupants of naturally ventilated buildings are more adaptable to a much warmer temperature than those specified in

International Standard such as the ISO 7730. The observation and semi-structured interviews components of the survey further revealed the different actions that participants took in order to adapt to the thermal conditions surrounding their work places. This included: clothing adjustment, the opening of doors and windows, taking a walk and turning fans on or off depending on the weather condition. Adaptive thermal comfort therefore is certainly becoming a better standard for the assessment of thermal comfort in the tropical climate of Nigeria. It is also a possible solution to achieving sustainable design that will enable building designers to combat the impact of climate change and to cope with the poor electricity supply situation being experience in Nigeria. This is my view will help to reduce reliance on the Country's epileptic power supply and to free up money that could have been used for the installation, maintenance and running of mechanical cooling devices in the design and construction of buildings.

Table 6.4: Summary of comparison with thermal comfort research done in Nigeria on neutral temperature and acceptable comfort range

Year	Researcher	Location (Climate Zone)	Building	Period (Season)	Key Research Findings
2014 ~ 2016	This Study	Enugu Hot Humid	Offices	Dry and Rainy Seasons	1. Regression equation: Y = 0.250*X - 7.197 2. Neutral temp. = 28.8^{0}C TOP* 3. Acceptable comfort range = 25.4 – 32.2^{0}C TOP* (-0.85 ≤ TSENS ≤ +0.85)
2012	Adunola A. O.	Ibadan (Hot Humid)	Residential	April	1. Regression equation: Y = 0.483*X – 15.59 (TSENS with respect to TOP*) 2. Neutral temp. = 32.3^{0}C TOP*
2010	Akande & Adebamowo	Bauchi (Hot Dry)	Residential	Dry and Rainy Seasons	1. Regression equation: Y = 0.357*X – 10.2 (Dry Season) 2. Regression equation: Y = 0.618*X – 15.4 (Rainy Season) 3. Combined neutral temp. = 28.44^{0}C TOP* 4. Acceptable comfort range = 25.5 – 29.5^{0}C TOP*
2008	Ogbonna & Harris	Jos (Temperate Dry)	Residential and Classrooms	July & August (Rainy Season)	1. Regression equation: Y = 0.3589*X – 9.4285 2. Neutral temp. = 26.27^{0}C TOP* 3. Acceptable comfort range = 24.88 – 27.66^{0}C TOP* (-0.5 ≤ TSENS ≤ +0.5) 4. PMV neutral temp. = 25.06^{0}C
2007	Adebamowo	Lagos (Warm Humid)	Residential		1. Neutral temp. = 29.09^{0}C
1988	Ojosu et al	Hot Dry			1. Acceptable comfort zone = 21 – 26^{0}C
		Temperate Dry			2. Acceptable comfort zone = 18 – 24^{0}C
		Hot Humid			3. Acceptable comfort zone = 21 – 26^{0}C
		Warm Humid			4. Acceptable comfort zone = 21 – 26^{0}C
1955	Ambler H. R.	Port Harcourt (Warm Humid)	Offices		1. Neutral temp. = 23.13^{0}C ET*

Note: *ET* (Effective Temperature), TOP* (Operative Temperature), TSENS (Thermal Sensation Vote)*

6.4.3 Estimating Comfort Temperature

Figure 5.28 shows the bivariate scatter plot of mean TSENS votes against the weighted indoor operative temperature. While the relationship is statistically significant with a p-value of p=0000, the R square value of 0.060 obtained indicates that only 6 percent of the relationship between total TSENS votes and indoor operative temperature can be explain by the plot. With a p-value of less than 0.05, the model obtained from this relationship appears to be a good predictor statistically. The low R square, on the other hand, explains why it is not always good to rely on statistical method alone in predicting human behaviours or perception. When compared to physical processes, humans are simply difficult to predict using the same statistical method that are employed in the physical sciences. Hence, while the statistical methods are still relevant in the field of thermal comfort, as shown in this analysis, there is need to include other qualitative methods such as interviews and observations of human behaviours in the study of human thermal comfort and adaptation. This will help to explain factors that might not be captured by the statistical processes.

6.4.4 Implication of Offset Between TSENS Scale and TPREF Scale on Neutral Temperature

On the ASHRAE seven-point TSENS scale, 0 is regarded as neutral (de Dear & Brager, 1998; de Dear et al., 1997). In this study the mean TSENS vote of participants during the field survey was -0.08; while the mean TPREF vote was -1.44. The -0.08 of the mean TSENS falls within the 90% comfort zone of ASHRAE scale with an offset of 0.08 from the neutral point, which is assumed to be optimum comfort. However, the mean TPREF vote of -1.44 is outside the 80% comfort limit of ASHRAE scale. This discrepancy between the two scales has implications for the estimation of energy use in buildings. If the ASHRAE assumption that optimum comfort temperature is equal to neutral point is incorrect, it means that temperature standards based on ASHRAE scale will be to some extent faulty in the context of the field study. The discrepancy also indicates that there is a strong climate-related semantic artefact in the rating scales.

The offset between the two scales also have an impact on the neutral temperature. Using the regression equation: $Y = 0.250*X – 7.197$, discussed in section 5.4.2(B); the mean value of -0.08 will yield a neutral temperature of 28.5^0C. This neutral temperature based on the mean value of the mean TSENS is comparable to the neutral temperature of 28.8^0C, assuming 0 equal to neutral. On the other hand, the mean value of -1.44 on the TPREF scale will yield a neutral temperature of 23.0^0C, which is a big offset from the 28.5^0C based on the TSENS scale. The semantic offset for both neutral temperature and the preferred temperature is 5.5^0C.

6.4.5 Summary of Neutral Temperature and Comfort Range

This study yielded a neutral temperature of 28.8^0C, with 80% acceptable comfort limits of $25.4–32.2^0C$ for the hot humid climate of Enugu, Nigeria. These results were consistent with comfort neutralities obtained by some researchers in hot humid climate zones in other part of the world, especially those obtained from Singapore. They were also comparable to some of the neutral temperature and acceptable comfort ranges obtained by researchers in other parts of Nigeria. This finding as well as those obtained from other works carried out in the tropical climate of Nigeria indicate that building occupants in Nigeria are adapting to higher temperatures than earlier predicted in historical research and international standards.

6.5 COMF Perception and Office Clothing Policy

One main objective of this study is to compare the thermal perception of office workers with strict uniform policy with those with flexible office clothing policy. In order to achieve this objective, participants were selected from two different establishments: FRCN (with flexible office clothing policy) and FRSC (with strict uniform policy).

As illustrated in Figure 5.20 and summarised in Table 5.10, about 85% of workers with flexible office clothing voted that they were comfortable with the thermal conditions surrounding their work environment. Whereas, for workers with strict uniform policy, the percentage of participants who voted that they were satisfied with their thermal environment was approximately 55%.

In order to show the extent to which the strict uniform policy of FRSC workers affected their perception of thermal comfort, these comfort votes were further analysed according to time of the day for each establishment. This analysis was necessitated by what the researcher observed among some office workers in FRSC during the morning hours. As explained in section 5.2.4(A), it was observed that majority of the participants from FRSC go to work in personal clothing and only later change to the official uniform before the late morning hours or mid-day. The extent to which the workers perception of comfort were affected by this action is discussed in the following sub-sections.

6.5.1 Breakdown of Office Workers COMF Votes According to Time of the Day

As shown in Figure 5.22; for FRCN workers, with flexible clothing policy, the percentages of participants who were satisfied with their thermal environment were consistent throughout the day. In the morning hours (before 11am), more than 86% voted that they were comfortable. At mid-day (between 11am and 1pm), the percentage of those comfortable was about 80%. While at late afternoon (after 1pm), the percentage was more than 85%.

Figure 5.21 shows the comparison between the comfort votes of FRCN workers and FRSC workers (with strict uniform policy). This comparison is summarised in Table 6.5. During the morning hours were most of the participants of FRSC were putting on flexible clothing, the percentage of those who voted that they were comfortable with their thermal environment were more than 90%. However, at mid-day and late afternoon, the percentage of those were satisfied with the thermal conditions surrounding their work spaces were less than 40%.

When the COMF votes of FRCN workers were compared with those of FRSC, the observations and the semi-structured interviews component of the field work indicated that the strict uniform policy of FRSC was the major contributing factor for the dissatisfaction of workers with their thermal environment. This further explains why the comfort votes of workers in the FRSC office spaces did not comply with the estimation of the adaptive model of ASHRAE Standard 55-2013.

Also, the result of the semi-structured interviews as presented in section 5.5.6, shows that all participants interviewed were not in support of strict uniform policy. They indicated that any office clothing policy that restrict their ability to adjust or change their clothing makes them feel uncomfortable.

Furthermore, the discomfort location of those who were dissatisfied, as illustrated in Figure 5.38, shows that more that 75% participants felt discomfort all over. This again support the findings that the strict uniform of workers of FRSC was a major factor that resulted to their dissatisfaction with the thermal conditions surrounding their work environment.

Table 6.5: Summary of comparison of breakdown of percentages of COMF votes between participants of FRCN and FRSC

	Morning (before 11am)	**Mid-Day (between 11am and 1pm)**	**Late afternoon (after 1pm)**	**Remarks**
FRCN (Flexible Clothing)	86.87%	79.79%	85.85%	√
FRSC (Strict Uniform)	90.19%	37.26%	37.26%	✕

6.5.2 Are Office Workers Uncomfortable Because of Their Office Clothing Rather Than Temperature or Humidity of the Workplace?

In order to show if office clothing made office workers to be more uncomfortable with the thermal conditions surrounding their work environment when compared with temperature and humidity of the office spaces surveyed; the temperature and humidity data presented in section 5.3.1 are summarised and categorised according to office clothing policy. Table 6.6 shows the comparison for the outdoor air temperature, indoor operative temperature and indoor relative humidity of both FRCN and FRSC office spaces.

A comparison of the immediate outdoor air temperature of FRCN office spaces with those of FRSC shows that there is no difference in the immediate outdoor temperature condition for both complexes. Both have the mean outdoor air temperature of 33.2^{0}C and a coefficient of variation of 9.8% and 9.4% respectively throughout the period of the field research work.

The mean indoor operative temperature for office spaces in FRCN and FRSC complexes are 28.2^{0}C and 28.9^{0}C respective. The coefficient of variation of the operative temperature for all office spaces during the period of the field survey are 6.0% for FRCN and 6.1% for FRSC. In terms of operative temperature, there is no difference in the thermal performance of the office spaces in the buildings of FRCN (where there is flexible office clothing policy) with those of the FRSC (where there is strict uniform policy).

There is also similarity in the indoor relative humidity for both office complexes. The office spaces in FRCN and those of FRSC, both have a coefficient of variation of 18.0% in relative humidity. While their mean relative humidity during the period of the survey were 56.2% and 66.0% respectively.

If temperature and humidity were the main determinant of the comfort satisfaction of office workers during the period of the survey, then, office workers in both complexes ought to have experienced similar comfort satisfaction level given the similarity between these thermal variables for both office complexes. However, this was not the case as illustrated in Figure 6.1. For participants in FRCN, with flexible office clothing policy, the percentage of those who voted that they were either “somewhat comfortable”, “comfortable” or “very comfortable” was about 85%. Whereas, it was a little less than 55% for participants in FRSC, where a strict uniform policy in place.

Given that the activities levels of both office spaces surveyed were similar, it can be concluded that office clothing was the major determinant of workers comfort satisfaction when compared with temperature and relative humidity. Another thermal variable that could have impacted on workers thermal satisfaction was air velocity. During the survey, this was not logged on a continuous basis the way the temperature and humidity data were logged. It could be argued that air velocity might have contributed to the variation in thermal satisfaction recorded in both office complexes surveyed during the field work (Cândido et al., 2011, 2010; Manu et al., 2014; Nasrollahi, 2007).

While this argument might be true, further comparison of the breakdown of participants’ thermal comfort vote according to time of the day (Figure 6.2) with the corresponding mean clothing insulation (Figure 6.3) reveals that office clothing played a significant role in the thermal comfort perception of participants. During the morning hours when the clothing insulation value of FRSC staff was much lower compared to mid-day and late afternoon, more than 90% voted that they were satisfied with their thermal environment. The reason for this variation and further discussion on this are presented in sections 6.5.2(A) and 6.5.2(B).

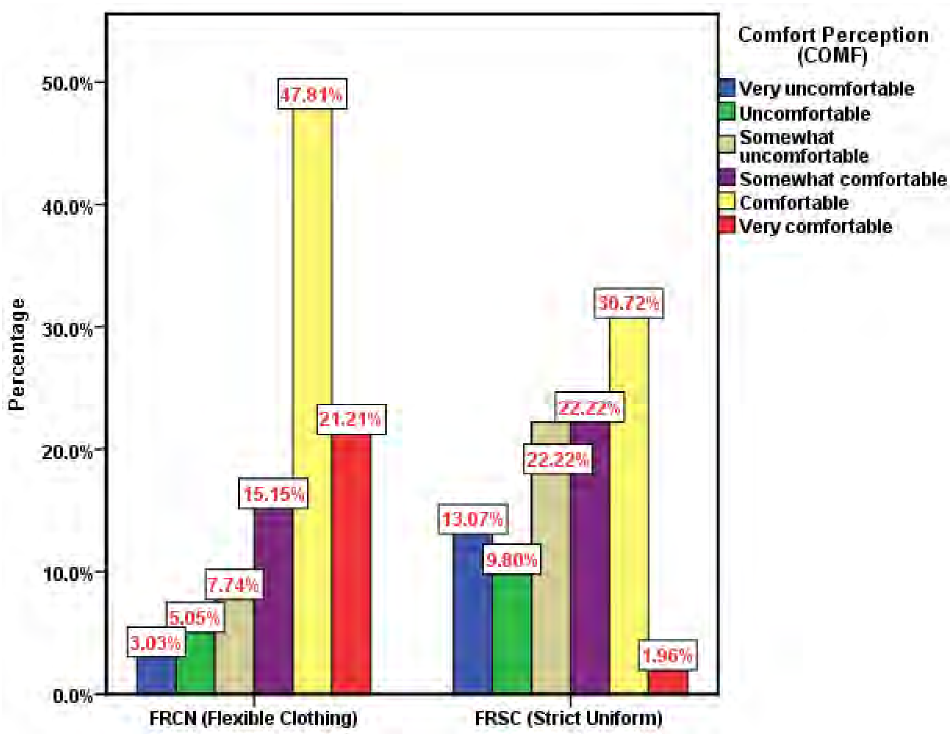


Figure 6.1: Comparison of thermal comfort vote of participants from FRCN with those of FRSC

Table 6.6: Comparison of between the measured thermal variables of FRCN office spaces with FRSC office spaces

Thermal Variables	FRCN Office Spaces						FRSC Office Spaces				
	Max	Min	Mean	Standard Deviation	Coefficient of Variation		Max	Min	Mean	Standard Deviation	Coefficient of Variation
Prevailing Outdoor Air Temperature (^{0}C)	39.8	24.4	33.2	3.239	0.098		39.6	24.9	33.2	3.112	0.094
Indoor Operative Temperature (^{0}C)	31.9	24.4	28.2	1.703	0.060		32.4	25.7	28.9	1.753	0.061
Indoor Relative Humidity (%)	83.7	41.9	56.2	10.116	0.180		82.5	40.2	66.0	11.853	0.180

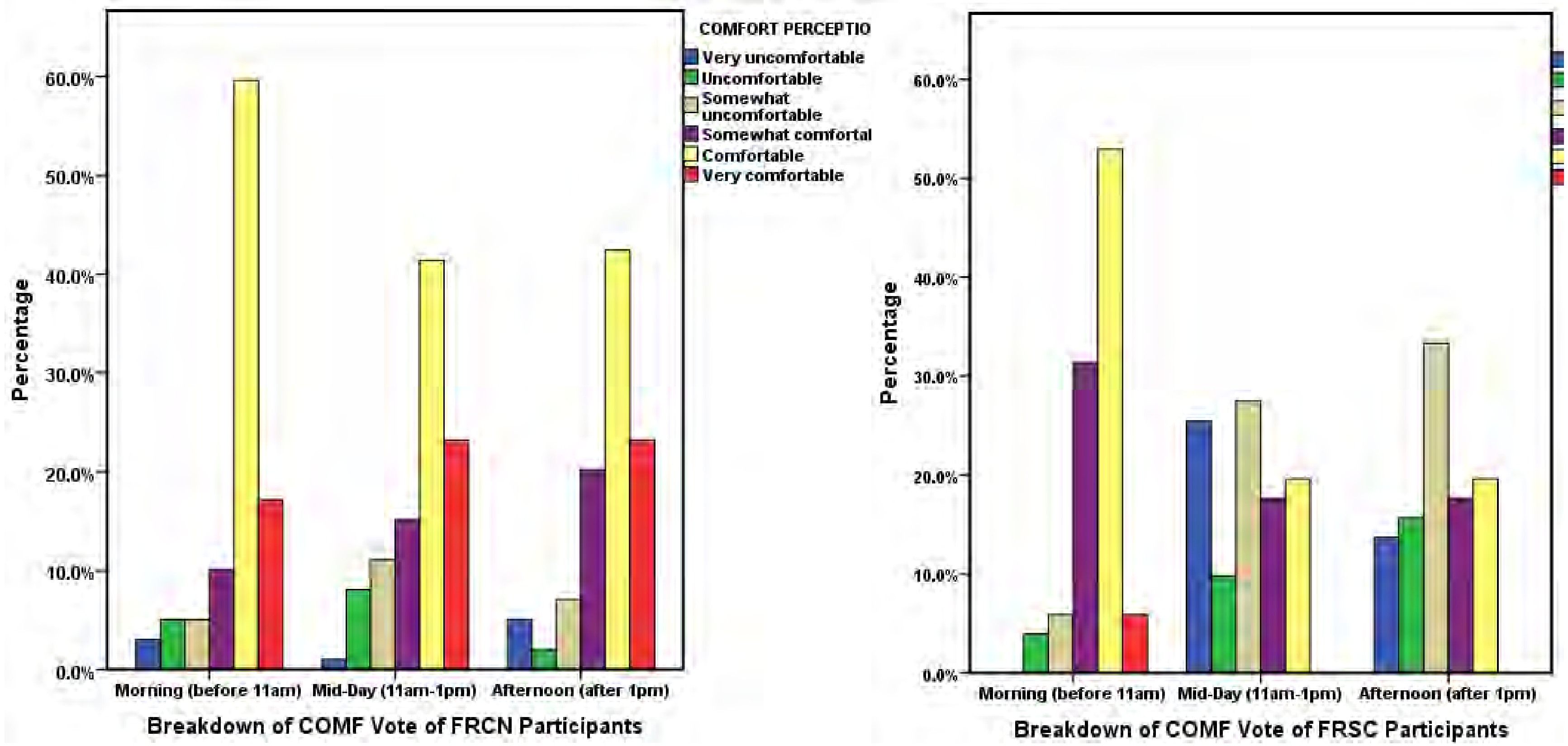


Figure 6.2: Comparison of breakdown of thermal comfort vote of participants of FRCN with those of FRSC

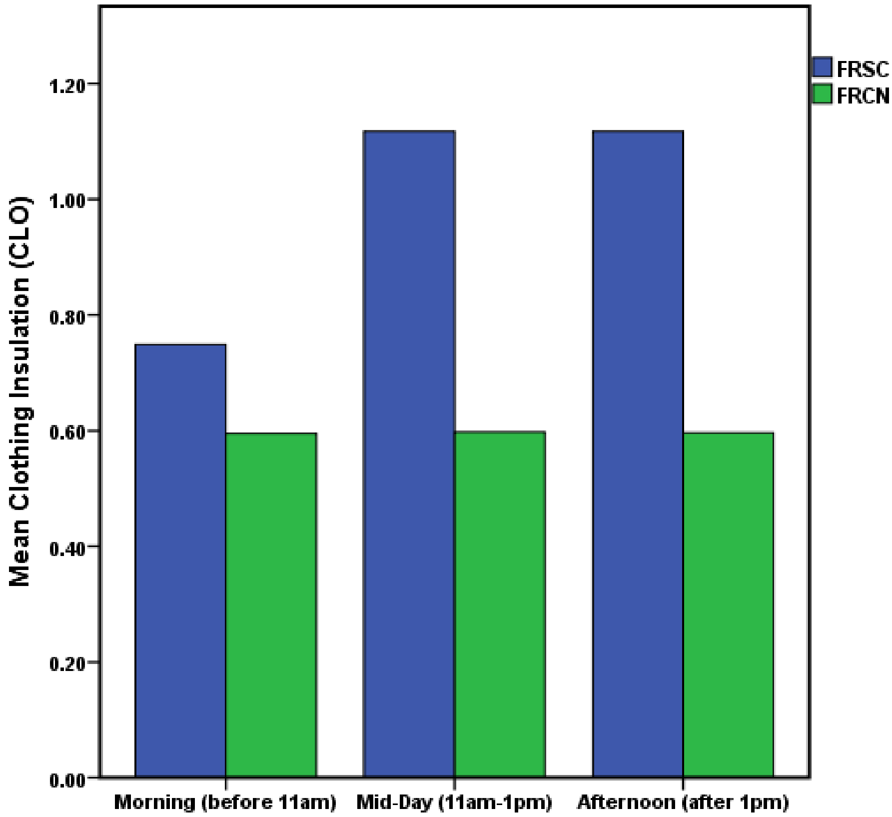


Figure 6.3: Comparison of breakdown of mean clothing insulation of participants of FRCN and those of FRSC

A. Discussion based on observational study

Based on the observational study, as reported in section 5.2.4(A) of Chapter 5, most of the participants from FRSC put on flexible clothing during the morning hours then change to their strict uniform clothing before mid-day. This accounted for the wide variation in the mean insulation value for the office clothing of participants from FRSC between the morning hours and during mid-day as well as late afternoon. This is a strong reason while the researcher concluded that office clothing has a significant role in the thermal comfort perception and adaptation of office workers in the cases studied.

The observed clothing changing habit of participating staff from FRSC and the corresponding thermal comfort votes clearly shows that policy makers and employers, who are responsible for making office clothing policies, should review their current strict uniform or office clothing policies. As this study have shown, flexible office clothing policy that gives workers the freedom to adapt or adjust their clothing will contribute to increase in satisfaction with the thermal conditions surrounding their work places.

B. Discussion based on semi-structured interviews

The semi-structured interviews report presented in section 5.5, also shows that participated did not favoured strict uniform or office clothing policy. They said that their office clothing have no connection with their comfort perception as long as there are some forms of mechanical cooling installed in their work places. The implication of this is that, strict uniform or office clothing policy are compensated for with mechanical ventilation systems. Such policy will not only increase cost but will also negatively affects effort toward mitigation and adaptation to climate change.

Furthermore, some of those interviewed said they will only accept strict clothing policy if it were compensated for with increased salary. This indicates that office workers in the hot humid climate zone of Enugu, Nigeria, preferred office clothing policy that will give them the flexibility to adjust or change their clothing policy.

All employers, private or public sector, are in business to make profit not to waste money unnecessarily. This study has shown that workers will only accept strict uniform or office clothing policy at a cost to the employer. This should make policy makers and employers, who make strict clothing policy for their staff, to consider reviewing their policy as this will benefit both the employers and the employees.

6.5.3 Summary of Thermal Comfort Perception With Respect to office Clothing Policy

The comparison of thermal comfort perception of office workers with strict uniform policy with those with flexible office clothing policy in the cases studied, indicated that office clothing policy has a major impact on how workers perceive their thermal environment. The findings from this study revealed that when workers are not given the flexibility to adjust their office clothing, it affects their ability to adapt to the thermal conditions surrounding their office spaces. This in turn will affects how comfortable they will feel with respect to thermal comfort.

6.6 Relationship Between Clothing Insulation (CLO) and Subjective Thermal Sensation (TSENS)

As presented in section 5.4.2(C) and summarised in Table 5.12, the linear regression analysis of the relationship between CLO and TSENS yielded the equation, Y = 3.960*X-2.961. The equation was statistically significant at a 0.01 with a Pearson correlation value of 0.521. This resulted to a subject clothing insulation comfort limits (TSENS between -0.85 and +0.85) of between 0.53 and 0.96 clo.

The adaptive comfort of ASHRAE Standard 55-2013 recommends that occupants should be free to adjust their clothing within a range of 0.5 to 1.0 clo. The results obtained from the relationship between CLO and TSENS in the study, therefore, complies with the ASHRAE Standard. This relationship thus indicates that the adaptive comfort is applicable to office workers in the hot humid climate of Enugu, provided workers are given the opportunity to adjust their clothing within the comfort range when necessary.

Previous studies carried out by Schiavon & Lee (2013), Morgan & de Dear, (2003) and those done by De Carli, Olesen, Zarrella, & Zecchin, (2007) have all related clothing insulation to mean outdoor air temperature and in some case mean indoor operative temperature. These have all shown that clothing insulation is strongly related to mean outdoor air temperature.

In this study, clothing insulation was related to mean TSENS. The results of the analysis also shows that there is a strong relationship between clothing insulation and the mean TSENS of the participants in this study. However, what this study did not determine is: How many employers are familiar with what clothing insulation value for different clothes and garment ensemble is all about in the study area? For this study, the clothing insulation values were estimated from the table published in ASHRAE Standard 55-2013. But how accurately can the insulation values of locally produced fabrics be estimated using clothing insulation tables contained in international standards such as those of ASHRAE and ISO?

In the context of this study, employers and employees appears not be aware or do not take into consideration clothing insulation value when taking decision regarding office clothing policy. This has had a negative impact on the overall thermal comfort satisfaction of office workers with strict uniform or office clothing policy. In the researcher's opinion, simplifying and publicizing the clothing insulation value in the local context of this research might also help in influencing the decision of employers and policy makers before deciding on any strict uniform or clothing policy. There is need to create awareness regarding clothing insulation value.

6.6.1 Significance of the Relationship Between CLO and Subjective TSENS in This Study

Figure 5.29 is the bivariate scatter plot of mean TSENS votes against clothing insulation of participants with an R square value of 0.271. While this shows that the regression equation could only explains 27.1% of the relationship, it is however statistically significant. Again, the low value of R square for the relationship explains how difficult it is to estimate human perception or psychology using statistical methods alone.

However, when this relationship is compared with the relationship between indoor TOP and TSENS as discussed in section 6.4.3, it could be seen that clothing insulation is a better predictor of the TSENS of participants than the indoor operative temperature. This result is also supported by the analysis result illustrated in the correlation matrix in Figure 5.25; which shows that of all the thermal variables measured or recorded, CLO has the strongest correlation to TSENS. This strong correlation between CLO and TSENS thus shows that clothing was the major determinant of how participants perceived their thermal environment during the period of the survey.

This clearly shows that for building occupants to be comfortable within the ASHRAE adaptive comfort limits, office workers in the hot humid region should be given the opportunity to adjust their clothing within the range of 0.53 and 0.96 clo as established from this study. Strict uniform policies that specify office clothing with CLO value higher than 1, with no opportunity for workers to make adjustment, will make it difficult for the adaptive comfort of ASHRAE Standard 55-2013 to be apply in such office spaces where they occupied.

6.6.2 Summary of Relationship Between Clothing Insulation (CLO) and Thermal Sensation (TSENS)

This study has shown that there is a strong relationship between building occupants CLO and their TSENS. The relationship has also yielded a clothing insulation range of 0.53 and 0.96 clo. Hence, for adaptive comfort standard to be applicable in the hot humid climate zone of Nigeria, building occupants must be able to adjust their clothing within this CLO range. Above, employers need to know what CLO values are and should be able to determine the CLO value of any office clothing ensemble they want to recommend to their staff.

6.7 Discussion on Methodology

The success of any research work or study depends to a large extend on the approach or methodology of the work. For this study; field research studies, which applied both the quantitative and qualitative methods of data collection and analysis, was the main research method. The traditional thermal comfort questionnaires were used in collecting participants' subjective thermal perception. The study adopted a longitudinal approach in administering the questionnaires. This approached yielded more comprehensive information regarding participants' perception of their thermal environment (Langevin et al., 2013).

A comparison of the thermal comfort votes from the questionnaires with those obtained from the semi-structured interviews, as presented in Table 5.13, reviewed that there was less than 30% inconsistency between the two different methods. The more than 70% consistency achieved in this study using both the quantitative questionnaires and the qualitative interviews shows that the quantitative approach used in thermal comfort study is very effective, especially since this study employed the longitudinal approach in administering the questionnaires.

However, the qualitative semi-structured interviews results presented in section 5.5 helped in revealing some significant facts about the participants' view of regulated office clothing, which the quantitative questionnaire did not captured. Some of the significant views expressed include:

- Participants were willing to talk freely about how they view their office clothing but were not willing to put these information in writing.

- ❖ Participants have no problem with strict uniform or office clothing policy as long as there are mechanical cooling systems in place to make them feel comfortable. This implies that; where there is no mechanical cooling in place, they are not willing to accept any form of regulation or policy that will restrict their choice of office clothing. This would mean constant reliance on alternative source of power supply since there is no constant electric power supply in the study location. These forms of alternative power supply are not friendly to the environment or to the human health.
- ❖ Workers interviewed clearly showed that they are not willing to accept strict uniform policy. In their view, regulations that restrict their choice of office clothing is synonymous to discomfort. Some who were willing to accept strict office clothing policy are only willing to do so if it will mean 'increased salary' for them.

Furthermore, the observation component of this study also revealed a significant clothing changes by participants in FRSC offices. Workers coming to work with clothing different from their official uniform and later change to the approved uniform before they will be noticed. These change of clothing occurs not because they are comfortable with the official clothing but because they do not want to incur the sanction or discipline that comes with not wearing the approved uniform (Efeoma & Uduku, 2015). The workers were not willing to note this changes in clothing in any form of questionnaire or put it in writing, despite the fact that they were told all information will be confidential and anonymous.

In summary, the mixed mode methodology used in this study appears to be an effective approach in achieving the main aim of this research. The observation and semi-structured interviews clearly showed that regulated office clothing has a big impact on the way office workers in the cases studies perceive and adapt to the thermal conditions surrounding their work places. Clothing thus provided the greatest adaptive opportunity for workers in the cases studied.

CHAPTER 7

CONCLUSIONS

7.1 Introduction

This study investigated the extent to which regulated office clothing affected the perception and adaptation of office workers in the hot humid climate zone of Enugu, Nigeria, to the thermal conditions surrounding their work environment. The research focused on the adaptive thermal comfort of local office workers in their normal day to day work settings. This chapter presents the summary of key research findings from this study. It also discusses the contributions of this research to the body of knowledge as well as some limitations of the study. It concludes with the discussion of some future research potentials.

7.2 Summary of Conclusions

The most significant findings from this study is that local office workers in naturally ventilated offices in the hot humid climate zone of Enugu, Nigeria, could achieve thermal comfort through adaptation under conditions which are defined as "uncomfortable" according to historic research work carried out in the same climate zone in Nigeria (Ojosu et al., 1988) as well as international standards such as ISO 7730. This conclusion regarding office workers' adaptive thermal comfort presents huge opening for more sustainable office building designs and construction that will reduce reliance on mechanical cooling systems. It means that passively cooled or naturally ventilated buildings that will be more energy efficient can be built, thereby reducing the impact of climate change. This is really significant in view of the poor electricity supply situation being experienced in Nigeria and high dependency on polluting electric power generator systems which are used in the running of air-conditioned cooling systems in office buildings. Other key research findings from this study are summarised as follows.

- ❖ Office workers who participated in this study took different actions that enabled them to adapt to their thermal environment. These actions included: clothing adjustment, the opening of doors and windows, taking a walk, turning fans, and other mechanical cooling devices on or off depending on the weather condition.
- ❖ Of all the thermal variables measured and recorded during the research, clothing insulation had the strongest correlations to the thermal sensation of the office workers who took part in the study. The correlation coefficient of clothing insulation was 0.516, whereas indoor operative temperature was 0.236, outdoor air temperature has a correlation coefficient of 0.131, relative humidity, 0.115 and metabolic rate was 0.020.
- ❖ More than 80% of the participants in this study accepted a clothing insulation comfort limits ($-0.85 \leq TSENS \leq +0.85$) of between 0.53 to 0.96 clo. The comfort range obtained from this research is consistent with the range suggested for the adaptive thermal comfort of ASHRAE Standard 55-2013, which recommends a range between 0.5 to 1.0 clo.
- ❖ Clothing afforded office workers the greatest adaptive opportunity during the period of the survey. In offices with strict uniform or clothing policies, where office workers are restricted in their ability to adjust their clothing, the percentage of those who were dissatisfied with their thermal environment was more than 45%. Whereas for workers with flexible clothing, only about 15% were

dissatisfied with the thermal conditions surrounding their work environment.

- This study yielded a neutral temperature of 28.8^{0}C, with a comfort range (-0.85≤TSENS≤+0.85) of between 25.4^{0}C and 32.2^{0}C; where less than 20% were dissatisfied with the thermal conditions surrounding their work environment. This results are comparable with some of the findings by some international researchers in hot humid climate zones in other countries, especially the results obtained from Singapore hot humid climate in naturally ventilated buildings. They were also in agreement with some of the few thermal comfort researches carried out in Nigeria.

- Local office workers' thermal sensitivity and thermal neutrality were consistent with the ASHRAE Standard 55-2013 adaptive thermal comfort. The only exceptions were in naturally ventilated offices with strict uniform policy for staff. Thus, in order for office workers in naturally ventilated offices in the hot humid climate of Nigeria to be satisfied with their thermal environment; this study has shown that they should have the freedom to adjust that clothing.

- While participating office workers' thermal sensitivity were in compliance with the adaptive comfort of ASHRAE Standard 55-2013, their thermal preference indicated that they would have preferred conditions that were cooler that those specified by the adaptive thermal comfort of ASHRAE Standard 55.

- The thermal conditions preferred by workers were consistent across different time of the day, in the two workplace typologies surveyed, in both mixed-mode and naturally ventilated spaces, and across offices with flexible office clothing policies and those with strict uniform policy.

- ❖ This study as well as a few others reviewed in this thesis shows that it is possible for Nigeria to develop a local adaptive thermal comfort standard that can be implemented during the design, construction and operations of office buildings. Such a standard will encourage design strategies that provide more adaptive opportunities for building occupants. By extension, such strategies will result to reduction in both building energy consumptions and greenhouse gas emissions.

7.3 Research Contributions and Limitations

The main original contributions of this study, especially in the local context of Nigeria, are summarised as follows.

- ❖ Conceptually, the findings from this study will provide policy makers and employers with strict uniform or office clothing policy in Nigeria a basis to review their current office clothing policy to a more flexible clothing policy that will encourage adaptive opportunities for workers to adjust their office clothing where necessary. This in turn will reduce reliance on mechanical cooling systems which are expensive to install and maintain.
- ❖ On a broader scale, this study also contributed to the database for general adaptive thermal comfort studies in the hot humid climate zones. The findings from this study could be valuable in contributing

to the development of a local adaptive thermal comfort standard for the local climate of Nigeria.

- The mixed-mode methodology as well as the longitudinal approach used for this study could be adopted for future thermal comfort studies. As the observations and the semi-structured interviews component of this research highlighted that these qualitative methods can help to capture vital details which are often overlooked in the purely subjective approach to thermal comfort studies employing solely questionnaires and statistical modes of analysis.
- The results from this study could be used for the development of simulation models that will be well suited for the hot humid climate zone of the sub-Sahara Africa, as most of the current simulations software do not really capture the actual conditions that are experienced in real buildings in the climate zone. The results could also be used by future researchers in the region as a basis for validating suitable simulation software.

Some of the limitations associated with this study can be summarised as follows.

- Due to unavailability of equipment to continuously log the air velocity for all office spaces surveyed, the impact of air movement on the adaptive thermal comfort of the local office workers was not analysed. This could have significant impact on the perception and adaptation of workers as some research works done in hot humid climate zone in other countries have shown (Cândido et al., 2011, 2010; Manu et al., 2014).

- ❖ The difficulty in gaining permission to access building also resulted to another major limitation to this study. The number of case study buildings and participants selected for this study are limited, hence, the results cannot be generalised without further research work involving more participants and buildings.
- ❖ The volatile security situation is some parts of the country as of the time the field research work was conducted also limits the climate zones that were originally intended to be covered in this study.

7.4 Recommendations for Future Research

Research into adaptive thermal comfort in Nigeria is still at it's early stage when compared to what has been accomplished in the West and Asia. Hence, the following suggestions are recommended for future research in Nigeria and African context.

- ❖ **Impact of air velocity on thermal perception and adaptation:** Various studies done in the field of thermal comfort research have shown the effect of air velocity on comfort sensation (Aronoff & Kaplan, 1995; Cândido et al., 2011, 2010; ISO, 2005; Manu et al., 2014; Nasrollahi, 2007). However, during this field research work, the air movement of the office spaces surveyed were not logged on a continuous basis as it was with temperature and humidity. Hence, it was not possible to establish a relationship between air movement and occupants' thermal comfort. Therefore, the author recommends more studies in the local context comparing the impact of air velocity on thermal perception and adaption of local residents.

- **Potential energy saving potential and building design strategies:** The author also suggests that future research should be focused on energy usage calculations and simulations in order to determine energy saving potential of adaptive thermal comfort in the local context. As the results from such studies can help in generating more sustainable energy efficient design strategies.
- **Methodology:** This study has also highlighted the significance of the mixed-mode approach in the field of thermal comfort studies, especially in adaptive thermal comfort research. Future research should always include some qualitative methods such as interviews and observational studies, which can help to capture details that could be overlooked in the traditional quantitative approach.
- **Re-calibration and publicising of clothing insulation:** In order to help the public and employers to understand what clothing is most appropriate to achieve thermal comfort in the local context; there is need for future research to look into the possibility of re-calibrating and publicising the clothing insulation scale as this research has shown that clothing was the most significant factor influencing thermal adaptation in the cases studied.

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Appendix A.1 – Part 1 of Questionnaire

SURVEY OF THERMAL ADAPTATION OF OFFICE WORKERS IN ENUGU, NIGERIA (HOT-HUMID REGION)

This survey is part of a PhD research work, which aims to investigate the impact of office clothing on the thermal adaptation of office workers in Enugu, Nigeria. In order to obtain broad and objective results, we sincerely request you to take part in this survey. Your answers will contribute to thermal comfort study and thermal environmental estimation in this climate region.

Please note: all of your answers are completely anonymous and confidential
For enquiries and additional information, please contact **Meshack Efeoma**
Email: m.efeoma@ed.ac.uk Tel: +44 7423 730451

PART 1

CODE:________________ **DATE:**_____________________ **TIME:**_______________

GENERAL INFORMATION

1. Please indicate your gender
( ) male ( ) female

2. Please indicate your age range
( ) less than 19 years old ( ) 19–29 years old ( ) 30–39 years old
( ) 40–49 years old ( ) 50–59 years old ( ) 60–69 years old
( ) 70–79 years old ( ) above 79 years old

3. How long have you lived in the hot-humid climate of Enugu?
( ) less than 1 year ( ) 1–5 years ( ) 6–10 years
( ) 11–15 years ( ) more than 15 years

OFFICE SPACE CONDITION

4. How would you describe your office space?
( ) Enclosed space ( ) open plan office

5. How would you describe the ventilation system of this office space?
( ) natural ventilation ( ) air-condition system ( ) mixed-mode

6. How many persons usually work in this office space?
( ) 1 ( ) 2 ( ) 3 ( ) 4 ( ) 5 ( ) more than 5 persons

7. How many external windows are there in this office space?
( ) 0 ( ) 1 ( ) 2 ( ) 3 ( ) 4 ( ) more than 4 external windows

8. Is your desk close to a window?
( ) yes ( ) no

9. How many floors are in this office building?
( ) 1 ( ) 2 ( ) 3 ( ) 4 ( ) other (provide the floor number) ________

10. What floor is your office space located?
( ) ground floor ( ) 1st floor ( ) 2nd floor ( ) 3rd floor
( ) 4th floor ( ) other (provide the floor number) ________

Appendix A.2 – Part 2 of Questionnaire

SURVEY OF THERMAL ADAPTATION OF OFFICE WORKERS IN ENUGU, NIGERIA (HOT-HUMID REGION)

Please note: all of your answers are completely anonymous and confidential
For enquiries and additional information, please contact Mr Meshack Efeoma
Email: m.efeoma@ed.ac.uk Tel: +44 7423 730451

PART 2

CODE:_______________ **DATE:____________________** **TIME:______________**

THERMAL COMFORT

1. SINCE YOU FIRST ARRIVED AT THE OFFICE, what has been the general trend in your THERMAL COMFORT?
   ( ) Staying the same ( ) Deteriorating ( ) Improving ( ) Fluctuating

2. How comfortable is the thermal environment in your office RIGHT NOW?
   ( ) Very Uncomfortable ( ) Uncomfortable ( ) Somewhat Uncomfortable
   ( ) Somewhat Comfortable ( ) Comfortable ( ) Very Comfortable

THERMAL SENSATION AND PREFERENCE

3. SINCE YOU FIRST ARRIVED AT THE OFFICE, what has been the general trend in your THERMAL SENSATION?
   ( ) Staying the same ( ) Getting colder ( ) Getting Warmer ( ) Fluctuating

4. Which single temperature sensation DO YOU MOST PREFER RIGHT NOW in your office?
   (Please select a single option)
   ( ) Cold ( ) Cool ( ) Slightly cool ( ) Neutral ( ) Slightly warm
   ( ) Warm ( ) Hot

5. HOW DO YOU ACTUALLY FEEL RIGHT NOW in your office?
   (Please select a single option)
   ( ) Cold ( ) Cool ( ) Slightly cool ( ) Neutral ( ) Slightly warm
   ( ) Warm ( ) Hot

   Please note here if your CURRENT THERMAL SENSATION is not fully captured by the scale above: (i.e. "Very Cold", "Very Hot", in between two of the available scale options, etc.)
   ____

LOCAL DISCOMFORT AND COMPLAINTS

6. Where do you most feel your thermal discomfort? (Please select all options that apply)
   ( ) Head ( ) Chest ( ) Back ( ) Pelvis ( ) Arms ( ) Hands
   ( ) Legs ( ) Feet ( ) All Over (No Particular Area)

CONTROL AVAILABILITY

8. Which of the following controls can you adjust?
( ) Window(s) ( ) Door(s) ( ) Blinds ( ) Fan
( ) Air-Conditional ( ) Thermostat ( ) None Of These Controls Are Available

CONTROL USE

9. SINCE YOU FIRST ARRIVED AT THE OFFICE, which available controls have you adjusted?
( ) Window(s) ( ) Door(s) ( ) Blinds ( ) Fan
( ) Air-Conditional ( ) Thermostat ( ) Others (Please Specify) ________________

10. What type of adjustment was made to the given control(s)?
(Please select all options that apply. For example: if you opened and then closed a window, select both an "OPENED" and "CLOSED" option)

	OPENED / TURNED ON / TURNED UP without asking others	OPENED / TURNED ON / TURNED UP after asking others	CLOSED / TURNED OFF / TURNED DOWN without asking others	CLOSED / TURNED OFF / TURNED DOWN after asking others	No Action
Window(s)					
Door(s)					
Blinds					
Fan					
Thermostat					

11. How did this action affect your thermal comfort?
( ) Staying the same ( ) Getting colder ( ) Getting Warmer ( ) Fluctuating

ACTIVITIES

12. What activities have you been engaged in for the past 15 minutes or less?
(Note: Only make a selection for activities that were actually engaged in. OK to leave other blank)
( ) Typing ( ) Reading/Writing (Seated) ( ) Reading/Writing (Standing)
( ) Having Conversation (Seated) ( ) Having Conversation (Standing)
( ) Filing (Seated) ( ) Filing (Standing) ( ) Walking About (Inside)
( ) Walking About (Outside) ( ) Eating ( ) Lifting/Packing
( ) Others (Please Speficy) ____

13. What activities have you been engaged in for the past 15 to 30 minutes?
(Note: Only make a selection for activities that were actually engaged in. OK to leave other blank)
( ) Typing ( ) Reading/Writing (Seated) ( ) Reading/Writing (Standing)
( ) Having Conversation (Seated) ( ) Having Conversation (Standing)
( ) Filing (Seated) ( ) Filing (Standing) ( ) Walking About (Inside)
( ) Walking About (Outside) ( ) Eating ( ) Lifting/Packing
( ) Others (Please Speficy) ____

14. What activities have you been engaged in for the past 30 minutes or more?
(Note: Only make a selection for activities that were actually engaged in. OK to leave other blank)
( ) Typing ( ) Reading/Writing (Seated) ( ) Reading/Writing (Standing)
( ) Having Conversation (Seated) ( ) Having Conversation (Standing)
( ) Filing (Seated) ( ) Filing (Standing) ( ) Walking About (Inside)
( ) Walking About (Outside) ( ) Eating ( ) Lifting/Packing
( ) Others (Please Speficy) ____

PRODUCTIVITY

15. SINCE YOU FIRST ARRIVED AT THE OFFICE, how BUSY with work have you been?
( ) Much LESS busy than usual
( ) A little LESS busy than usual
( ) As busy as usual
( ) A little MORE busy than usual
( ) Much MORE busy than usual

16. SINCE YOU FIRST ARRIVED AT THE OFFICE, how PRODUCTIVE have you felt?
( ) Much LESS productive than usual
( ) A little LESS productive than usual
( ) As productive as usual
( ) A little MORE productive than usual
( ) Much MORE productive than usual

CLOTHING

17. What kind of clothing are you wearing right now?
( ) Traditional
( ) English
( ) Others (Please Specify)__________________

18. What determines your work cloth? (Please select all options that apply)
( ) Office clothing policy
( ) Weather condition
( ) Culture
( ) What is available
( ) Colour of clothing
( ) Fashion
( ) Others (Please specify) __________________

19. Using the list below, please check each item of clothing that you are wearing right now. (Please select all options that apply)

( ) Short-Sleeve	( ) Long-Sleeve	( ) T-shirt
( ) Long-Sleeve Sweatshirt	( ) Sweater	( ) Vest
( ) Jacket	( ) Knee-Length Skirt	( ) Ankle-Length Skirt
( ) Dress	( ) Shorts	( ) Athletic Sweatpants
( ) Trousers	( ) Undershirt	( ) Long Underwear Bottoms
( ) Long Sleeve Coveralls	( ) Overalls	( ) Slip
( ) Nylons	( ) Socks	( ) Boots
( ) Shoes	( ) Sandals	

Appendix B – Collected Data

Available in electronic form

Appendix C – Sample of Application Letter Used in Requesting for the Use of Office Building(s)

THE UNIVERSITY of EDINBURGH
EDINBURGH SCHOOL of ARCHITECTURE
AND LANDSCAPE ARCHITCTURE
Room 4.17, Minto House
20 Chambers Street
Edinburgh
EH1 1JE
United Kingdom

Phone: +44 (0) 7423 730451
Email: m.efeoma@ed.ac.uk

3rd December 2013

____

____

____

____

Dear Sir/Madam,

USE OF OFFICE BUILDING/COMPLEX FOR THERMAL COMFORT RESEARCH

I, **Meshack O. Efeoma,** am a PhD researcher in Architecture with the above named University. My research is focused on **Office Clothing and Thermal Comfort** in tropical office buildings in West Africa. As part of my research, I will be conducting a thermal comfort evaluation of office workers in Enugu during the peaks of both the dry season (January to March) and the rainy season (May/June) of 2014.

The purpose of this letter is to get your approval to use your office complex for this research. The research will involve some form of thermal comfort measurements within the office working environment, some observations and the administering of questionnaires on selected participants.

I hope that you will be able to respond positively to this request. I would be most willing to provide you with any other information you may need in connection with this, and look forward to your favourable approval.

Sincerely,

Meshack O. Efeoma
Research Assistant/PhD Researcher
Edinburgh School of Architecture and Landscape Architecture
University of Edinburgh
m.efeoma@ed.ac.uk

Appendix D – Samples of Photograph Taken During Field Survey

Appendix E

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Longitudinal Survey of Adaptive Thermal Comfort of Office Workers in the Hot Humid Climate Zone of Enugu, Nigeria

Meshack Efeoma[1] and Ola Uduku[2]

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[2] Edinburgh School of Architecture and Landscape Architecture, University of Edinburgh, UK, o.uduku@ed.ac.uk

Abstract
The aim of this paper is to investigate the acceptable comfort temperature range of office workers in Enugu, Nigeria, in the hot humid climate zone, focusing on adaptation. A longitudinal approach, which surveyed occupants' subjective thermal perception over the dry and the rainy seasons, was adopted for this study. A mixed-mode methodology, combining a quantitative and qualitative methods, was employed in the collection and analysis of data relating to occupants' subjective thermal perception. Both the indoor and outdoor environmental variables were monitored simultaneously throughout the period of the survey in 2014 from the dry season; January to March, and the rainy season; from May to June. The analysis of the thermal performance of the office spaces surveyed found that they were in compliance with the ASHRAE Standard 55-2013 adaptive thermal comfort. The thermal sensation component of the results suggests a neutral temperature of 28.8^{0}C; with 80% thermal satisfaction, in a comfort range of between 25.4^{0}C and 32.2^{0}C. These results were consistent with a number of earlier studies on thermal comfort conducted in other climate zones in Nigeria.

Keywords: Adaptive thermal comfort, hot humid climate zone, Nigeria, neutral temperature and comfort range

1 Introduction

With a population of over 180 million, according 2015 estimate, Nigeria is the most populous country in African and the seventh in the world. According to the United Nations, it is estimated that by 2050, the population of Nigeria will be more than that of the United States (United Nations, 2015). This will put the country as the third most populous country in the world after India and China. Apart from population, Nigeria is also the largest economy in Africa with an annual Gross Domestic Product (GDP) of more than 568 billion US dollars in 2015 (World Bank Group, 2016). The Country's GDP experienced 6.3% growth in 2014. The World Bank Group has also projected an annual growth of 4-6% in GDP for the Country's economy.

An effect of this level of increased population and economic growth has been the demand for more buildings and infrastructural development in Nigeria. Also, the process of building and the running of physical infrastructure requires energy. In Nigeria as elsewhere in Africa this energy need is usually met by electricity. However, according to the Africa Progress Report 2015, more than 90 million Nigerians lack electricity (African Progress Panel, 2015). By way of comparison with other developing economy, Nigeria has nearly double Vietnam's population but generates less than 25% of the electricity that Vietnam does. Furthermore

Nigeria's main businesses are Small and Medium Enterprises (SMEs), of which more than 80% rely on fuel-powered electricity generators to sustain their business (Scott et al., 2014).

In addition to this pathetic power supply situation, there is also the issue of climate change. Nigeria, as with Africa in general, is experiencing the most damaging effects of climate change (African Progress Panel, 2015). In order to mitigate the impact of climate and to reduce reliance on the poor electricity supply, there is need to focus on more energy efficient ways of designing and constructing buildings. This is especially important since cooling load alone is responsible for about 40% electricity consumption in buildings, especially in office buildings, in Nigeria (Batagarawa et al., 2011). However, in Nigeria; there is no standard energy efficiency code for buildings, nor is there a national thermal comfort standard. The current National Building Code in Nigeria provides guidelines for the design and specification, costing, construction, alteration, addition to, moving, demolition, location, repair and use of any building or structure; but has no reference to either thermal comfort or energy efficiency (Federal Ministry of Housing and Urban Development, 2006).

Some researchers have conducted research work, into thermal comfort in buildings in Nigeria. These include; Adunola (2012); on residential comfort in relation to indoor and outdoor air temperatures in Ibadan. Also Akande and Adebamowo (2010), conducted field research on indoor thermal comfort for residential buildings in Bauchi, in the hot dry climate zone. In another study, Ogbonna and Harris (2008) undertook field studies examining thermal comfort in residential buildings in the temperate climate of Jos. Furthermore, a study of thermal comfort in the urban residential buildings in the warm humid climate of Lagos was undertaken by Adebamowo (2007). These are in addition to the historic research undertaken by Ambler in the warm humid climate of Port Harcourt in the 1950s and the one done by Ojosu et al. in the 1980s (Ambler, 1955; Ojosu et al., 1988). The results from these studies are summarised in Table 1.

Some of the research work has only been carried out for a short period of time and not covering the two seasons usually experienced in Nigeria. This highlights the need for a more comprehensive research focusing on adaption, over at least an annual period, taking into account both the dry and rainy seasons as well as Nigeria's different climate zones that have not been covered in the existing works. In addition to filling the gaps in the field of adaptive thermal comfort research in Nigeria, this paper also proposes that there should be either the inclusion of adaptive thermal comfort standard in future revision of the National Building Code or the development of a new thermal comfort standard for use in building design and construction.

Table 1: Summary of thermal comfort research done in Nigeria on neutral temperature and acceptable comfort range

Year	Researcher	Location (Climate Zone)	Building	Period (Season)	Key Research Findings
2012	Adunola A. O.	Ibadan (Hot Humid)	Residential	April	1. Regression equation: Y = 0.483*X – 15.59 (TSENS with respect to TOP*) 2. Neutral temp. = 32.3^{0}C TOP*
2010	Akande & Adebamowo	Bauchi (Hot Dry)	Residential	Dry and Rainy Season	1. Regression equation: Y = 0.357*X – 10.2 (Dry Season) 2. Regression equation: Y = 0.618*X – 15.4 (Rainy Season) 3. Combined neutral temp. = 28.44^{0}C TOP* 4. Acceptable comfort range = 25.5 – 29.5^{0}C TOP*
2008	Ogbonna & Harris	Jos (Temperate Dry)	Residential and Classrooms	July & August (Rainy Season)	1. Regression equation: Y = 0.3589*X – 9.4285 2. Neutral temp. = 26.27^{0}C TOP* 3. Acceptable comfort range = 25.5 – 29.5^{0}C TOP* ($-0.5 \le$ TSENS $\le +0.5$) 4. PMV neutral temp. = 25.06^{0}C
2007	Adebamowo	Lagos (Warm Humid)	Residential		1. Neutral temp. = 29.09^{0}C
1988	Ojosu et al	Hot Dry			1. Acceptable comfort zone = 21 – 26^{0}C
		Temperate Dry			2. Acceptable comfort zone = 18 – 24^{0}C
		Hot Humid			3. Acceptable comfort zone = 21 – 26^{0}C
		Warm Humid			4. Acceptable comfort zone = 21 – 26^{0}C
1955	Ambler H. R.	Port Harcourt (Warm Humid)	Office		1. Neutral temp. = 23.13^{0}C ET*

Note: *ET* (Effective Temperature), TOP* (Operative Temperature), TSENS (Thermal Sensation Vote)*

2 Methodology

2.1 The Study Area

The field research for this study was conducted in Enugu, a city in the hot humid climate zone of Nigeria. It is located at an altitude of approximately 223m above sea level and it lies between latitudes 5°55'15"N and 7°6'36"N, and longitudes 6°55'39"E and 7°54'26"E. It has an undulating topography with scattered hills and knolls (Reifsnyder et al., 1989; Sanni et al., 2007). It covers an approximate area of about 7,161km^2.

Being in tropical Nigeria, Enugu is hot all year round with a mean daily temperature of 26.7^{0}C (Sanni et al., 2007). The climate of Enugu is humid and the peak of the humidity is experienced between March and November (Reifsnyder et al., 1989). As with the West African geographical land mass, Enugu experiences two major seasons, the rainy and dry seasons. During the dry season months of December and January, the city is also affected by the 'Harmattan', a dust-laden trade wind from the Sahara desert, usually occurring over two to three week period, which can also affect visibility.

2.2 Data Collection

Six typical office spaces were selected for this study—three from the office complex of the Federal Radio Corporation of Nigeria (FRCN) and three from Federal Road Safety Corps (FRSC), Enugu. The surveys were conducted during the dry and rainy seasons in 2014. In order to determine the wide range of environmental conditions that office workers in the climate zone can adapt to, surveys were carried out in office spaces that were both naturally ventilated and others which had mixed-mode[1] ventilation in place. Also, spaces included open plan (OP) offices and enclosed space (ES) offices.

Throughout the period of the field survey conducted during the dry season, from January to March 2014, and during the rainy season; May to June 2014, dataloggers were placed in all the office spaces surveyed to record indoor operative temperature and humidity at 15 minute intervals. The dataloggers were located within 1 meter of each participants' workstation to record the actual thermal conditions being experienced by participants during normal working hours. Dataloggers were also placed outside the buildings to simultaeneously record the corresponding air temperature and humidity of the immediate outdoor environment at the same time intervals as the indoor dataloggers. A Hand-held instrument was used to measure the air speed in the different spaces surveyed at different instances during the study period.

The field study questionnaires were administered in two parts. Part One of the questionnaire was used for the recruitment of participants on a voluntary basis. Paper copies of the first part of the questionnaires were distributed to a self-selected group of participants, who were office workers in both offices of FRCN and FRSC. For the purpose of anonymity, codes were assigned to each participants that completed the first part of the questionnaires. Part One of the questionnaire was only administered during the first stage of the field research, since the information collected from that part of the questionnaire remained unchanged throughout the course of the survey.

[1] Mixed-mode ventilation in this research refers to office spaces that utilises a combination of natural ventilation from operable windows and some form of air-conditioning cooling system

Part Two of the questionnaire was administered in both stages of the field research work using a longitudinal approach. In contrast with a one-off 'point-in-time' assessment, a longitudinal approach that studies the same subject repeatedly over time can yield more comprehensive results (Langevin et al., 2013). Hence, this study adopted the longitudinal approach in administering Part Two of the thermal comfort questionnaires during both stages of the survey. For each day of the survey, three thermal comfort questionnaires were administered to each participant; one in the morning (before 11am), another one at mid-day (between 11am and 1pm), and the last one in the afternoon (after 1pm). This process was repeated for different days throughout the period of the two stages of the survey. Subjective thermal variables collected included: participants' subjective thermal comfort votes (COMF), thermal sensation (TSENS) and thermal preference (TPREF).

3 Analysis and Results

3.1 Participants

At the initial stage of the survey, 47 staff from both FRCN and FRSC were recruited on a voluntary basis for the survey. However, only 38 (approximately 80%) of the initial participants completed the longitudinal survey, for both the dry and rainy seasons. A total of 201 valid responses were obtained during the first stage of the survey. While a total number of 249 valid responses were obtained from participants during the survey. In all, 450[2] valid responses were obtained from the field research work.

Table 2 gives a summary of participants' background information on gender, age and the duration of years they have lived in the hot humid climate conditions of Enugu. During both stages of the survey, there were slightly more female participants (56.7% during the dry season and 54.2% during the rainy season). The majority of the participants (more than 89%) were below 39 year of age. While about half of the participants had lived in the hot humid climate of Enugu for more than 1 year but less than 5 years.

3.2 Comparison Between Indoor and Outdoor Temperature

In order to show the environmental comparison between the indoor and outdoor temperature obtained from the dataloggers a Paired-Samples T test and Bivariate Correlation testing was carried out. The results from these tests are summarised in Table 3. The comparisons of measured indoor and outdoor thermal conditions show that the indoor operative temperature were correlated with the outdoor air temperature. With the exception of the naturally ventilated office spaces where the significance of the correlation between indoor and outdoor air temperature was 0.05, all the mixed-mode ventilated spaces had a correlation significance of 0.01.

3.3 Comparison With ASHRAE Adaptive Comfort

In order to compare the buildings' thermal performances with ASHRAE Standard 55 adaptive comfort, the prevailing daily mean outdoor temperature from the loggers were plotted against the corresponding mean indoor operative temperature for office spaces used for the survey in FRCN and FRSC complexes. As shown in Figure 1 and Figure 2, these were compared with the 80% and 90% acceptable comfort ranges of the ASHRAE Standard 55-2013 adaptive comfort model (ASHRAE, 2013). The results from the comparisons show

[2] A total number of 564 questionnaires were administered during the survey periods. About 20% of the administered questionnaires, which is 114, were either invalid or not returned by participants.

that all the office spaces surveyed comply with the ASHRAE Standard 55 adaptive comfort standard.

Table 2: Summary of respondents' background information

		Total (n=450)		Dry season (n=201)		Rainy season (n=249)	
		Sample size	Percentage	Sample size	Percentage	Sample size	Percentage
Gender	Male	201	44.7	87	43.3%	114	45.8%
	Female	249	55.3	114	56.7%	135	54.2%
Age (years)	19-29	192	42.7	102	50.7%	90	36.1%
	30-39	210	46.7	78	38.8%	132	53.0%
	40-49	24	5.3	15	7.5%	9	3.6%
	50-59	24	5.3	6	3.0%	18	7.2%
Years in Enugu	<1	36	8.0	18	9.0%	18	7.2%
	1-5	207	46.0	99	49.3%	108	43.4%
	6-10	75	16.7	30	14.9%	45	18.1%
	11-15	12	2.7	3	1.5%	9	3.6%
	>15	90	20.0	39	19.4%	51	20.5%
	Missing	30	6.7	12	6.0%	18	7.2%

Table 3: Paired-Samples T Test and Bivariate Correlations testing between indoor operative temperature and outdoor temperature

	Office Spaces						
	Combined	A	B	C	Da	Db	Dc
Sample Size	450	72	168	57	51	39	63
Mean Indoor Temperature (^{0}C)	28.5	27.8	28.0	29.5	28.9	29.4	28.7
Mean Outdoor Temperature (^{0}C)	33.2	33.3	33.1	33.3	33.0	33.4	33.1
Differences in Mean	-4.7	-5.5	-5.1	-3.8	-4.1	-4.0	-4.4
Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pearson Correlations	0.520	0.502	0.680	0.774	0.577	0.397	0.253
Correlations Sig.	0.000	0.000	0.000	0.000	0.000	0.012	0.046

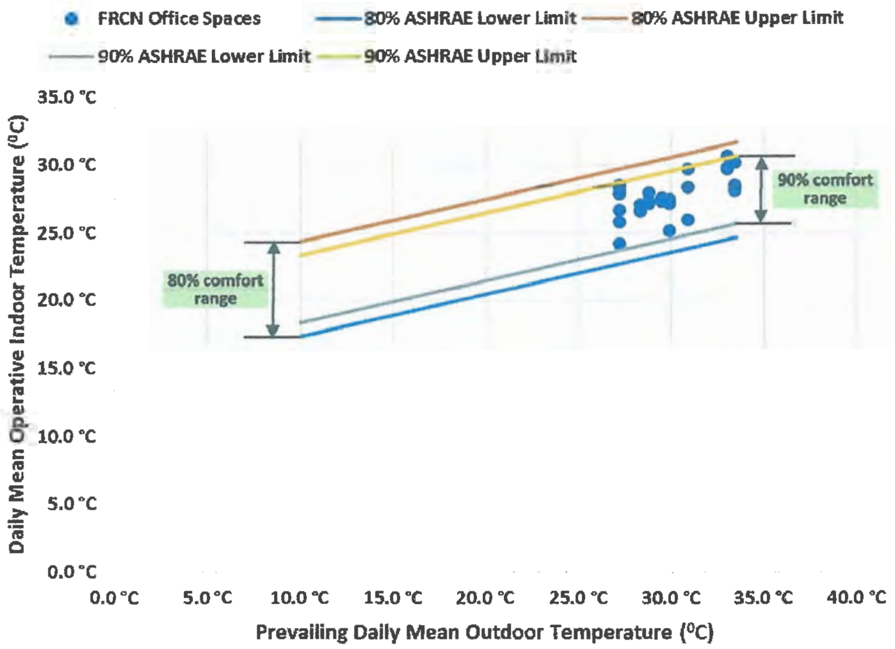

Figure 1: Daily mean indoor operative temperature for Office Spaces in FRCN Complex plotted against the prevailing mean outdoor temperature and overlaid with the adaptive model of ASHRAE Standard 55-2013

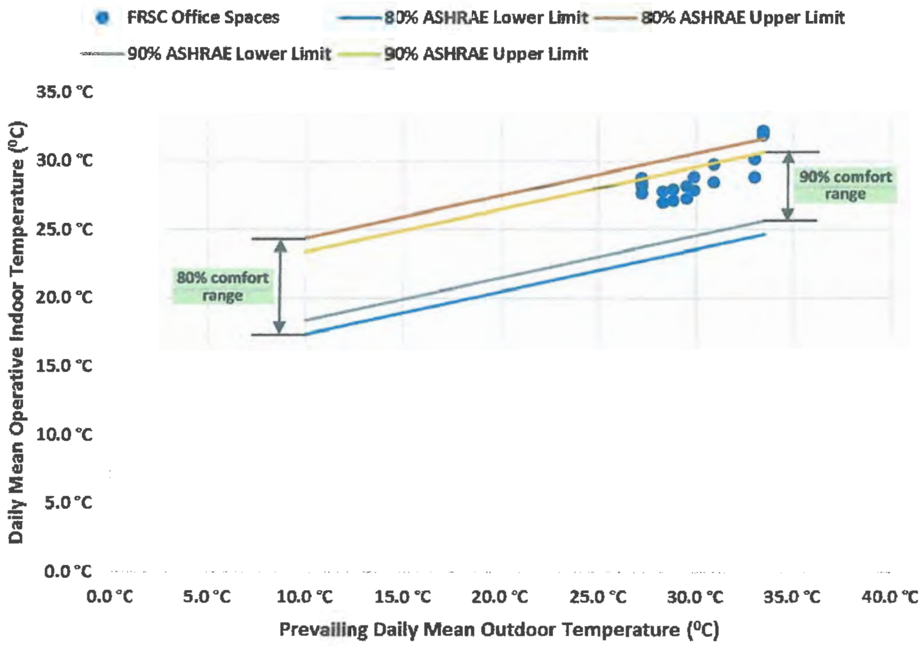

Figure 2: Daily mean indoor operative temperature for Office Spaces in FRSC Complex plotted against the prevailing mean outdoor temperature and overlaid with the adaptive model of ASHRAE Standard 55-2013

3.4 Neutral temperature and comfort range

The questionnaire adopted the ASHRAE seven-point thermal sensation scale (-3 = Cold, -2 = Cool, -1 = Slightly cool, 0 = Neutral, 1 = Slightly warm, 2 = Warm, 3 = Hot). Participants were allowed to select all the options that apply and the resulting mean from options selected was used to determine the participants vote. The mean TSENS vote for all participants in the survey was slightly below "Neutral", between "Slightly cool" and "Neutral" with a value of -0.08.

In order to determine the neutral temperature and comfort range, a linear regression analysis of thermal sensation was carried out with respect to weighted indoor operative temperature using SPSS software package. The resulting linear regression models was fitted according to the format as shown in Equation 1. Table 4 is the summary of the linear regression analysis of thermal sensation on weighted operative temperature.

$$Y = m*X + b \qquad (1)$$

Where,

m is coefficient or gradient

b is constant

Y is mean thermal sensation

X is operative temperature

The approach employed in ASHRAE adaptive comfort standard was used to define the indoor operative comfort range, it defines the 80% operative comfort range as $-0.85 \leq TSENS \leq +0.85$ (de Dear and Brager, 1998). This corresponds to approximately 80% thermal satisfaction, where Predicted Percentages Dissatisfied (PPD) is less than 20%. The neutral temperature corresponding to TSENS value equalling "0" was also calculated.

As shown in Table 4, the linear regression for the mean TSENS on weighted indoor operative temperature resulted to the equation: Y = 0.250*X – 7.197 with a correlation coefficient of 0.245 and a p-value of 0.000 (less than 0.05). This equation yielded a subject neutral temperature of 28.8^{0}C and comfort range (TSENS between -0.85 and +0.85) of between 25.4^{0}C and 32.2^{0}C. The gradient of the linear regression which is represented as "m" in Equation 1, indicates how much the thermal sensation (TSENS) changes with each operative temperature unit.

Table 4: Summary of thermal sensation votes responding on weighted indoor operative temperature

Sample size (n)	Comfort Range -0.85≤TSENS≤+0.85 (^{0}C)	Regression Equation	Pearson correlations	P-value
450	25.4 – 32.2	Y = 0.250*X-7.197	0.245	0.000

4 Discussion

The adaptive model relates the indoor neutral temperature to the monthly outdoor mean temperature. The results of the comparison of indoor and outdoor temperature as shown in Table 3, shows a strong correlation between indoor and outdoor temperature conditions. The relationship also shows statistical significance, at a value of 0.01. Also, the results of the comparison with the ASHRAE adaptive comfort chart also shows that office spaces surveyed comply with the adaptive component of ASHRAE Standard 55-2013.

The neutral temperature of 28.8^{0}C obtained from this study is outside the comfort range of the results of Ojosu et al (1988), which predicted a PMV comfort range of 21–26^{0}C for the climate zone. However, it is more consistent with some more recent studies, such as those of Akande and Adebamowo (2010) in the hot dry region, northern Nigerian city of Bauchi which is 28.44^{0}C. The neutral temperature is also slightly closer to the 29.09^{0}C obtained by Adebamowo (2007) in the southern city of Lagos in the the warm humid climate zone. While it is within the 90% comfort range of the works of Ogbonna and Harris (2008), which was carried out in the city of Jos in the temperate dry zone; the neutral temperature is slightly higher than the 26.7^{0}C obtained. Taking into consideration the characteristic of the city of Enugu's hot humid climate zone where this study was carried out in comparison with the temperate dry zone where Ogbonna and Harris carried out their studies, there is a clear indication that there is little or no disparity in the thermal neutralities obtained.

Apart from the climate zone of study location, other factors that might account for the little disparity in thermal neutrality of this study with some of the selected previous works done in Nigeria might be time and duration of study, methodology used or accuracy of reading of equipment used. For example, the result obtained from work carried out in another hot humid climate zone of Ibadan by Adunola (2012), yielded a thermal neutrality of 32.3^{0}C. This result is much higher than the 28.8^{0}C obtained from this study. The neutral temperature is also outside the 80% comfort limits ($-0.85 \leq TSENS \leq +0.85$) of 25.4^{0}C – 32.2^{0}C obtained from this study. Several factors might account for this disparity. Compared with this study which was carried out in office buildings, the work of Adunola was done in residential buildings. Also, in contrast with this work that was done in both the rainy and dry seasons, Adunola's work was carried out during the month of April only. Another important factor to highlight is that, this study also adopted a longitudinal approach instead of the traditional one-off 'point-in-time' assessment.

In summary, the comparison of the results obtained from this study with other similar works carried out in the different climate zones in Nigeria suggest that occupants of naturally ventilated buildings are more adaptable to a much warmer temperature than those specified in International Standard such as the ISO 7730. The observation and semi-structured interviews components of the survey further revealed the different actions that participants took in order to adapt to the thermal conditions surrounding their work places. This included: clothing adjustment (Efeoma and Uduku, 2015), the opening of doors and windows, taking a walk and turning fans on or off depending on the weather condition. Adaptive thermal comfort therefore is certainly becoming a better standard for the assessment of thermal comfort in the tropical climate of Nigeria. It is also a possible solution to achieving sustainable design that will enable building designers to combat the impact of climate change and to cope with the poor electricity supply situation being experienced in Nigeria. This is my view will help to reduce reliance on the Country's epileptic power supply and to free up money that could have been used for the installation, maintenance and running of mechanical cooling devices in the design and construction of buildings.

5 Conclusion and Recommendations

The results and analysis from this study clearly showed that the ASHRAE adaptive comfort is certainly applicable to the different climate zones of Nigeria, especially the hot humid climate zone where this research work was carried out. In view of the poor electricity situation currently being experienced in Nigeria; the adaptive comfort appears to be a possible solution to the design and construction of buildings in Nigeria. This will no doubt reduce reliance on mechanical cooling systems that require constant electricity supply to run effectively. In turn, reliance on backup generators, which are currently the main source of power supply in Nigeria today can be reduced significantly, if buildings are better able to adopt passive means of cooling and take into account local adaptive thermal comfort levels, which give more realistic comfort tolerances amongst populations than other international standards.

In view of the findings from this field study and associated research; the inclusion of adaptive thermal comfort assessments in future revisions of the Nigeria Building Code, would be justified in order to improve comfort standards and reduce reliance on energy-hungry mechanical cooling systems. Also, there is the need for the development of a local adaptive thermal comfort standards that respond better to the different climate zones in Nigeria.

Finally this study also recommends that future studies should include specific investigation of the relationship of clothing and air velocity to the subjective thermal perception of the environmental conditions experienced by local residents of different climate zones in Nigeria.

Acknowledgements

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Appendix F

OFFICE CLOTHING AND ITS EFFECT ON THERMAL COMFORT AMONGST OFFICE WORKERS IN HOT-HUMID CONDITIONS: A CASE STUDY OF OFFICE WORKERS IN NIGERIA

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Fig 1: Examples of office clothing worn by staff of FRCN (left) and FRSC (right)

Research summary

This paper reports on what effect the wearing of regulated office clothing, or official uniform, by administrative staff in the city of Enugu, in Eastern Nigeria, has had on staff perceptions of thermal comfort. This has been achieved by the analysis of the results of field studies conducted in offices of two different establishments in Enugu, Nigeria. The initial results from the field research work suggest that at the office with a strictly regulated clothing policy workers were less comfortable in the same temperature range, when compared to those working in offices with a more flexible approach to work clothing. The paper, therefore, recommends a change in office dress code policy by office management for office workers in the tropical West African climates. Such changes in office lifestyle and people's need will allow for some flexibility of adjusting or adapting office clothing to prevailing thermal conditions. This, in turn, will reduce reliance on mechanical form of ventilation which are expensive to run and maintain in an economy which rely mainly on backup power supply.

Keywords: Enugu, hot-humid climate, office clothing, thermal adaptation and perception.

1. Introduction

Office workers in Nigeria and elsewhere in the emerging world are often required to wear official clothing or uniforms by their employers. The military and the paramilitary, wear uniforms, as do officials of state parastatals and other organisations. In private companies, employers have a dress code policy for all staff, which is expected to promote the company's corporate image. Workers, in these situations, have little or no control over their choice of clothing. Furthermore dress code policies usually give little or no consideration to how the specified clothing will affect the thermal adaptation and perception of the office workers in their work environment.

In the field of human thermal comfort, clothing has historically been identified as one of the major factors that affect thermal comfort of occupants of any given space (Fanger, 1970). Clothing also affords occupants of a space the opportunity to control and adapt to their thermal environment. Over the years, research has been undertaken to determine how the choice of clothing and clothing insulation is determined by the climate of a place (de Dear & Brager, 1998, 2001; Morgan & de Dear, 2003; Schiavon & Lee, 2013). However, little has been done to determine to what extent socio-cultural parameters affect occupants clothing choice and in turn the thermal comfort in their work environment.

The Japanese *Cool Biz* Campaign in 2005 is a practical example to explain the importance of clothing in human thermal comfort (Japanese Ministry of Environment, 2005). During the *Cool Biz* campaign, office workers in government ministries were expected to adopt a certain dress code. The *Cool Biz* dress code advises workers to wear short-sleeved shirts without ties or jackets. They were also expected to starch collars of their shirts to stand up and to wear trousers made from materials that breathe and absorb moisture. The purpose of this campaign, according to the Ministry of the Environment, is to reduce energy consumption by limiting the use of air conditioning. Hence, in all central government ministries the temperatures of air conditioners were set at 28^{0}C until the end of the summer. A similar campaign, *Super Cool Biz,* was repeated in the summer of 2012 following the great east Japan earthquake of March 11, 2011 (Tanabe, Iwahashi, & Tsushima, 2012).

The main objective of this paper, therefore, is to determine to what extent regulated office clothing or uniform policy affects the adaptation of office workers to the thermal conditions surrounding their work environment in the tropical climate of sub-Sahara Africa. The field research work for this paper was carried out in Enugu, a city in South-eastern Nigeria. The research was conducted using office spaces from two different establishments—one with a strict official uniform policy and the other with no official staff dress code policy.

2. Methods

2.1 The Study Area

The field research work was carried out in Enugu, a city located in the south eastern part of Nigeria (6^{0}26'0"N, 7^{0}29'0"). According to Köppen-Geiger Climate Classification, Enugu is situated in the tropical savannah climate (Peel, Finlayson, & McMahon, 2007). However, Ojosu et al., (1988) classify Enugu as being in the hot-humid zone.

As with most of Nigeria, Enugu is predominantly hot all year round with a mean daily temperature of about 26.7^{0}C (Sanni, L. et al., 2007). The average diurnal difference is about 8^{0}C. This is slightly higher during the dry season (about 11^{0}C) and slightly lower during the rainy season (about 6^{0}C). The average daily humidity is

about 70% with a maximum average of 80% in the morning and 60% in the evenings. The humidity is higher during the rainy season, when the maximum can get close to 100% with a minimum that is hardly below 80%.
The rainy season and the dry season are the only seasons experienced in Enugu, just as it is with other part of Nigeria. During the months of December and January, Enugu is usually affected by a weather condition called Harmattan, a dusty trade wind which usually occurs for few weeks.

2.2 Case Study Buildings

The office spaces used for the field research were located within the office buildings of the Federal Radio Corporation of Nigeria (FRCN) and the Federal Road Safety Corps (FRSC), both in Enugu. Four office buildings were selected for the study—Three buildings (A, B, C) are located within the premises of FRCN while the other (building D) is located within the premises of FRSC. Enclosed office spaces which are mixed-mode ventilated[1] were selected from building A. The office space selected from building B is an open plan office space that also had a mixed-mode ventilation system. Building C is an open plan space which also operates on a mixed-mode system of ventilation. Three different office spaces were selected from building D; two enclosed office spaces (mixed-mode and naturally ventilated) and one naturally ventilated open plan office space.

2.3 Data Collection

The data from the study were collected at two different time periods in 2014, from late January to March (representing the dry season) and from late May to June (representing the rainy season). The study adopted both the quantitative and the qualitative methods of data collections and analysis. Participants for the survey were recruited on a voluntary basis from among office workers from FRCN and FRSC. As shown in figure 1, the staff of FRCN had no office clothing policy while those of FRSC had to wear an official staff uniform.
Participants' recruitment was undertaken using a questionnaire, to get basic information from participants about their work spaces. Information collected included: gender, age, working hours, and participants' period of residence in Enugu. Information regarding the office condition of each participants comprising; office typology, ventilation system, number of persons working in the office space, number of external windows in the office space, workstation within the room space and number of floors in the buildings were also collected during the first stage using the questionnaire.
Dataloggers were placed in all the office spaces being surveyed to record indoor operative temperature and humidity at 15 minutes interval throughout the study period. The loggers were located within 1 meter of the participants' workstation to record the actual thermal conditions being experienced by participants during normal working hours. Dataloggers were also placed outside the buildings to automatically record both the corresponding temperature and humidity of the immediate outdoor environment at the same time intervals as the dataloggers placed indoors. Hand-held instruments were also used to measure the air speed in the different spaces surveyed at different time during the study period.
Using a longitudinal approach, thermal comfort questionnaires were administered to participants to record their perceptions of the thermal comfort within their workplaces on a 'right-here-right-now' basis, which included

[1] Mixed-mode ventilation in this research refers to office spaces that utilises a combination of natural ventilation from operable windows and some form of air-conditioning cooling system.

standardized clothing ensemble in clo and activity checklist. For each day of the survey, three thermal comfort questionnaires were administered to each participant; one in the morning (before 11am), another one at mid-day (between 11am and 1pm), and the last one in the afternoon (after 1pm). This process was repeated for different days throughout the period of the two stages of the survey.

A self-selecting cross-section of the participants also participated in a semi-structured interview during the field work. The interview focused on finding out how participants select their work clothing, and how this affects thermal perception and adaptation. Participants were also observed whilst at work, and records of participants' clothing adjustment during a typical working day in the office were also noted.

3. Results and Discussion

The prevailing daily mean outdoor temperature from the dataloggers were plotted against the corresponding mean indoor operative temperature for each of the office spaces that were used for the survey. These were compared with the 80% and 90% acceptable comfort ranges of the ASHRAE Standard 55 (ASHRAE, 2013). As illustrated in figures 2a to 2e, all the office spaces comply with ASHRAE Standard 55 adaptive comfort standard. A further analysis of the few points that are outside the comfort ranges in figures 2d and 2e shows that at an air velocity of 0.6m/s, these spaces will comply with the ASHRAE Standard 55 adaptive comfort standard (Efeoma, Meshack O. & Uduku, Ola, 2014). This, thus, indicates that the adaptive model could be used to describe the thermal comfort in all the case study spaces.

A comparison of the statistical analysis of the prevailing outdoor temperature, indoor operating temperature and humidity of the office spaces studied in both complexes as shown in both tables 1a and 1b, shows that office spaces used for the research work have similar thermal performances. For example, the coefficient of variation for operative indoor temperature for office spaces A, B and C compared with that of Da, Db and Dc are 0.060 and 0.061 respectively. While that of the humidity are both 0.180. These indicate a strong similarity in the spread of the operative temperature and humidity during the period of the survey for all the spaces selected for the studies.

Table 2 is a summary of the responses that were obtained from the thermal comfort questionnaires administered during the field research work in the dry season and the rainy season. The rate of responses received were generally higher during the second stage of the survey compared to the first stage. While on a more specific scale, the responses received from the staff of FRCN were almost the same or slightly lower but those received from the staff of FRSC increased sharply during the second stage of the survey.

Given the similarity that existed in the thermal performance of the office spaces studied, it would have been expected to see the same level of similarity in the perception of thermal comfort of the respondents with generally the same activity level. However, as shown in figures 3a and 3b, there is a sharp contrast in the thermal perception of workers of FRCN when compared with that of FRSC. The percentage of staff who are comfortable (either somewhat comfortable, comfortable or very comfortable) for the office spaces surveyed in FRCN buildings was higher when compared with those who were uncomfortable (either very comfortable, uncomfortable or somewhat uncomfortable). This trend runs through the entire day (morning, mid-day and afternoon). Whereas the percentage of FRSC staff who were comfortable was lower at mid-day, and in the afternoon, compared to those who were uncomfortable. The only exception was in the morning when the percentage of those who comfortable was higher than those uncomfortable.

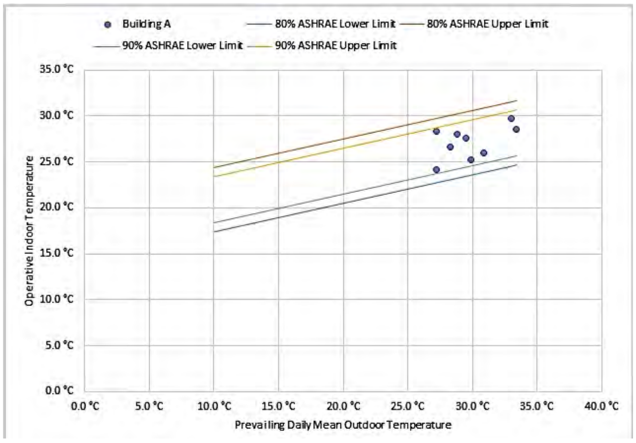

Fig. 2a: Indoor operative temperature for office space A plotted against the prevailing mean outdoor temperature and overlaid with the adaptive model of ASHRAE Standard 55-2013

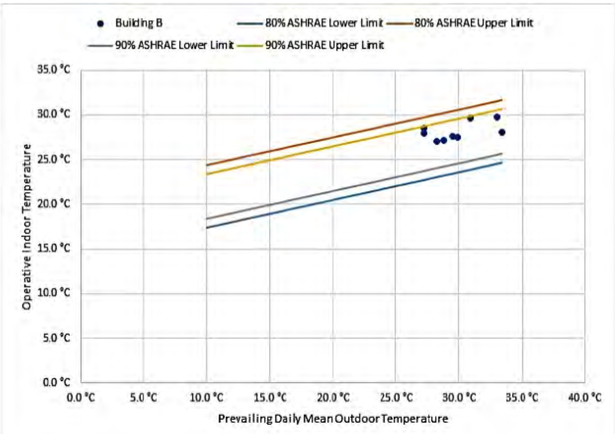

Fig. 2b: Indoor operative temperature for office space B plotted against the prevailing mean outdoor temperature and overlaid with the adaptive model of ASHRAE Standard 55-2013

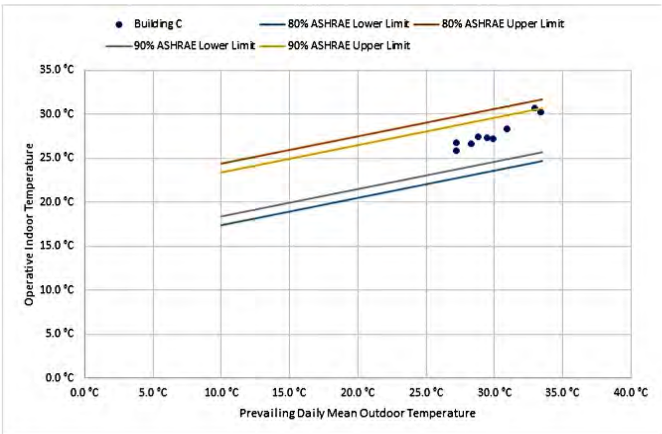

Fig. 2c: Indoor operative temperature for office space C plotted against the prevailing mean outdoor temperature and overlaid with the adaptive model of ASHRAE Standard 55-2013

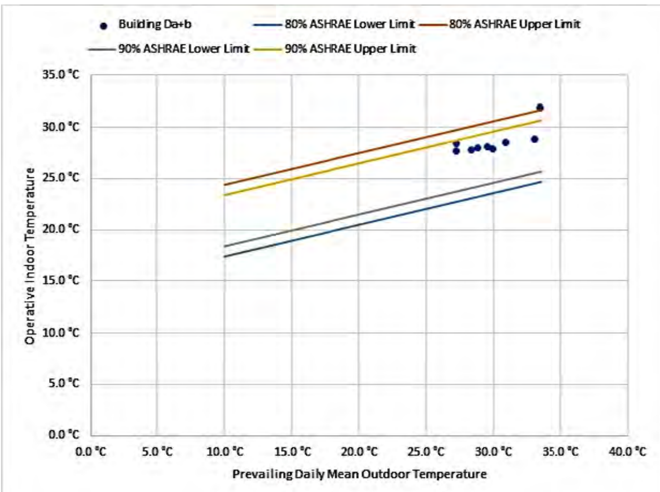

Fig. 2d: Indoor operative temperature for office space Da and Db plotted against the prevailing mean outdoor temperature and overlaid with the adaptive model of ASHRAE Standard 55-2013

Fig. 2e: Indoor operative temperature for office space Dc plotted against the prevailing mean outdoor temperature and overlaid with the adaptive model of ASHRAE Standard 55-2013

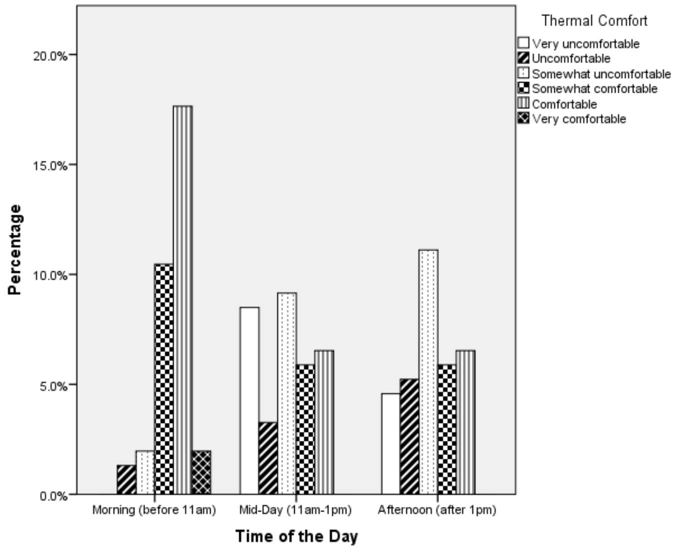

Figure 3b: Comparison of participants' thermal comfort perception for office spaces Da, Db and Dc

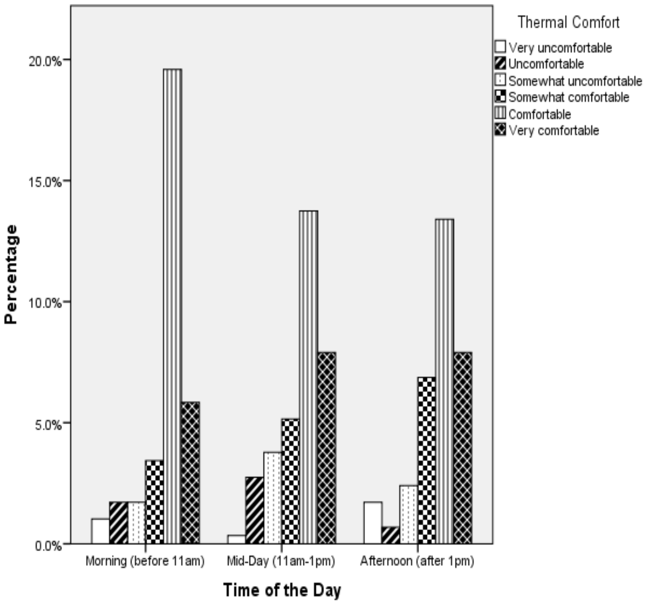

Fig 3a: Comparison of participants' thermal comfort perception for office spaces A, B and C

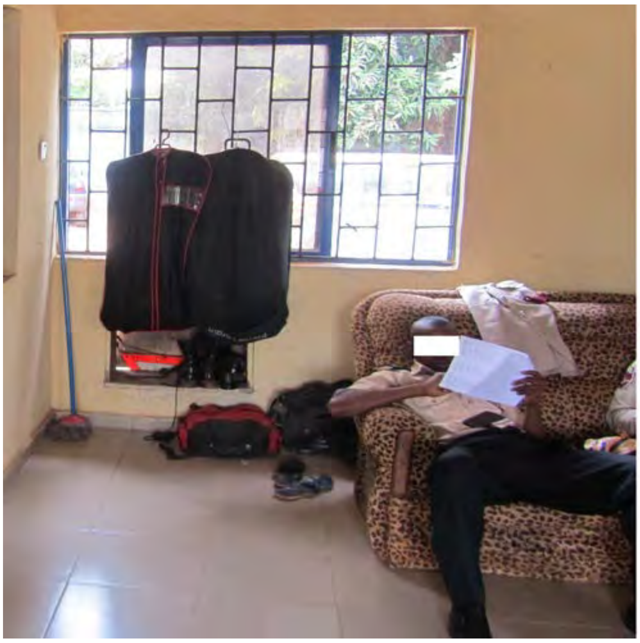

Fig 4: Typical example of what staff of FRSC use in bringing different cloths to the office

Table 1a: Summary of values obtained for central tendency and dispersion for Buildings A, B and C

	Max	Min	Mean	Standard Deviation	Coefficient of Variation
Prevailing Outdoor Temperature (^{0}C)	39.8	24.4	33.2	3.239	0.098
Indoor Operative Temperature (^{0}C)	31.9	24.4	28.2	1.703	0.060
Indoor Operative Humidity (%)	83.7	41.9	56.2	10.116	0.180

Table 1b: Summary of values obtained for central tendency and dispersion for Buildings Da, Db and Dc

	Max	Min	Mean	Standard Deviation	Coefficient of Variation
Prevailing Outdoor Temperature (^{0}C)	39.6	24.9	33.2	3.112	0.094
Indoor Operative Temperature (^{0}C)	32.4	25.7	28.9	1.753	0.061
Indoor Operative Humidity (%)	82.5	40.2	66.0	11.853	0.180

Table 2: Summary of responses obtained from field survey in January to March and May to June 2014

Building	**A**	**B**	**C**	**D**			**Total**
				a	**b**	**c**	
Location	FRCN	FRCN	FRCN	FRSC	FRSC	FRSC	
Office Typology	ES	OP	OP	ES	ES	OP	
Ventilation System	MM	MM	MM	MM	NV	NV	
No of Responses	72	168	57	51	39	63	450
Dry Season	39	87	30	15	12	18	201
% of Dry Season	54.2	51.8	52.6	29.4	30.8	28.6	44.7
Rainy Season	33	81	27	36	27	45	249
% of Rainy Season	45.8	48.2	47.4	70.6	69.2	71.4	55.3

Notes: FRCN (Federal Radio Corporation of Nigeria, Enugu), FRSC (Federal Road Safety Corps, Enugu Command), ES (Enclosed Office Space), OP (Open Plan Office Space), MM (Mixed-Mode), NV (Naturally ventilated)

The observational study showed that the office uniform worn by the participants from FRSC was what accounted for the variation in their thermal perception when compared with participants from FRCN with no dress code policy. It was observed that the majority of the participants from FRSC go to work in personal clothing bringing in their work uniforms with them. Most will work in the morning hours with their personal clothing and only later change to the official uniform before the late morning hours or mid-day (usually before 11am) . The change to official uniform happens before senior staff appear in the office and check that uniforms are being worn by the junior staff. Whilst there are no detailed photographs to show this, as participants did not wish to be photographed, figure 4 gives an example of what they use in bringing different cloths to work.

The interview conducted with the staff of FRSC further confirmed that the office uniform regulation is a major factor that influences their perception and adaptation to the thermal environment of workplaces. For example, when they were asked: *Do you support a strict dress code policy?* All those interviewed responded 'No' to this question. Their further comments on this question suggested that they would prefer the option of flexible personal work clothing. Their reasoning was that wearing uniforms would make them uncomfortable. A few said that they would only adapt to an office uniform policy if it included an 'increased salary'.

4. Conclusions

This paper through field studies, which was focused on the determination of the extent regulated office clothing or office uniform affects the perception and adaptation of office workers to thermal comfort in the hot-humid climate of Enugu in Nigeria, examines and compares both the comfort levels of similar office spaces and the perception of workers from FRCN to that of FRSC. The studies employed both the quantitative and the qualitative approach in this research.

Results showed that all the office spaces studied in both the complexes of the FRCN and FRSC were in compliance with the adaptive comfort standard of ASHRAE Standard 55. While the spaces exhibited similar thermal performances, the thermal comfort perception of workers with the same activity level were different. Administrative staff of FRCN, with no dress code policy, were more comfortable in a wide range of temperature conditions compared to FRSC staff who have official work uniforms. The analysis of the observational studies along with the semi-structured interview conducted, and the subjective thermal comfort questionnaires inferred that the strict office uniform regulation of respondents from FRSC accounted for the variation in their thermal perception and adaptation.

From these initial research findings the following recommendations can be made:

(i) staff should be allowed to adopt a dress code policy that allows some flexibility of adjusting or adapting office clothing to prevailing thermal conditions whilst still maintaining the corporate image of the establishment or company. This flexibility will enable staff to adapt to the thermal environment surrounding their work places and reduce reliance on mechanical form of ventilation which are expensive to run and maintain,

(ii) the implementation of a refined model of the Japanese *Cool Biz* and *Super Cool Biz* campaigns in offices in the tropical climate, as the results from those campaigns indicate a great potential for energy savings while still maintaining the comfort of the occupants (Japanese Ministry of Environment, 2005; Tanabe et al., 2012),

(iii) future studies in thermal comfort perception should not rely solely on the quantitative methods most commonly employed in the field of thermal comfort studies. These should also include forms of qualitative data collection and analysis methods such as observations and interviews, as the results from these studies showed how these methods can help to capture vital details that are usually not considered in subjective thermal comfort questionnaires,

(iv) the need to re-calibrate and publicise the clothing (clo) scale, so the public and employers can understand what clothing is most appropriate to achieve thermal comfort in tropical conditions.

5. Acknowledgments

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Appendix G

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Assessing thermal comfort and energy efficiency in tropical African offices using the adaptive approach

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Abstract

Purpose – The purpose of this paper is to adduce the most appropriate thermal comfort assessment method for determining human thermal comfort and energy efficient temperature control in office buildings in tropical West Africa.

Design/methodology/approach – This paper examines the Adaptive Thermal Comfort Standard, from its research evolution to its contemporary use as an environmental design assessment Standard. It compares the adaptive component of ASHRAE Standard 55 and the European CEN/EN 15251. It begins by reviewing relevant literature and then produces a comparative analysis of the two standards, before suggesting the most appropriate Adaptive Thermal Comfort Standard for use in assessing conditions in tropical climate conditions. The suggested Standard was then used to analyse data collected from the author's pilot research into thermal conditions, in five office buildings situated in the city of Enugu, South Eastern Nigeria.

Findings – The paper provides insight as to why the ASHRAE adaptive model is more suitable for thermal comfort assessment of office buildings in the tropical West African climate. This was demonstrated by using the ASHRAE Thermal Comfort Standard to assess comfort conditions from pilot research study data collected on Nigerian office buildings by the author.

Originality/value – The paper compares the adaptive component of ASHRAE Standard 55 with CEN/EN 15251, and their different benefits for use in tropical climates. It suggested the need for further research studies and application of the ASHRAE Adaptive Thermal Comfort Standard in the tropical West African climate.

Keywords Energy efficiency, Adaptive thermal comfort, Thermal comfort, Thermal comfort models, Thermal comfort standards, Tropical office buildings

Paper type General review

1. Introduction

Efficiency and sustainability are terms that are commonly used by politicians, policy makers, economists, planners, architects and engineers in the building industry; and these themes are discussed frequently in academic practice also. Attaining optimal thermal comfort conditions in buildings can greatly enhance building efficiency and consequently sustainability. This is because buildings which have proper thermal control, their users feel comfortable and can work effectively; this in turn means that the buildings can be run more efficiently and sustainably as less energy will be used in heating or cooling to achieve optimal comfort conditions.

The challenge facing the building industry is therefore how to achieve thermal comfort in buildings and ensure this is achieved in a sustainable manner, thus enhancing significant energy efficiency. Tanabe *et al.* (2012) in their field studies have suggested that there was a link to the satisfaction of office workers with their thermal environment, which demonstrated that this had a significant effect on workers'

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productivity. We therefore need to ensure that energy efficient strategies for buildings are keeping with the required or reported thermal comfort levels for occupants in order not to compromise workers' productivity.

2. Thermal comfort

"The term 'comfort' can be used to describe a feeling of contentment, a sense of cosiness, or a state of physical and mental well-being" (Shove, 2003). The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) define the term "thermal comfort" as "that condition of mind that expresses satisfaction with the thermal environment" (ASHRAE, 2013). The wider research community; architects, engineers, quantity surveyors and others in the building industry, accept this definition of thermal comfort. It is used as a basis for thermal comfort standards such the ASHRAE Standard 55 and the International Standards Organisation, ISO 7730 (ASHRAE, 2013; ISO, 2005).

The specific ASHRAE definition of thermal comfort describes a person's psychological state of mind, and is used to describe a condition in which a person feels neither "too hot nor too cold". It is essentially a subjective response, or state of mind, where a person expresses satisfaction with his environment (Olesen and Brager, 2004). However, in deciding what people find thermally comfortable, one must take into account a range of environmental or climatic and personal factors.

2.1 Factors affecting thermal comfort

The environmental or climatic factors and personal factors taken into account comprise the "human thermal environment" (Parsons, 2003). Fanger (1970) suggested that the most important factors or variables that determine the thermal condition of a given space are as follow:

- air temperature;
- mean radiant temperature;
- air velocity;
- humidity;
- metabolic rate or activity level; and
- clothing insulation.

Jones (2008) defines thermal comfort as the achievement of a balance between metabolic heat production and heat loss, and suggests that it is a function of the thermal environmental conditions such as activity rate and clothing insulation.

Figure 1 gives an illustration of how thermal comfort is affected by four environmental factors; (air temperature, mean radiant temperature, air velocity and humidity) and two personal factors (activity level and clothing insulation). Hence, thermal comfort in any given space can be achieved with a combination of the above factors.

2.2 Thermal comfort models

To determine thermal comfort standards environmental scientists work with models in which the neutral or optimal thermal comfort condition can be achieved, considering mainly the six factors affecting thermal comfort as discussed. The two most popular thermal comfort models that have been developed are shown in Figure 2. The first, the predictive mean vote (PMV) or heat balance model, was developed from Fanger's

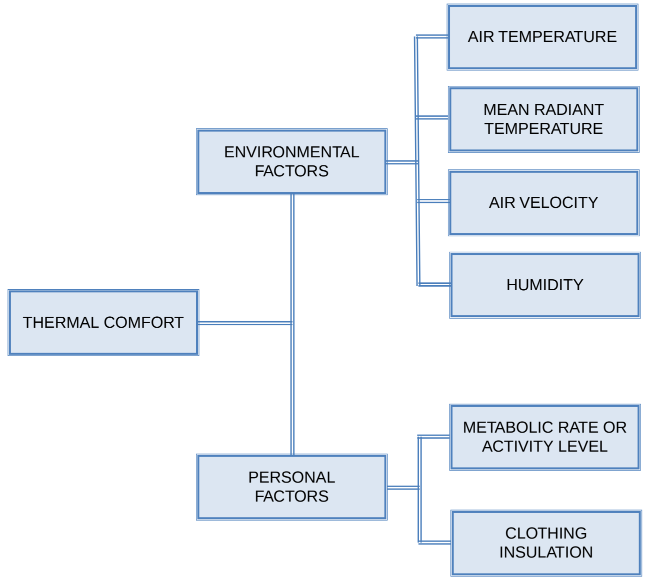

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Figure 1.
Factors affecting thermal comfort

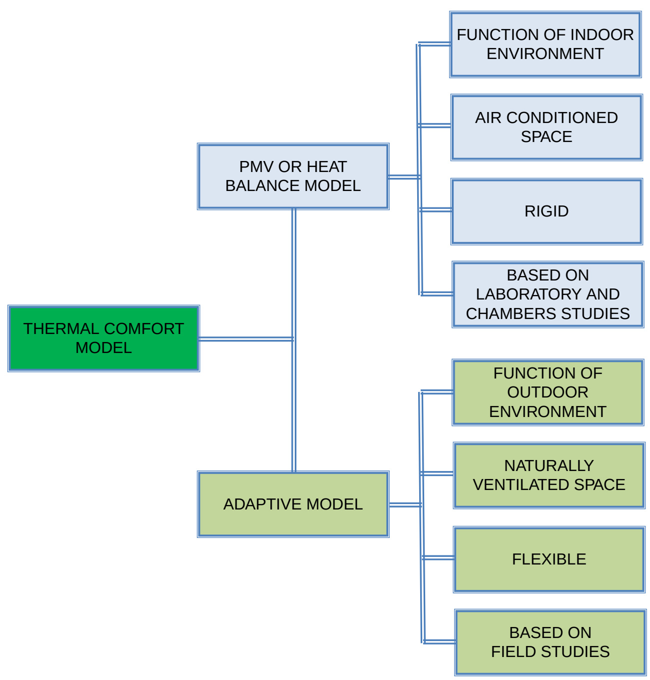

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Figure 2.
The two thermal comfort models and their basic differences

laboratories and chambers studies (Fanger, 1970). The second, the Adaptive Comfort Model, was developed as a result of series of field studies carried out by various researchers over two decades (Auliciems, 1981; de Dear and Brager, 1998; Humphreys and Nicol, 1998).

In both models the concept of the predicted mean vote, which gives the percentage of people who are satisfied (PPS) or dissatisfied (PPD) with their comfort levels is often used as well to determine comfort. 100 percent suggesting total satisfaction and 0 percent dissatisfaction.

2.2.1 PMV or heat balance model. In 1970, Fanger developed the heat balance equation which is based on a combination of six factors affecting the thermal balance between the human body and the environment. These factors include four primary factors (Fanger, 1970):

- air temperature – TA;
- mean radiant temperature – TM;
- air velocity – VEL; and
- relative humidity – RH.

Two personal factors:

- activity rate–MET; and
- clothing insulation–CLO).

The basic equation for the thermal heat balance is shown in Equation (1), while Equation (2) shows the functional notation of the six factors affecting thermal comfort. As represented in Equation (2), within the skin temperature and sweat rate limits, a person will feel thermally comfortable if the thermal load of his body is equal to zero (Nicol *et al.*, 2012; Xiong, 2011):

$$M - W = C + R + E + (C_{res} + E_{res}) + S \; [W/m^2] \tag{1}$$

where M is the metabolic rate, W is mechanical work done, C is convective heat loss from the clotted body, R is radiative heat loss from the clothed body, E is evaporative heat loss from the clothed body, C_{res} is convective heat loss from respiration, E_{res} is evaporative heat loss from respiration, and S is the rate at which heat is stored in the body tissues:

$$f(TA, \; TM, \; VEL, \; RH, \; MET, \; CLO) = 0 \tag{2}$$

The PMV model predicts the thermal sensation as a function of these six factors listed above. The model quantifies the absolute and relative impact of these six factors in determining what is thermally comfortable. Using a seven-point thermal sensation scale (see Table I), the PMV index predicts the mean value of the votes for a large group of person. It is used in determining the predicted percentage of dissatisfied (PPD) persons. The PPD is the index that establishes a quantitative prediction of the percentage of dissatisfied persons in a given environment. These two indices are currently being used as the basis of thermal comfort evaluation in both the ASHRAE Standard 55 and the ISO 7730.

Table I shows the relationship to the Bedford scale, the current thermal sensation scale that is currently included in both the ASHRAE Standard 55 and ISO 7730 and the modified ASHRAE scale by Humphreys and Nicol. The corresponding thermal preference is also shown in the table. All three scales used the seven-point scale with little variation in nomenclature (Bedford, 1936; Feriadi *et al.*, 2003; Humphreys and Nicol, 2004). Going by the principle of "neutral equals heat balance," Fanger then constructed the PMV model to evaluate a particular thermal condition. The model calculates the thermal load and predicts occupant's vote of thermal sensation. Equation (3) as shown below is the model constructed by Fanger for predicting occupant's thermal sensation vote for a given space (Fanger, 1970):

$$PMV = (0.352e^{0.042(M/Adu)} + 0.32)Load \tag{3}$$

where PMV is the predicted mean vote of thermal sensation, M/Adu is the internal heat production and, Load is the heat load.

2.2.2 Adaptive comfort model. The Adaptive model relates the indoor neutral temperature to the monthly outdoor mean temperature. The only variable input required for this model in finding thermal comfort is the mean monthly outdoor temperature.

One major advantage of this model over the PMV model is the simplicity of its application for situations where it applies. While one will need to estimate the personal factors, clothing and activity, before using the PMV model; the relationship between these factors and climate has already been accounted for in the adaptive model.

Unlike the PMV or heat balance model, the adaptive model is based on a wide range of field studies across the world. The results from field studies in warmer climates in buildings without air-conditioning revealed that the PMV model predicts a warmer thermal sensation than the occupants actually feel (Brager and de Dear, 1998; Humphreys, 1978).

Field study results have shown that respondents from different climate regions, and of different socio-cultural and socio-economic backgrounds have different perceptions of comfort that straddle a large temperature spectrum. For example, Busch (1992) conducted field research into comfort perception amongst office workers in Thailand that showed that they were comfortable at higher indoor temperatures than those working in more temperate regions. Another study conducted in Pakistani offices shows that indoor thermal preference is a function of the local climate and season (Nicol *et al.*, 1999; Nicol and Roaf, 1996). Furthermore studies carried out by de Dear and Auliciems (1988) also showed a disparity between the thermal perceptions and preferences of occupants of air condition buildings and those that were naturally ventilated. The studies also related thermal comfort to cultural expectation and climatic conditions.

Table I. Comparisons of the Bedford, ISO 7730, ASHRAE thermal sensation scale, modified ASHRAE scale in relation to thermal preference

Bedford (Bedford, 1936)	ASHRAE and ISO 7730 scale	Modified ASHRAE scale (Humphreys and Nicol, 2004)	Thermal preference
+3 = much too warm	+3 = hot	+3 = much too warm	Much cooler
+2 = too warm	+2 = warm	+2 = too warm	Cooler
+1 = comfortably warm	+1 = slightly warm	+1 = slight too warm	Slightly cooler
0 = comfortable	0 = neutral	0 = Just right	No change
−1 = comfortably cool	−1 = slightly cool	−1 = slightly too cool	Slightly warmer
−2 = too cool	−2 = cool	−2 = too cool	Warmer
−3 = much too cool	−3 = cold	−3 = much too cool	Much warmer

There are also field studies that shows that occupant behaviour can affect thermal comfort (Nicol and Humphreys, 2007). Instead of limiting thermal comfort to the six factors which determine the Fanger's PMV model, these field studies show that people tend to make themselves thermally comfortable by changing their clothing, activity and posture (Nasrollahi, 2007). Field studies have also shown that people can easily adapt to higher temperatures in occupant-controlled naturally ventilated buildings than those predicted by PMV or the heat balance model (Olesen, 2004).

3. Evolution of adaptive thermal comfort

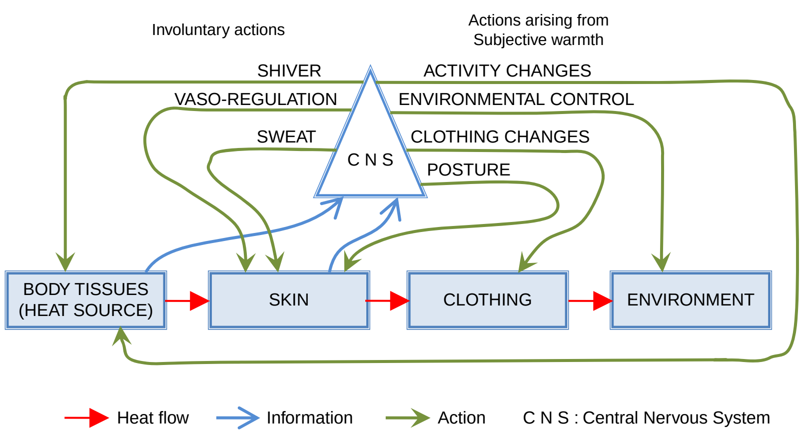
The historical development of adaptive thermal comfort can be traced back to the 1950s. A number of researchers have been involved in the development of adaptive thermal comfort. Some key actors who have contributed immensely to this development include the following persons discussed below (de Dear, ca 2011).

3.1 Charles webb (1950s)

Charles Webb, a physicist and a field study comfort researcher at UK Building Research Station, is regarded as the originator of the adaptive thermal comfort concept (Nicol, 1974). Webb conducted longitudinal field studies in Singapore, North India, Bahgdad and North London during the 1960 s. From his studies, Webb noticed that his subject were comfortable at the mean conditions they experienced, whether in Singapore, North India, Bahgdad or North London. Hence, he concluded that they had adapted to their indoor climates (Webb, 1959).

3.2 Nicol and Humphreys (1970s)

Based on Webb's counter-intuitive finding (Nicol, 1974), Nicol and Humphreys proposed the idea that building occupants and their indoor climate were two parts of an integrated, self-regulating (feedback) system (Figure 3). These are the physiological adaptation (otherwise known as acclimatization) and behavioural adaptation (personal and environmental). They, therefore, postulated the adaptive principle: If a change occurs that produces discomfort, people will tend to act to restore their comfort. That is to say, the target of the "controlled variable" in this homeostatic system was thermal comfort (Nicol and Humphreys, 1973).



Source: Adapted from Nicol and Humphreys (1973)

Figure 3. The thermal regulatory system

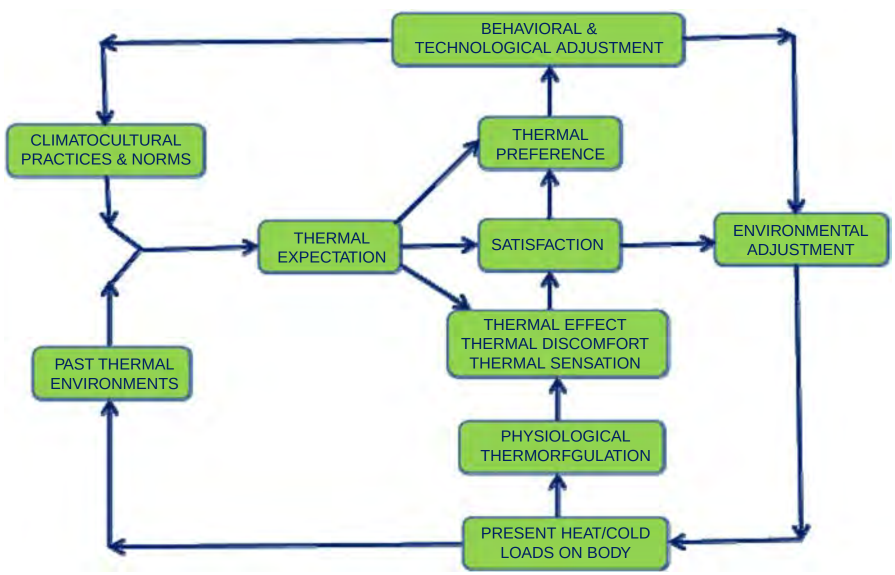
3.3 Andris Auliciems (1981)
Andris Auliciems postulated that the driver for adaptation was not only indoor temperature, but also outdoor climate. He, therefore, outlined the factors that determine adaptation to include: physiological adaptation (acclimatization), behavioural (adjustment), psychological (expectation) and cultural (technology) (Auliciems, 1981). He shows that the combinations of past and current thermal experiences, cultural and technical practices are the determinant of thermal expectation. Figure 4 is a schematic diagram developed by Auliciems to show the relationship among these factors that determine thermal expectation, adaptation and perception (Auliciems, 1981, 1989; de Dear *et al.*, 1993; Nicol, 1993).

3.4 Richard de Dear (1980s)
In 1981, Richard examined this topic and made the following observation with regard to Humphreys', Nicol's and Auliciems' seminal ideas on the one hand, and Fanger's ingenious heat-balance approach to thermal comfort:

(1) Humphreys', Nicol's and Auliciems' seminal ideas had not progressed as far as he thought they should have, and

(2) Fanger's ingenious heat-balance approach to comfort had displaced the adaptive concept and its supporting evidence.

Hence, for his work, Perceptual and Adaptational Bases for the Management of Indoor Climate, he compared these two competing hypotheses against each other (adaptive approach with heat-balance approach) in a series of field experiments in Australia (de Dear, 1985). The field experiments were carried out in the tropical Darwin, sub-tropical Brisbane and temperate Melbourne in Australia. In each of the climatic zones, he compared naturally ventilated office buildings with centrally air-conditioned office buildings, collected all six of Fanger's PMV model parameters, and compared actual comfort with predicted comfort (de Dear and Auliciems, 1985; de Dear *et al.*, 1997).



Sources: Adapted from Auliciems (1981) and de Dear *et al.* (1993)

Figure 4.
The "adaptive model" of thermal perception

At the end of the field experiment, he found out that there were systematic discrepancies, particularly in the warmer climate zones, that could not be explained by the classic six comfort parameters in Fanger's heat-balance model (PMV) (de Dear, 1985; de Dear and Auliciems, 1985).

de Dear also played a key role in the field research studies and the development of the ASHRAE Adaptive Thermal Comfort Model. The development of the ASHRAE Thermal Comfort Model is discussed in the next session.

3.5 The ASHRAE RP-884 Comfort Database (1990s)

In the 1990s ASHRAE became interested in field studies of thermal comfort with a view to bridging the gap between comfort theory and practice. It therefore commissioned field experiments on thermal comfort. A standardized procedure was adopted for collecting both physical and subjective thermal comfort data from field studies in different parts of the world. The resulting database from these field surveys contained about 21,000 sets of raw field data collected using objective measurements of indoor climate with laboratory precision and subjective assessments of those conditions using standardized questionnaires from 160 different office buildings spread across four continents, and covering a wide range of climate zones. The buildings in the database were separated into those that had centralized HVAC buildings and those that were naturally ventilated (de Dear and Brager, 2002).

The data of the PMV or the heat-balance thermal comfort model were all taken from the indoor environment immediately surrounding the building occupants. While those of the adaptive comfort models were based on the outdoor thermal environmental variables. As explained by de Dear and Brager (2002), the choice of outdoor climate for the adaptive comfort model was informed by the following: they believe that our behavioural adaptations to the thermal environment is greatly affected by weather and seasons, and they think our psychological adaptations in the form of thermal expectation is determined by weather, both recent past and predicted near-future, along with longer-term seasonal swings.

The result from those studies and many others carried out by different individuals in different geographical locations collected over many years is a consolidated database on the web (see http://sydney.edu.au/architecture/staff/homepage/richard_de_dear/ashrae_rp-884_appendc.shtml).

This database forms the basis for the development of the adaptive component of ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy. The adaptive thermal comfort model was first included in the 2004 edition of the ASHRAE Standard 55; and subsequent revision of the Standard thereafter.

4. Thermal comfort standards

There are three international organisations that are involved in the development of well-known and widely used international standards that set the minimum requirement for temperature control and thermal comfort in the built environment (Nicol *et al.*, 2012). These include:

(1) The ASHRAE – ASHRAE Standard 55-2013: Thermal Environmental Conditions for Human Occupancy.

(2) The ISO – ISO 7730-2005: Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

(3) The European Committee for Standardisation (Comité Européen de Normalisation – CEN) – CEN/EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings – addressing indoor air quality, thermal environment, lighting and acoustics.

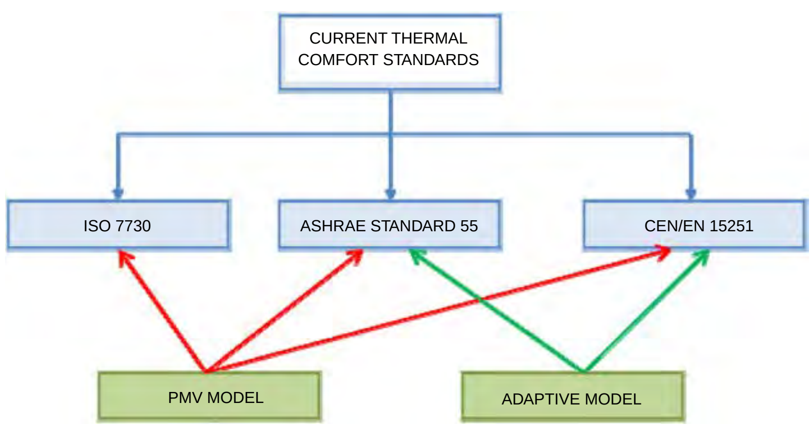
All three standards mentioned above are subject to continuous review. As at the time of this writing, the current edition of ASHRAE Standard 55 is that of 2013. The latest edition of ISO 7730 is that of 2005, while the latest edition of CEN/EN 15251 is that of 2007 (ASHRAE, 2013; CEN, 2007; ISO, 2005). All these standards used the PMV/PPD index as a basis for defining the standard for temperature control or thermal comfort. As illustrated in Figure 5, the adaptive component has also been included in both the ASHRAE Standard 55 and CEN/EN 15251 (ASHRAE, 2004, 2010, 2013; CEN, 2007).

4.1 Comparison between the ASHRAE and CEN adaptive comfort standard

The main differences between the adaptive component of the ASHRAE Standard 55 and that of CEN/EN 15251 are summarized in Table II. As highlighted the table, the geographical locations covered by the source data for the adaptive component of ASHRAE Standard 55 has wider coverage compared to those of CEN. The adaptive component CEN/EN 15251 was based on European SCATs project database. The data of SCATs database were collected from five western European countries (Nicol *et al.*, 2012). On the other hand, the adaptive component of ASHRAE Standard 55 was based on ASHRAE project RP-884 database (de Dear and Brager, 1998). The data of ASHRAE RP-884 were obtained from climate zones that cover four continents. These climate zones include (but not limited to) the humid tropical, the tropical savannah, wet equatorial; which are the major climate zones that runs through the West African region.

4.2 Use of the ASHRAE Standard for assessing West African office buildings

From the above comparison, the adaptive model of ASHRAE Standard 55 is considered to have a closer relationship and be of more relevance to the tropical West African climatic region than the CEN/EN 15251 Standard. The ASHRAE Standard was



Source: Author

Figure 5.
Thermal comfort standards and their respective models

Table II. Differences between the ASHRAE and CEN adaptive comfort

	ASHRAE standard 55	CEN/EN15251
Geographical coverage	The RP-884 data sets that form the basis for the ASHRAE Adaptive Thermal Comfort were obtained from four continents cutting across different climate zones	The SCATS database used for the development of CEN Adaptive Thermal Comfort used data from only five Western European countries
Size of database	The RP-884 database comprises a total of 9,000 votes from the 21,000 votes collected from 36 of the 160 buildings surveyed, that were used for developing the ASHRAE Adaptive Thermal Comfort Model	Only a few thousand votes were obtained from the 26 offices covered in the SCATS database
Scope of application	Can only be applied to occupant-controlled naturally-ventilated spaces without mechanical cooling	Can be applied to any building in the free-running mode
Method of estimating comfort	Uses the regression of observed comfort votes on observed indoor temperatures for each building	Uses Griffiths' extrapolation from observed sensation to hypothetical neutrality by assuming 1 sensation category equal to 2 degree Celsius
Representation of outdoor temperature	Uses the mean monthly outdoor air temperature	Uses the exponentially weighted running mean daily outdoor air temperature

therefore adopted for use in analysing the pilot study of the thermal performance of five offices in Enugu, a city situated in South Eastern Nigeria.

The study was carried out in February 2014, one of the hottest months in Nigeria; using the office complexes of Federal Radio Corporation of Nigeria, Enugu and Federal Road Safety Corps, Enugu Commands. Table III shows the statistical summary of the operative temperatures of the five office spaces that were surveyed.

The initial results showed that the prevailing mean outdoor temperature for February, the month the survey was carried out, was 33.4°C; which is within the accepted comfort limits of the ASHRAE adaptive model. These data where analysed using the Center for the Built Environment Thermal Comfort Tool, an online thermal comfort analysis tool for ASHRAE Standard 55 (Hoyt *et al.*, 2013). The results of the analysis show that, at the minimum air velocity, office spaces *A*, *B* and *C* comply with the adaptive model of ASHRAE Standard 55 (see Figure 6(a-c)). While at air velocity of 0.6 m/s, office spaces D and E will comply with the adaptive model of ASHRAE Standard 55 (see Figure 6(d) and (e)). This shows that with some form of adaption, thermal comfort can be achieved in compliance with the adaptive model of ASHRAE Standard 55.

Further analysis of the observations made of the office workers, and the results of the semi-structured interviews carried out during the pilot study, showed that the workers took different actions to adapt to their work environment. These depended on the adaptive opportunities that were available to them at their various office spaces, such as openable windows, fans, clothing or changes in activity level. The study also highlighted that instead of limiting data collection to the quantitative method that is generally used by thermal comfort researchers; a mixed research approach which comprises some form of qualitative aspect of analysis, such as open ended interviews, or in this case observation, will produce more realistic results and a better understanding of different responses to achieving and maintaining thermal comfort. With a more detailed understanding of personal responses and comfort levels, internal environments, (in this case office buildings) can be better designed to use less energy in mechanical modes of thermal conditioning by responding more to observed and recorded human behaviour and less to the standardised comfort tables currently in use.

5. Benefits of applying adaptive comfort standard

A major benefit of applying the adaptive thermal comfort model in occupant-controlled naturally ventilated buildings therefore is the dramatic reduction in energy consumption

Table III. Statistical summary of indoor operative temperature of five office spaces for Enugu, Nigeria at monthly mean outdoor temperature of 33.4°C

Office space	Plan system	Ventilation system	Indoor operative temperature (°C) Max	Min	Mean
A (FRCN)	Enclosed/traditional office	Mixed-mode	31.2	26.2	28.5
B (FRCN)	Open plan office space	Mixed-mode	30.0	27.1	28.1
C (FRCN)	Open plan office space	Mixed-mode	31.8	28.7	30.2
D (FRSC)	Enclosed/traditional office	Mixed-mode	32.0	31.8	31.9
E (FRSC)	Open plan office space	Naturally ventilated	32.7	31.7	32.2

Notes: FRCN (Federal Radio Corporation of Nigeria, Enugu), FRSC (Federal Road Safety Corps, Enugu Command). Pilot study conducted in February 2014

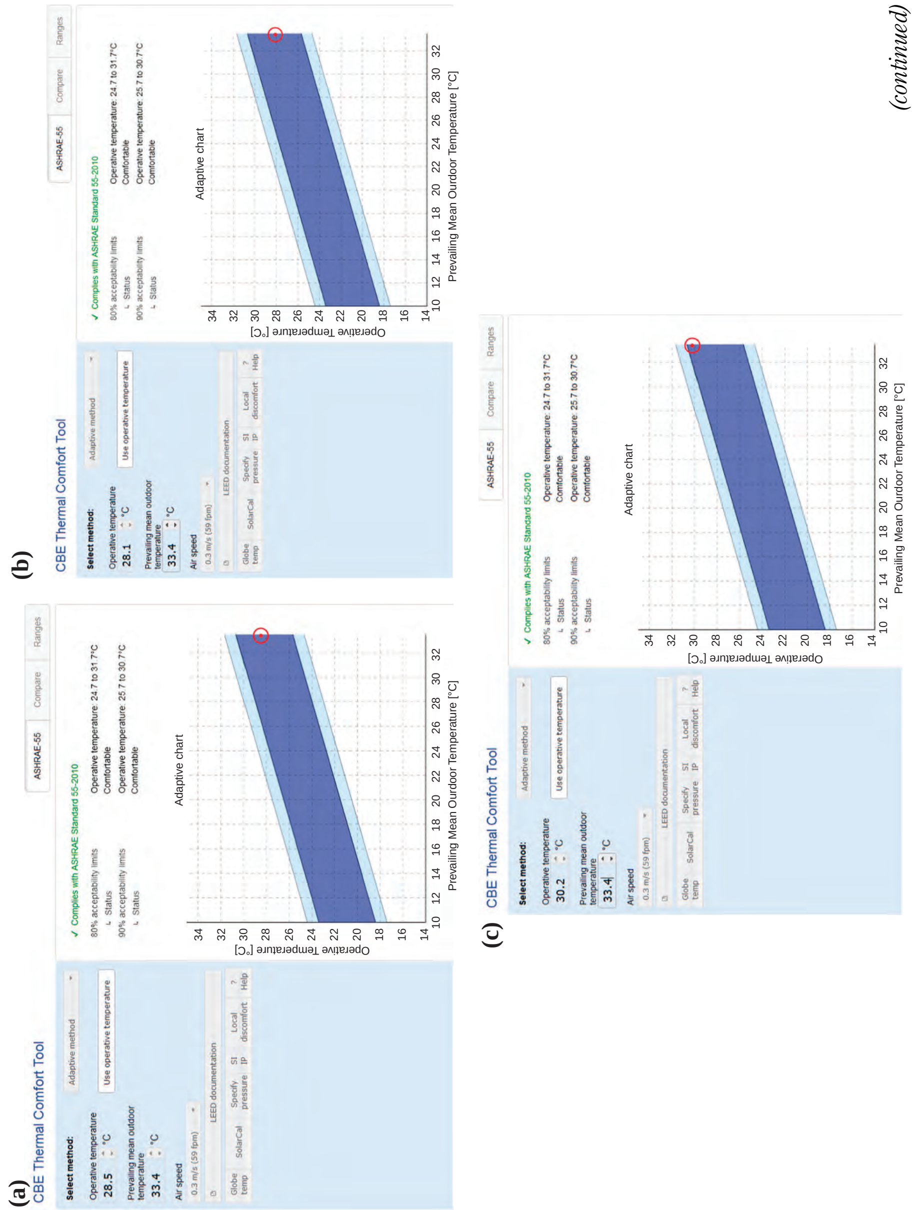


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Figure 6.
Result of analysis of "Office Space" using the adaptive method

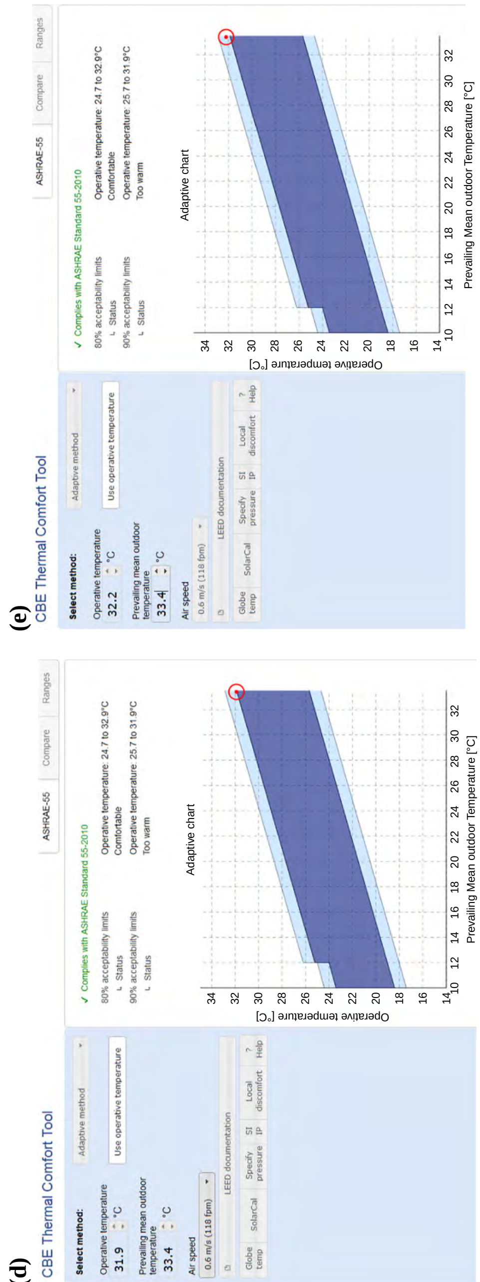
(d)
CBE Thermal Comfort Tool
Select method:
Adaptive method
Operative temperature
31.9
Prevailing mean outdoor temperature
33.4
Use operative temperature
Air speed
0.6 m/s (118 fpm)
LEED documentation
Globe temp
SolarCal
Specify pressure
SI IP
Local discomfort
? Help
ASHRAE-55
Compare
Ranges
✓ Complies with ASHRAE Standard 55-2010
80% acceptability limits
Operative temperature: 24.7 to 32.9°C
Status
Comfortable
90% acceptability limits
Operative temperature: 25.7 to 31.9°C
Status
Too warm
Adaptive chart
Operative temperature [°C]
Prevailing Mean outdoor Temperature [°C]
(e)
CBE Thermal Comfort Tool
32.2
33.4

Figure 6.

(energy efficiency). Apart from this, other co-benefits according to de Dear, 2010 include the following:

(1) increased availability of daylight as a result of the narrow floorplate necessitated by cross-flow ventilation;

(2) reduced greenhouse gas emissions by avoiding mechanical cooling and minimizing electrical lighting;

(3) reduced thermal boredom for the occupants, that is to say, it leads to improved productivity (Leaman and Bordass, 1993 cited by de Dear);

(4) fewer health issues, that is, building related illness, and therefore reduced absenteeism which results from improved health of the occupants; and

(5) negligible risk of sick building syndrome is also said to be another benefit of applying adaptive comfort model in occupant-controlled naturally conditioned buildings, as there is less reliance on potentially harmful mechanical air conditioning systems.

6. Conclusions

Designing for natural ventilation is becoming more permissible in a vastly increased range of climate zones especially in tropical and subtropical zones. As can be seen from the benefits discussed above, there is no doubt that the adaptive approach in determining indoor environmental quality is more suitable for occupant-controlled naturally ventilated buildings than the conventional heat-balance or PMV model. Besides, the application of the adaptive thermal comfort model in defining thermal comfort and temperature control in buildings will reduce the energy consumption (improve energy efficiency).

Also, there has been more research that has been undertaken to develop the concept of the adaptive thermal comfort model to the level of which we understand and use it today. However, most of this research development appears to be taking place in the East and South Asian regions.

From the research undertaken so far with regard to the adaptive approach to thermal comfort, the following conclusions can be reached:

(1) Whilst the ASHRAE Standard 55 adaptive comfort standard has taken different climate zones into consideration in its development process, there is need to further review the standard to take into consideration individual respondents' perceptions of comfort. The research carried out by Nakano *et al.*, shows that there are differences in the perception of indoor environment by occupants of the same space and climate zone (de Dear and Brager, 2002).

(2) This therefore highlights the need for further research in other areas currently not adequately covered, such as in Africa, and its sub-continental climatic zones. This will take into account not just the climate zone but also the micro-climate, culture and other specific particularities of cities towns and villages, in each climate zone, which if known will have a direct impact on how the occupants of a space can perceive indoor environmental condition.

Also, the following questions need to be addressed in future thermal comfort research:

- Should we continue to rely on a "one-size-fits-all" standard, or should future thermal comfort standard be regionalised?
- When and how should we start to look for a new vocabulary, new methods of comfort measurement, and of analysis to adequately respond to this new era of climate change, and our need to respond to new sustainability protocols?

Finally the pilot field work undertaken, highlighted a clear need for further research into West African office building design, in order to explore how these office work spaces can be designed more efficiently to achieve thermal comfort. This can be best tested using the Adaptive Thermal Comfort model as this paper has demonstrated.

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Appendix H