Thermal comfort in buildings: evaluation and semi-empirical modeling of occupant adaptation to environmental stimuli

Tosin Omoya

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Par Tosin OMOYA

Confort thermique en bâtiments : évaluation et modélisation semi-empirique de l'adaptation des occupants aux sollicitations environnementales

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Membres du jury :

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Mme TORNAY Nathalie	Maîtresse des ENSA (HDR)	ENSA de Toulouse	Rapporteuse
M. BRUNEAU Denis	Professeur des ENSA	ENSAP Bordeaux	Directeur de thèse
Mme. BARLET Aline	Maîtresse de conférences	ENSAP Bordeaux	Co-encadrante
M. RECHT Thomas	Maître de conférences	Université de Bordeaux	Co-encadrant

ABSTRACT

Thermal comfort in buildings: Evaluation and semi-empirical modeling of occupant adaptation to environmental stimuli

The objective of this research is to analyze and characterize the effect of thermal conditions on the perceived comfort of occupants in indoor spaces. For this purpose, an approach was developed to quantify the role of psychological adaptive factors in the thermal comfort evaluation of occupant, by examining comfort evaluations in different 'hot' and 'cold' situations. Therefore, it is based on an experimental protocol; this protocol entails an indoor space (experimental room) that imitates an office environment of which the internal surfaces of the enclosure generates radiant heat into the space. This radiant heat is being modified when the subjects are within the space then the measurements of some thermal parameters and physical condition of the indoor space and enclosure surfaces were taken, as well as the quantifiable thermal perceptions of the subjects.

The study aims to evaluate the adaptive factors that create the deviation between the physiological evaluation and actual thermal perception. Hence, the magnitude of the adaptation influencing the perceived comfort of occupants is linked to the physical stimuli experienced due to the thermal conditions and some cognitive "information" in the occupant due to the climate conditions. These adaptive weights were further related to the indoor operative temperature and outdoor air temperature of the occupants.

Keywords: experimental approach, thermal radiation, stimuli, thermal perception, psychological factors, perceived comfort.

RÉSUMÉ

Confort thermique en bâtiments : évaluation et modélisation semi-empirique de l'adaptation des occupants aux sollicitations environnementales

L'objectif de cette recherche est d'analyser et de caractériser l'effet des conditions thermique sur la perception du confort des occupants dans les espaces intérieurs. À cette fin, une approche a été développée pour quantifier le rôle des facteurs psychologiques adaptatif dans l'évaluation du confort thermique de l'occupant, en examinant les évaluations du confort dans différentes situations "chaudes" et "froides". Elle est donc basée sur un protocole expérimental ; ce protocole comprend un espace intérieur (salle expérimentale) qui imite un environnement de bureau dont les surfaces internes de l'enceinte génèrent de la chaleur rayonnante dans l'espace. Cette chaleur rayonnante est modifiée lorsque les sujets se trouvent dans l'espace. Les mesures de certains paramètres thermiques et de l'état physique de l'espace intérieur et des surfaces de l'enceinte ont été effectuées, ainsi que les perceptions thermiques quantifiables des sujets.

L'étude vise à évaluer les facteurs adaptatifs qui créent l'écart entre l'évaluation physiologique et la perception thermique réelle. Ainsi, l'ampleur de l'adaptation influençant le confort perçu des occupants est liée aux stimuli physiques ressentis en raison des conditions thermiques et à certaines « informations » cognitives chez l'occupant dues aux conditions climatiques. Ces poids adaptatifs étaient en outre liés à la température opérative intérieure et à la température de l'air extérieur des occupants.

Mots clés: approche expérimentale, rayonnement thermique, stimuli, perception thermique, facteurs psychologiques, confort perçu.

RÉSUMÉ DÉTAILLÉ

Confort thermique en bâtiments : évaluation et modélisation semi-empirique de l'adaptation des occupants aux sollicitations environnementales

Le changement émergent du climat mondial et le réchauffement climatique sont devenus un facteur crucial qui influence constamment le confort thermique des occupants. Ce changement climatique a induit des changements correspondants dans l'adaptation thermique humaine et les informations psychologiques qui ont influencé sa perception thermique de son environnement. Il est donc nécessaire d'adapter ces variations thermiques, adaptatives et psychologiques dans les évaluations de confort thermique.

L'American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) a défini le confort thermique comme un état d'esprit qui exprime la satisfaction à l'égard de l'environnement thermique, à partir d'une évaluation subjective. Cette définition précise l'importance et la nécessité de la satisfaction humaine comme critère de confort thermique aux occupants. Néanmoins, la satisfaction humaine est soumise à de nombreuses conditions liées à l'environnement, au corps et au fonctionnement psychologique de l'homme. Cela englobe les conditions physiques et thermiques ambiantes du corps humain, l'état du corps humain tel que le métabolisme, la physiologie, l'anthropométrie et l'anatomie ainsi que l'état psychologique. Ainsi, les éléments influençant le confort thermique appartiennent à différents domaines qui explorent les aspects physiques et non physiques influençant la perception thermique humaine. Par conséquent, il est complexe de définir la satisfaction thermique humaine en raison de la difficulté à synchroniser tous ces facteurs dans une seule évaluation du confort. Néanmoins, pour définir et évaluer précisément le confort thermique, il est essentiel d'énumérer avec précision ces relations complexes qui existent. Par conséquent, tous les facteurs influençant le confort thermique doivent être pris en compte et la relation complexe entre les facteurs doit être modélisée avec précision. Ces facteurs incluent, mais sans s'y limiter (i) les facteurs thermiques physiques tels que la température de l'air et l'humidité relative, la température radiant, la vitesse de l'air, l'isolation des vêtements, (ii) les facteurs physiologiques tels que l'échange de chaleur par convection, radiant, évaporatif et respiratoire, et le taux métabolique lié au système de thermorégulation du mécanisme du corps humain, et (iii) les facteurs psychologiques incluant les expériences, les représentations, les attentes, le contrôle perçu, les émotions, l'attitude, l'habituation et, les comportements personnels de l'occupant ainsi que certains facteurs socioculturels connexes (la culture, le niveau de vie et l'avancement technologique d'un occupant en fonction de sa région d'habitation. Dans cette recherche, une méthodologie qui vise à évaluer chacun des aspects influençant le confort thermique est proposée, dans le but de délimiter la relation entre les stimuli causés par les conditions thermiques dans l'espace intérieur et la composante psychologique du confort perçu par l'occupant.

Deux types d'approche existent dans l'évaluation du confort thermique contemporain : (1) l'approche du bilan thermique basée sur des études en laboratoire et (2) l'approche adaptative basée sur des études de terrain. L'approche du bilan thermique considère principalement l'équilibre thermique et l'échange de chaleur entre le corps de l'occupant et son environnement, tandis que l'approche du confort thermique adaptatif considère les rétroactions adaptatives et le comportement des occupants comme une composante importante de l'évaluation du confort thermique.

L'approche de l'équilibre thermique intègre les principes fondamentaux du transfert de chaleur, de l'équilibre thermique, de la physiologie thermique et de la thermorégulation ainsi que de l'anthropométrie et de l'anatomie dans les représentations mathématiques du corps humain et de ses systèmes de thermorégulation. Il est donc très cohérent avec le système de thermorégulation physiologique du corps humain. Il fonctionne sur le principe que pour atteindre l'équilibre thermique dans le corps, le taux de chaleur produit par le métabolisme du corps doit être égal au taux de perte de chaleur vers son environnement externe via la surface du corps, le système respiratoire et tout autre milieu physiologique de transfert de chaleur. Ces mécanismes de transfert de chaleur comprennent les processus d'échange de chaleur par convection, rayonnement, conduction et évaporation. Ainsi, un individu éprouve et perçoit un certain niveau d'inconfort en fonction de l'ampleur de la différence entre le taux de production de chaleur métabolique et la perte de chaleur via les surfaces corporelles et les voies respiratoires. Selon l'approche du bilan thermique, cet inconfort perdure jusqu'à ce que l'équilibre thermique soit atteint.

Sur la base du principe du bilan thermique, Fanger (1970) a réalisé des études expérimentales sur les sensations de confort thermique et a pu générer un ensemble d'équations appelé modèle de vote moyen prédit (PMV). Néanmoins, le modèle Fanger PMV ne peut être considéré comme universel, en raison de certaines divergences fondamentales entre les études sur le terrain et les études en laboratoire de Fanger. Par conséquent, le concept d'approche de confort « thermique adaptatif » a été développé.

L'approche adaptative implique les processus physiques et psychologiques de l'homme pour améliorer l'adéquation entre les conditions environnementales et les conditions requises. Pour intégrer certains de ces facteurs adaptatifs dans l'évaluation du confort thermique, des modèles et des corrélations mathématiques ont été développés. L'un de ces modèles est le modèle de vote moyen prédit adaptatif (aPMV) de Yao et al. (2009) qui considère les comportements adaptatifs des occupants en quantifiant le poids et l'influence de ces facteurs adaptatifs à travers un modèle « boîte noire ».

Yao et al. pu démontrer théoriquement que le PMV de Fanger était principalement une relation entre les processus physiologiques du corps humain et les conditions thermiques physiques de son environnement. Ce modèle omet donc le facteur adaptatif et psychologique influençant le confort perçu de l'occupant. Par conséquent, Yao a proposé un modèle de confort adaptatif appelé vote moyen prédit adaptatif (aPMV). Il s'agit d'un modèle de « boîte noire » basé sur le principe adaptatif selon lequel, si un changement se produit de manière à produire de l'inconfort, les personnes réagissent d'une manière qui tend à restaurer leur confort. Yao a également expliqué et postulé que, comme dans la théorie de l'état d'équilibre, les processus physiologiques existent dans une « boîte noire », mais les processus psychologiques et comportementaux donneront une rétroaction « adaptative (contraire) » (Yao, 1997). Cela implique que la composante physiologique qui existe dans la « boîte noire » répond proportionnellement à l'ampleur de la charge thermique influençant les facteurs d'entrée physiques ou stimuli. Tandis que le composant adaptatif dans la « boîte noire » agit de manière adaptative contrairement à l'ampleur de la sensation physiologique lorsqu'elle est mesurée sur une échelle de sensation thermique.

Le modèle de Yao est donc utile pour cette recherche car il évalue distinctement la composante physiologique et la composante adaptative de la « boîte noire » puis intègre ces composantes dans une seule évaluation du confort thermique. Ces qualités du modèle de Yao valident son aptitude à être utilisé pour examiner et quantifier la composante psychologique du confort perçu des occupants. Ainsi, le modèle a été amélioré pour évaluer le coefficient psychologique des occupants dans l'espace intérieur.

Pour améliorer le modèle de Yao, certains paramètres ont été modifiés ; cela inclut le paramètre qui détermine le facteur d'entrée physique (stimuli). Yao et al. ont suggéré que le poids du facteur d'entrée physique affectant le sujet est fonction de la différence entre la température de l'air et la température neutre. Par conséquent, la température opérative est proposée comme un paramètre plus pertinent que la température de l'air car elle prend en compte davantage de paramètres thermiques et de facteurs influençant les stimuli de l'occupant. La température opératoire tient compte du poids moyen de la température radiante moyenne, de la température de l'air et de l'influence de la vitesse de l'air.

Deuxièmement, l'équation aPMV de Yao implique que lorsque PMV = 0, aPMV = 0. Ce n'est pas vrai dans la plupart des cas, comme le confirment les expériences que nous avons menées. Il est donc nécessaire de modifier le modèle aPMV afin de s'affranchir de cette anomalie. Ainsi nous proposons une nouvelle équation modèle basée sur le principe adaptatif et les postulats de Yao.

Sur la base des équations résultantes de ce modèle, 6 variables inconnues sont présentes dans 5 équations. Par conséquent, l'obtention de la 6ème « équation de fermeture » est nécessaire ; cette « équation de fermeture » est générée en réalisant des expériences et en analysant les données acquises. Cette équation formule les relations qui existent entre le coefficient psychologique et les conditions thermiques des sujets.

L'objectif de l'expérience et de l'analyse est d'évaluer le poids de la composante adaptative et psychologique du confort perçu du fait de l'influence des conditions thermiques ambiantes sur le corps du sujet. Ainsi, cela conduit au calcul des valeurs du facteur adaptatif et à la détermination de la température neutre des sujets. Le concept de base de ces expériences est de permettre aux sujets de rester dans un espace clos où les conditions thermiques à l'intérieur de l'enceinte sont modifiées. Au fur et à mesure que les sujets expérimentent les conditions à l'intérieur de l'enceinte, les mesures des conditions thermiques physiques dans l'espace clos et la perception thermique des sujets ont été prises. Ainsi, ces valeurs mesurées ont été évaluées pour étudier l'écart des évaluations physiologiques par rapport à la perception thermique réelle des sujets.

Les expériences sont réalisées dans une pièce rectangulaire fermée d'une surface au sol de 45 m^2 et d'un volume d'air d'environ 100 m^3. Dans cette salle, une cellule expérimentale de 2,55 m × 4 m est construite. Chaque paroi de cette cellule est constituée d'un matériau de surface uniforme et conducteur (plaque métallique ayant une émissivité relativement élevée à température ambiante) afin d'avoir une émissivité efficace de ces parois. Le plafond et le sol sont respectivement constitués de panneaux de gypse et de revêtement de sol en Terrazzo. Toutes les surfaces intérieures sont caractérisées par une valeur d'émissivité élevée.

La température de chaque surface a été modifiée en chauffant et en refroidissant l'enceinte extérieurement. Le chauffage et le refroidissement des murs ont été effectués pour imiter un environnement de bureau réel bénéficiant des gains solaires d'un mur extérieur. Par conséquent, ce mur est refroidi (gamme de températures de surface de 20°C à 10°C) ou chauffé (gamme de températures de surface de 20°C à 40°C) de l'extérieur et certains capteurs de température de surface sont placés sur les surfaces intérieures des parois verticales et horizontales. Une mini station d'acquisition météorologique est installée à proximité des sujets afin de collecter les données de température de l'air, d'humidité relative, de vitesse de l'air et de température du globe noir. La température radiante du mur a été modifiée au cours des expériences au fur et à mesure que chaque sujet remplissait un questionnaire.

Le questionnaire a été structuré pour fournir des informations et des données sur le vote de sensation thermique émanant des sujets afin d'évaluer l'aPMV. Il comprend également des questions qui fournissent des valeurs quantitatives sur l'évaluation de l'adaptation physique et psychologique des sujets.

Deux types de protocole expérimental sont menés ; cela comprend (1) les expériences en période froide et (2) les expériences en période chaude. Les expériences en période froide sont menées pendant la période hivernale et génèrent un vote de sensation thermique (TSV) allant de -3 à +2. Alors que les expériences en période chaude sont menées pendant la période estivale avec des TSV attendus allant de -2 à +3. Cette plage est pensée pour laisser place à la variance qui existe entre aPMV et PMV en raison de l'adaptation du sujet.

Ainsi, la valeur du coefficient psychologique est calculée, puis la fonction de régression linéaire du coefficient psychologique versus le facteur d'entrée physique est tracé pour déterminer une estimation du facteur adaptatif. Alors, le facteur adaptatif étant déterminé, il est utilisé pour l'évaluation du confort perçu des sujets.

La corrélation entre le coefficient psychologique et le facteur d'entrée physique ou les stimuli avait un coefficient de corrélation élevé pour trois conditions thermiques : les conditions thermiques « fraîches », « froides » et « chaudes ». Le facteur adaptatif pour ces conditions thermiques était de -0,7, -1,4 et 0,5 respectivement. Ces facteurs adaptatifs ont été appliqués dans l'évaluation du confort perçu, à savoir l'aPMV comme suit :

$$aPMV = PMV + 0.7$$

$$aPMV = PMV + 1.4$$

$$aPMV = PMV - 0.5$$

De plus, conformément au modèle proposé, le confort perçu de l'occupant est évalué comme la fonction du PMV, du coefficient psychologique K_{δ}, de la température opérative T_{op} et de la température extérieure T_{out} comme exprimé ci-dessous :

$$\text{aPMV} = \text{PMV} - \left(\frac{K_{\delta}}{T_{op} - 0.36T_{out} - 15} \right)$$

Sur la base de cette équation modèle, nous pouvons conclure que le facteur adaptatif est fonction de la durée d'exposition à un climat extérieur spécifique, de la période climatique de l'année, de l'ampleur des stimuli initiés en raison des conditions thermiques dans l'espace intérieur et de certaine autres émotions et croyances. Ainsi, le confort perçu par l'occupant est mesuré, évalué et prédit.

MOTS CLÉS : confort thermique perçu, adaptation psychologique, évaluation du confort thermique, facteur adaptatif, évaluation physiologique

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NOMENCLATURE

Latin letters

A	Area	(m^2)
B	Radiosity	(W/m^2)
C	Convective Heat	(W/m^2)
d	Diameter	(m)
e	Emitted Heat	(W)
E	Evaporative Heat	(W/m^2)
f	Field Factor	(-)
F	View Factor	(-)
g	Black Globe	(-)
G	Black Box Factors	(C^{-1})
h	Heat Transfer Coefficient	(W/m^2 °C)
H	Irradiance	(W/m^2)
K	Psychological coefficient	($°C^{-1}$)
L	Heat loss from the body	(W/m^2)
P	Vapor pressure	(kPa)
q	Heat per unit surface area	(W/m^2)
Q	Heat Transfer loss/gain	(W/m^2)
R	Radiant Heat	(W/m^2)
T	Temperature	(°C)
V	Velocity	(m/s)
X	Physiological Factors	(-)
Y	Psychological Factors	(-)

Greek letters

α	Thermal absorptivity	(-)
δ	Physical input factors	(-)
ε	Emissivity	(-)
η	Adaptive coefficient/factor	(-)
ρ	Thermal reflectivity	(-)
σ	Stefan Boltzman constant (5.67×10^{-8})	(W/m^2K^4)
φ	Heat flux density	(W/m^2)
Φ	Heat flow	(W)

Subscripts and Superscripts

a	Ambient Air
b	Black Body
b	Back
c	Convection
cr	Core
comf	Comfort
conv	Convection
cl	Clothing
d	Down
diff	Diffusion

dry	Dry
eff	Effective
Evap	Evaporation
Exp	Experiment
f	Front
g	Globe
i	Direction
l	Left
m	Mean
mrt	Mean Radiant Temperature
n	Neutral
n	Number
net	Net
o	At rest
op	Operative
out	Outdoor
pr	Plane radiant
r	Radiant
r	Right
rad	Radiation
res	Respiratory
s	Surface
sa	Saturated
sk	Skin
skr	Skin temperature required at thermal comfort
sw	Sweating
u	Up
td	Duration
vap	Vapor

Abbreviations

ACS	Adaptive Comfort Standard	
AH	Absolute Humidity	(g/kg)
AMV	Actual Mean Vote	(-)
aPMV	Adaptive Predictive Mean Vote	(-)
BMR	Basal Metabolic Rate	(W/m^2)
Clo	Clothing Resistance	(clo)
DOE	Design of Experiments	
HVAC	Heating Ventilation and Air Conditioning	
MST	Mean Skin Temperature (34^{o}C)	(^{o}C)
MRT	Mean Radiant Temperature	(^{o}C)
NV	Naturally Ventilated	
OBS	Observed	
PMV	Predicted Mean Vote	(-)
PMV*e*	Predicted Mean Vote with expectancy factor	(-)
Psych	Psychology	
RH	Relative Humidity	(%)

SH	Saturation Humidity	(g/kg)
SKBF	Skin Blood Flow	L/hrm^2
SMT	Skin Mean Temperature	(^oC)
TS	Thermal Sensation	(-)
TSV	Thermal Sensational Vote	(-)

Table of contents

Abstract i

Résumé ii

Résumé détaillé iii

Acknowledgements x

Nomenclature xii

Table of contents xvi

Introduction 1

Research problematic 3

Research questions 3

Objectives...3

Theses structure 3

1 The evolution of thermal comfort factors and evaluations 5

1.1 Fundamentals of thermal comfort 5

1.2 Factors affecting thermal comfort 6

1.2.1 Objective factors 7

1.2.2 Subjective factors 10

1.3 Evaluation of thermal comfort 13

1.3.1 Heat balance approach 13

1.3.2 Adaptive thermal comfort approach..20

1.4 Chapter Conclusion 38

2 Proposed modeling-experimentation methodology for evaluating thermal adaptation 39

2.1 Analysis of proposed model 39

2.2 Model operations...42

2.3 Design of Experiments (DOE) 45

2.3.1 Design and operation of experimental-cell 46

2.3.2 Design of experimental conditions and scenarios 52
2.3.3 Design of Questionnaires 53
2.4 The evaluation of data 55
2.5 Chapter Conclusions 58
3 Data analysis for the evaluation of the adaptive and psychological component of perceived comfort 60
3.1 Cool and cold experiments 60
3.1.1 Characterization of the physical thermal factors 61
3.1.2 Characterization of the physiological factors 66
3.1.3 Characterization of the adaptive and psychological factors 70
3.1.4 Further modifications of Yao's aPMV model 74
3.1.5 Characterization of psychological coefficient and thermal conditions parameters..80
3.2 Hot experiment conditions 83
3.2.1 Characterization of the physical thermal factors 84
3.2.2 Characterization of physiological factors 86
3.2.3 Characterization of the adaptive and psychological factors 90
3.2.4 Characterization of psychological coefficient and thermal conditions parameters..93
3.3 Chapter conclusions 95
4 Conclusions and discussions 97
4.1 Conclusion 97
4.2 Discussions 101
References 104
List of figures 122
List of tables 124
Appendices 125
A. Details of physical thermal factors 125

B. Physiological factors of thermal comfort 127

C. Psychological factors of thermal comfort 129

D. Socio-cultural factors of thermal comfort 134

E. Parameters and equations of heat balance approach 136

F. Other heat balance models 143

G. Evolution of adaptive comfort standards by international organizations 151

H. Other psychological adaptive models 157

I. The concept of schema 163

J. Content of the questionnaire administered 169

INTRODUCTION

The emerging change in the world climate fixture and global warming has become a crucial factor that consistently influences the thermal comfort of occupants. This climate change has induced some corresponding change in the human thermal adaptation and psychological information which has influenced his thermal perception of his environment. It's therefore necessary to adapt these thermal, adaptive and psychological variations into thermal comfort evaluations. Hence this research aims to evaluate the magnitude of physical and psychological adaptation of occupant considering the climate change and global warming at the present time. This kind of adaptive comfort evaluation can also be important for the energy designs and energy management of buildings, so that excessive energy can be controlled and minimized.

Thermal comfort has been defined by the American Society of Heating refrigerating and air conditioning Engineers (ASHRAE) as that "*condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation*" (ASHRAE 55-2017). This definition highlights that thermal comfort is the satisfaction validated by the mind from the perceptions derived through the human body when it interacts with the physical environment. It also emphasizes the importance and necessity of human satisfaction as a criterion in providing thermal comfort to occupants. However, human satisfaction is subject to many conditions related to the individual's environment, physical state, and mental state, making the definition of human thermal satisfaction complex.

de Dear et al. 2002 suggest that people's satisfaction with the indoor climate is achieved when the actual thermal environmental conditions at a given time and space matches with their individual thermal expectations. Therefore, occupant satisfaction is not solely determined by the physical environment, but rather by a complex perception resulting from the intersection between objective *stimuli* with cognitive and emotional processes (Brager et al. 2003). Due to the influence of the cognitive and emotional processes in comfort perception, Nikolopoulou et al (2003) explain that individuals perceive the environment in different ways, and their responses to a physical *stimulus* are not solely related to its magnitude but depend on the "information" they have about a particular situation. Thermal satisfaction may be evaluated by considering the complex relationship that exists between the *psychological* information of the human mind, the *physiological* reactions and sensation of the human body, and the *physical* factors affecting the individual in his environment.

Physiological factors play an important role in determining the comfort levels of the occupants, as the human body continuously undergoes both conscious and unconscious physiological processes to maintain its health and activity. Among these processes, some are aimed at managing and regulating the thermal balance between the body's inner core and its exterior which interacts with the external environment. This regulation aims to ensure that the human sensory system perceives an optimal sensation. Psychological factors can also distort the perception resulting from these physiological reactions. For example, the perception of an occupant experiencing the physiological process of sweating can be deviated due to his past experiences of living in a warm-humid region. Therefore, the magnitude of the psychological factor should be deliberately included in thermal comfort evaluation.

Thus, to be able to define and evaluate thermal comfort in a precise sense, all the factors influencing thermal comfort should be considered, and the complex relationship between the physical and cognitive factors must be accurately modeled. These factors include:

- *physical* factors such as air temperature, mean radiant temperature, relative humidity and air velocity;
- *physiological* factors such as metabolic rate of the occupant, the convectional, radiant, evaporative and respiratory heat exchange and the heat produced based on the thermoregulatory system of the human body mechanism;
- *psychological* factors such as experiences, expectations, perceived control, emotions, attitude, habituation, cognition, personal behavior and representation of the occupant. It can also be related to the socio-cultural factors such as culture, standard of living and technological advancement of an occupant regarding his living region location and believe.

Therefore, the grouping of these factors into their respective domain and endeavoring to weigh and quantify the influence and impact of each of these factors on the human thermal comfort perception is important in achieving accurate thermal comfort evaluations and standards. Furthermore, the capacity to distinctly weigh the influence of the psychological factors in thermal comfort evaluation will be a great progress in thermal comfort researches.

Research problematic

What are the relationships between the thermal conditions and the adaptive psychological factors affecting thermal perception?

Research questions

- How do we evaluate the weight of the psychological component of perceived comfort?
- What are the psychological factors influencing the thermal perception of occupant?
- What is the relationship between the thermal conditions and the physiological component of perceived comfort?
- What is the relationship between the thermal conditions and psychological component of perceived comfort?

Objectives

- To create a methodology that can distinctively evaluate and integrate the physiological and psychological component of perceived comfort evaluation
- To quantify precisely the weight of the physiological and psychological load on the thermal perception of occupants
- To investigate and calibrate the effect of the thermal conditions on the psychological component of thermal comfort and on the overall thermal perception of the occupants.

Theses structure

The first chapter of this thesis examines the various definitions of thermal comfort based on past literatures and researches and discusses the numerous factors affecting occupants comfort. It then considers various methodologies adopted by researchers to evaluated and predict thermal comfort. In the second chapter a model that can distinctly evaluate the physiological and psychological component of thermal comfort was proposed. It explained the relationships between the parameters of the proposed model equations and the modifications made on the existing model. It also indicates the known and unknown variables within the equations and explained the operations of the model which resulted into the experiment protocols. Furthermore, the third chapter described the data acquired during the experiments and grouped them into their respective domain for analysis. The chapter is outlined into two main sections; the cold experiments conditions and the hot experiment conditions. The data were characterized based on their physical, physiological and psychological evolutions. Finally the fourth chapter explained the inferences and conclusions of the results obtained from the experiments. It also enumerated the significance of adaptive and psychological factors in the evaluations of thermal comfort. It also explained the importance of this research to the architectural and engineering design of indoor space.

CHAPTER 1

1 THE EVOLUTION OF THERMAL COMFORT FACTORS AND EVALUATIONS

This chapter examines the various definitions of thermal comfort found in the literature and discusses the numerous factors affecting it. It explores the methodologies used by researchers to evaluate and predict thermal behaviors. Additionally, it investigates the thermal comfort indices and standards derived from the research processes and methods. The chapter aims to outline the thermal comfort standards, indices and factors, with particular emphasis on the psychological factors that have often been overlooked in thermal comfort evaluation.

1.1 Fundamentals of thermal comfort

Thermal comfort is defined as "*that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation*" (ASHRAE, 55-2017). This definition of thermal comfort being the condition of mind correctly emphasizes that, the judgment of comfort is a cognitive process involving many inputs, influenced by physical, physiological, and other factors (Lin, 2008). Hence it can be influenced by personal differences, moods, cultures, as well as individual, organization and social factors. As such, the definition of thermal comfort is not a state of condition, but rather a state of mind (Noel et al., 2010). Furthermore, taking into consideration the behavior of occupants, Hensen (1991) defines thermal comfort as "*a state in which there are no driving impulses to correct the environment by the behavior*". This definition has similarities with Givoni's definition (1976), that it is "*the absence of irritation and discomfort due to heat or cold, and as a state involving pleasantness*". This can also depict the state where the person is entirely unaware of the thermal condition around them, without considering whether the space is too hot or too cold. In this state, the body temperatures are expected to remain within narrow ranges, skin moisture is low, and the physiological effort of regulation is minimized.

Fanger (1973) defined thermal comfort as the condition that an individual feels neither too cold nor too warm while wearing an amount of clothing suitable to the task they need to perform. Therefore, thermal comfort can be described as a state of the mind where the individual is satisfied with the thermal environment, without any urge to make adjustments to the environmental condition or their physical and mental behavior within a specific space and time.

Maximizing thermal comfort is crucial for the health and productivity of occupants, as well as for ensuring the protection and enjoyment of the indoor environment. Additionally, the urgent need to optimize energy consumption costs and minimize environmental impacts in indoor spaces has driven extensive researches in this domain. Hence the quest to comprehend this subject has resulted into the development of some models (de Dear et al., 1998) and indices (Gagge et al, 1992), carrying out experiments in climate chambers (Fanger, 1970) and field surveys (de Dear, 2002), as well as establishing thermal comfort standards and evaluation methods (EN ISO 7730:2005).

These thermal comfort standards and evaluations evolved from understanding the characteristics, behavior, impacts and influence of various factors affecting the thermal sensation and perception of occupants. Therefore, a fundamental aspect of thermal comfort evaluation is the comprehension of the characteristics and functions of these factors.

1.2 Factors affecting thermal comfort

Thermal comfort factors (physical and non-physical) influence the thermal perception of a person in given space and time, due to its intrinsic characteristics, weight and potentials. These factors can be grouped into *objective* and *subjective* factors. Objective factors can be further divided into *physical* and *physiological* factors while subjective factors can be divided into *psychological* and *socio-cultural* factors.

Figure 1 depicts the grouping of various factors that notably affect occupant’s thermal comfort. This organization of factors facilitates enhanced interpretation and quantitative evaluation of thermal comfort. These factors in Figure 1 were deduced from the research work of Auliciems et al 2007, Enescu 2019, Fanger 1970, Gagge et al. 2011, Knez et al.2008, Nikolopoulou 1999, Lenzholzer 2020.

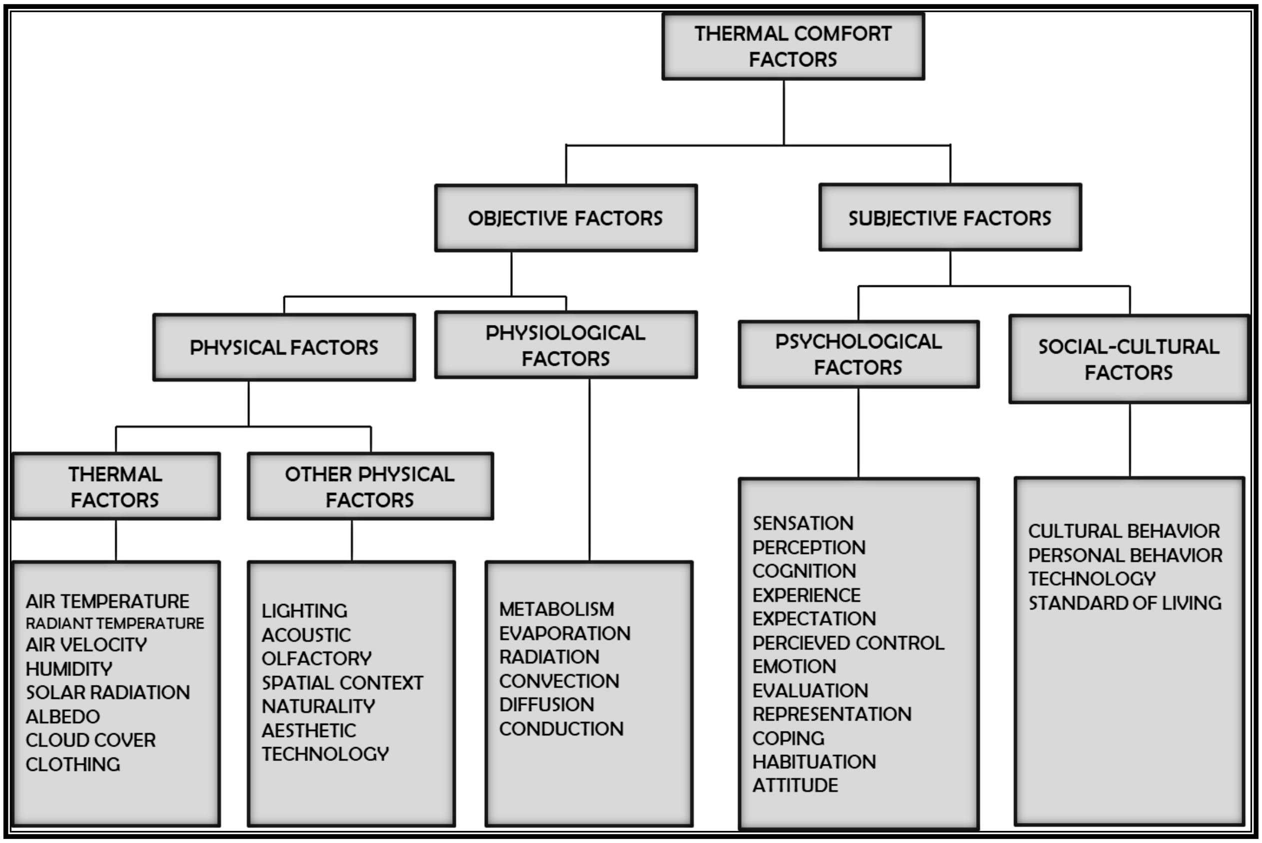

Figure 1: Factors influencing the thermal comfort of occupants

It is essential to note that some or all of these factors listed above can simultaneously influence the thermal comfort of an individual in a given space. As a result, each of these factors needs to be quantified, and their combined impact on the human body and mind should be accurately understood to generate precise comfort evaluation and standards. The following subsections will be dedicated for expounding the characteristics of each of these listed factors.

1.2.1 Objective factors

They are factors that relates to some inherent characteristics of objects, elements, entity, or systems which are not influenced by a person's feelings or opinions in considering and representing the facts or value of its characters.

Physical factors

These are thermal comfort factors that relates to some inherent characteristics of objects or elements that are available and can be sensed from our environment, but are not influenced by a person's feelings or opinions in considering the value or quantity of such characters. These factors can be further divided into *thermal* factors and other physical factors such as acoustics, visual aspects, and olfactory influences. Only the thermal factors will be detailed in this study because of its relevance to this research.

The thermal factors include the;

- **Air temperature**: It is the ambient temperature (T_a) in ^0C of the air surrounding the occupants, with respect to location and time (ASHRAE, 2013). It aids to perceive the temperature differences between the human body and his immediate surroundings
- **Mean radiant temperature**: It is the solid-angle-weighted average temperature of the surrounding surfaces surrounding an occupant. It is also a means of expressing the influence of these surface temperatures on occupant's comfort in the indoor space.
- **Air velocity**: It is the average speed of the air surrounding a representative occupant, over a time interval at a specific location. It can result from free buoyant motion, forced ventilation, or bodily motion caused by the activity of the object.
- **Relative humidity**: Relative humidity (RH) 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, 2013).
- **Clothing insulation**: According to the ASHRAE definition, clothing insulation is "*the resistance to sensible heat transfer provided by a clothing ensemble*" (ASHRAE, 2017). It is usually expressed in clo units and 1 clo is equal to $0.155m^2C/W$

For more details, see **Appendix A, page 125.**

Physiological factors

They factors are related with the functioning of body' system which regulate the body's thermal balance. These factors are based on the situation and body's need at a particular space in time. They include, but not limited to, heat transfer through the human metabolism, evaporation, convection, radiation and conduction.

- **Metabolic rate** is "*the rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, it is usually expressed in terms of unit area of the total body surface*" (ASHRAE, 2013). It is usually expressed in met units and one met is equal to 58.2 W/m^2, which is equal to the energy produced per unit surface area of an average person seated at rest.
- **Evaporation** is the process through which a liquid turns into gas. The human body utilizes by perspiration and diffusion from the skin and respiratory track to release energy to their surroundings, even in conditions when the surrounding temperature is higher than the body temperature.
- **Convection** is the transfer of heat by gas or liquid, where the amount of heat transferred depends on the temperature differences between the two mediums and the velocity of the fluid. Three different processes exist: free, mixed and forced convection.
- **Thermal radiation** refers to the emission of electromagnetic waves from any matter with a temperature above absolute zero (José, 2012). The characteristics of thermal radiation depend on various properties of the surface, such as temperature, emissivity, absorptivity, reflectivity, and the view factor or geometric factor of the surfaces.
- **Heat conduction** occurs between two objects in contact, and heat energy transfers from one object to another. This usually occurs between the clothing and skin surfaces and the amount of heat transfer is determined by factors such as the clothing material conductivity or resistance.

For more details, see **Appendix B, page 127.**

1.2.2 Subjective factors

They are factors related to feelings or opinions in considering the facts or value of an entity, objects, elements or system. In thermal comfort evaluation, the subjective factors can be grouped into psychological and socio-cultural factors.

Psychological factors

They are thermal comfort factors that are related to the human mind and behavior. This includes conscious and unconscious phenomena such as feelings and thoughts that can directly affect the behavior of individuals and groups. Psychological processes affecting thermal comfort includes sensation, environmental cognition (perception, representation, evaluation), Emotions, experiences, expectation, attitude, coping, habituation, based on past researchers especially Knez et al 2009.

- **Sensation** is the initial detection of a stimulus resulting from the stimulation of a receptor in a sense organ. Our sense organs are engaging in transduction, and sensation is possible if the stimulus is strong enough to excite sensory receptors and send nerve impulses to the brain.
- **Environmental cognition** refers to the mental process of acquiring knowledge and understanding our surroundings through thought, experience, and the senses. It is how we learn, remember, and think about information (Knez et al. 2009). Cognition includes perception, representation and evaluation.
- **Perception** was defined by Knez et al. 2009 as the conscious interpretation and elaboration of sensory data. In order for sensations to be useful, we must add meaning to those sensations, which create our perceptions.
- **Representation** is a hypothetical internal cognitive code that represents external reality (Morgan Alex 2014). It can be referred to as the internal image of one's environment that constitutes a functional means of organizing information. Thus, people can codes and stores information relating to the positions and qualities of phenomena taking place in his or her environment.
- **Evaluation** is the process of making valued judgements about our environment. The perception of our environment can be deduced when it is evaluated according to more or

less normative codes or criteria. Therefore the process of weighing the relevance of environmental elements against our system of reference (our representations) is referred to as evaluation.

- **Emotions** are mental states brought on by neurophysiological changes, variously associated with feelings, behavioral responses, and a degree of pleasure or displeasure (Cabanac Michel, 2002; Damasio, 1998).
- **Experience** refers to conscious events and the practical knowledge and familiarity that are produced by these conscious processes. It is associated with recurrent past acquaintance and the present contents of consciousness, as well as the stimulus that has resulted from its learning.
- **Expectation** is a perceptual state of anticipation of an event or occurrence. They are personal beliefs about occurrences that may occur in the future, which are usually developed from a combination of individuals' experiences and knowledge. Therefore, they serve a basic function to prepare humans for future action.
- **Attitude** can be defined as the readiness of the psyche to act or react in a certain way (Main, 2004). It can also refer to a mental and neurophysiological state, determined by experience that exerts a dynamic influence on the individual by preparing him to act in a particular way towards a number of objects or events.
- **Coping** refers to a complex set of behaviors and cognitions that individuals uses to deal with stress and adversity. Hence, in thermal comfort, coping is psychological regulation and strategic ways for dealing with some place-related stimulation and surpassing environmental situations (Knez et al. 2009)
- **Habituation** is a form of non-associative learning in which an innate (non-reinforced) response to a stimulus decreases after repeated or prolonged presentations of that stimulus (Bouton, 2007).

For more details, see **Appendix C, page 129.**

Socio-cultural factors

Culture is shared behaviors and ideas that are passed down through generations; this includes shared values, beliefs, norms, language, and even geography. Socio-cultural factors focus on how situations and cultural factors affect a person's behavior and thinking. It emphasizes that understanding a person's behavior requires knowing about the cultural context in which the behavior occurs (Matsumoto & Juang, 2013). It also submits that human learning is largely a social process, and that our cognitive functions are formed based on our interactions with those around us who are “more skilled”. Here are some of the socio-cultural factor that can influence the behavior of individuals: Culture and cultural expectations, Parental and peer influences, Community influences, Gender norms, Societal norms, Family, personal, and/or religious values, standard of living, mainstream media and social media, technological advancement.

- **Cultural behavior** depicts how culture reflects and shapes the mind and behavior of its members (Heine, 2015). The culture cycle consists of four layers; this includes individuals, interactions, institutions, and ideas. (Markus, & Conner, 2013)
- **Standard of living** implies the level of welfare provided to the residents of a country. Practically, it is reflected in the way in which people live, such as how much money they have to spend, how their houses are constructed, how educated they are, what facilities are available to them, etc.
- **Technological advancement** refers to the making, modification, usage, and knowledge of tools, machines, techniques, crafts, systems. Technological advancement equips individual with advanced devices and systems that enable him to live a more comfortable life.

For more details, see **Appendix D, page 134.**

Man is a complex being and he’s affected by complex systems from different domains which are simultaneously active, fussing together into a single scenario of perception. Therefore methods, models and procedures, that will include all these factors distinctively and equitably, needed to be developed to achieve a precise evaluation of the perceived comfort of the occupants.

1.3 Evaluation of thermal comfort

Methods, indices and models are used to quantify and assess the factors influencing occupant's thermal comfort, and determine their comfort level. An overview of this section can be viewed in Figure 2.

Two approaches exist in contemporary thermal comfort evaluation: (1) the heat balance approach, which focuses on laboratory studies and thermal equilibrium between the occupant and his surrounding, and (2) the adaptive comfort approach, which considers occupant's adaptive behaviors as a significant component of the thermal comfort evaluation (Yao et al.2009, Prek, 2006, Broday, et al. 2017).

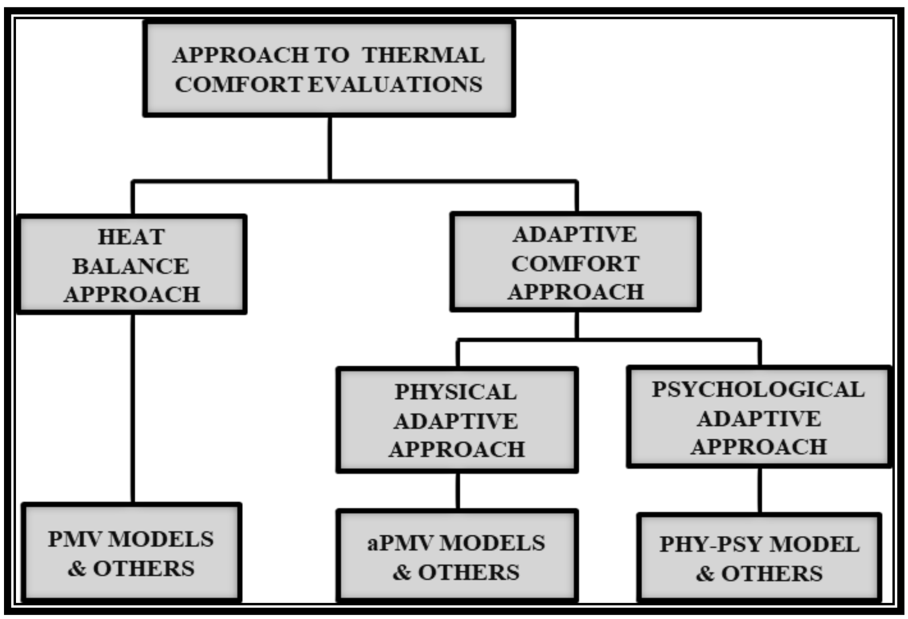

Figure 2 : Two main approaches to thermal comfort evaluation and their corresponding models

1.3.1 Heat balance approach

The heat balance approach combines principles of heat transfer, thermal physiology, thermoregulation, anthropometry and anatomy to create mathematical representations of the human body and its thermoregulatory systems (Krittiya, 2017). This approach aligns closely with the physiological thermoregulatory system of the human body. It functions on the principle that for thermal balance to be achieved, the rate of heat production through body metabolism must equal the rate of heat loss to the external environment through the body surface, respiratory system, and other physiological heat transfer mechanisms. These heat transfer mechanisms include convection, radiation, conduction and evaporation processes.

The metabolic process involves the conversion of consumed nutrients into metabolic energy through chemical and biological processes. While a portion of this energy is used for mechanical work, the majority is transformed into internal heat generation. To maintain thermal equilibrium, the heat generated by metabolism must be transferred to the surrounding environment at the same rate at which it is produced. The body consists of a central core with an average temperature, T_c, surrounded by an outer layer of tissue with an average temperature, T_{sk}, known as the mean skin temperature. The core temperature varies normally between 36-38°C in a healthy body without heat strain. The skin temperature varies depending on factors such as clothing, air temperature, air velocity, perspiration rate and metabolic activity. In a resting person within an environment that is neither hot nor cold, the mean skin temperature is approximately 34°C and this is termed the neutral skin temperature. However, when the environment removes heat from the human body at a rate that differs from the metabolic heat generated, a physiological response occurs. This response is an involuntary action taken by the body to restore a stable heat balance with the surroundings, known as *body thermoregulation*.

The human body contains temperature sensitive receptors in both the core and skin, which respond to deviations of core temperature (T_c) and skin temperature (T_{sk}) from their neutral values. Heat transfer from the core to skin tissues primarily occurs through blood flow. When the core receptors signal a high temperature, *vasodilation* occurs, causing expansion of the relevant blood vessels to facilitate increased blood flow. Further increases in the high signals from core receptors trigger perspiration and evaporative cooling. When the skin receptors detect low signals indicating cold conditions, *vasoconstriction* occurs. This causes the blood vessels supplying the skin tissues to contract. The vital organs in the core of the body receive a continuous supply of warm blood, prioritizing their protection while allowing the skin to cool. As a result, in extremely cold conditions, the extremities such as fingers, toes, or ears can be vulnerable to tissue damage from frostbite. Reduced skin temperature can also trigger involuntary muscular movements, known as shivering, in an attempt to generate additional metabolic heat. Therefore, heat balance in the human body is maintained through continuous physiological heat exchange and metabolic heat production.

The heat balance equations system was developed to consider the metabolic processes involved in body-environment heat exchanges. It takes various forms but follows with the same principles, and then, all equations share a common underlying concept, encompassing the balance of heat generation, heat transfer, and heat storage in the human body. The metabolic rate of the body (φ) provides energy for mechanical work (W), with the remaining energy released as heat (φ-W). This heat is transferred from the body through conduction (φ^{cond}), convection (φ^{conv}), radiation (φ^{rad}), and evaporation (φ^{evap}) (Hensen, 1990). By combining these rates, the heat production equals the sum of heat loss rates, including heat storage (S). All terms are expressed in watt per square meter (W/m^2). The conceptual thermal balance equation is:

$$\varphi - W = \varphi^{evap} + \varphi^{rad} + \varphi^{conv} + \varphi^{cond} + S \quad (1)$$

For thermal balance, the heat storage (S) should be zero (S=0). If S>0 (net heat gain), the body's core temperature will increase. Conversely, if S<0 (net heat loss), the heat storage will be negative and the body's core temperature will decrease. Thus, thermal balance is achieved when S=0.

$$\varphi - W - (\varphi^{evap} + \varphi^{rad} + \varphi^{conv} + \varphi^{cond}) = 0 \quad (2)$$

(Gagge et al. 2011, Krittiya, 2017)

Thus to expound the heat balance concept, the various means of heat loss and their respective parameters of evaluation are described in **appendix E, page 136.**

Thus, the heat balance approach to thermal comfort evaluation is based on the equilibrium sustained due to the heat loss or gain by the body metabolism. This concept has resulted into various types of heat balance models. The following subsection will describe some of these models.

Heat balance comfort models

Researchers have been exploring ways to evaluate and predict the thermal sensation of people in their environment based on the personal, environmental and physiological variables that influence thermal comfort. From the research done, some mathematical models that simulate occupants' thermal response to their environment have been proposed, and some of these thermal comfort models use a seven or nine point thermal sensation scale. The most notable models have been developed by P.O. Fanger (the Fanger comfort model), and the J. B. Pierce Foundation (the

Pierce Two-Node model). The similarity of the models is that they both applied the energy balance principles of the human body. They related the heat exchange mechanisms and the physiological parameters of their experiments, to the thermal sensation or the physiological response of occupants. Other models include the new standard effective temperature SET*, heat stress index HIS, Munich energy balance for individual MEMI, the physiological equivalent temperature PET and much more.

Fanger's comfort model

a. Fundamentals of Fanger's comfort model

Fanger's comfort model was first published in 1967 (Fanger 1967) and then in 1970 (Fanger 1970), which set the stage for other models. The mathematical model developed by P.O. Fanger is probably the most well-known model used. Fanger's model is based upon an energy analysis that takes into account all the modes of energy loss (L) from the body.

The model was created to solve the heat balance equation between the human body and its surrounding environment (Macpherson, 1962). The heat balance was obtained by taking into account the physiological and physical factors, such as the heat production by metabolism, and the heat loss due to evaporation, respiration, radiation, conduction and convection from the surface of the clothing and skin (Chen, et al., 2006). The clothing system is simulated as uniform insulation over the entire body surface (Zolfaghari et al., 2010) while the whole body is considered as a single node.

Fanger's experimental studies were carried out on a large number of subjects in air-conditioned chambers. He measured and took into account the physical quantities that can be obtained by the experiments such as the air velocities, air temperatures, and humidity, then, he observed that the values evolved with the values of the outer surrounding of the human body. The result of the experimental researches was that the thermal sensation (TS) could be connected to the mean skin temperature (T_{sk}) and the heat loss by evaporation, depending on the metabolic rate of the subject (d'Ambrosio Alfano, et al., 2017). Marn, et al., 2019 explained that the metabolic heat generated is transferred from the body core to the skin, and then it is dissipated by the processes of heat transfer taken into account by Fanger's model. Hence, Fanger comfort equation mainly focused on the thermal physiology of the human body (Prek, 2006) and it is applicable to subjects with a constant metabolic rate, exposed to steady-state conditions in uniform thermal environments for an extended period. Therefore, it is appropriate for sedentary people. Physiologically, thermal comfort can be attained when the body temperature is maintained with the lowest effort of physiological regulation (Broday, et al., 2017). Meaning that thermal sensations (TS) at thermal comfort state can be obtained when there is a narrow range of skin temperature and low evaporative rate by the body. The practical concepts that emerged from Fanger's model are the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD).

b. Fangers comfort index (PMV-PPD)

The PMV index is based on the thermal neutrality concept, it has been used to predict TS on a seven-point scale from "cold" (−3) to "hot" (+3) for a single-segment human body in a uniform environment and steady-state conditions in buildings with HVAC systems (ISO 17772-1:2017). The PMV index represents the expected average thermal sensational vote TSV, and predicts TS as a function of the environmental and physiological parameters that affect the human heat balance. It expresses the disequilibrium between the actual heat flow from the human body in a given environment and the heat flow required to get optimum comfort for a given activity. Hence, the index equation is a function of the difference between the heat loss and the metabolic rate and it is thus:

$$\mathrm{PMV} = (0.303e^{-0.036\,\varphi} + 0.028) \times (\varphi - L) \tag{3}$$

The value of L is the total sum of all the heat flux density loss from the body surface due to convection, radiation, evaporation and conduction. This can be expressed as the equation (4);

$$L = \varphi_{cl}^{Conv} + \varphi_{cl}^{rad} + \varphi_{sk}^{Sw} + \varphi_{sk}^{Diff} + \varphi_{res}^{Conv} + \varphi_{res}^{evap} \tag{4}$$

Where :

- $\varphi_{cl}^{Conv} = F_{cl} h_c (T_{cl} - T_a)$
- $\varphi_{net}^{rad} = h_r f_{cl} (T_{cl} - T_{mrt})$
- $\varphi_{sk}^{Sw} = 0.42[(\varphi - w) - 58.15]$
- $\varphi_{sk}^{Diff} = 3.05 \times 10^{-3}[5733 - 6.99(\varphi - W) - P_a]$
- $\varphi_{res}^{Conv} = 0.0014\varphi(34 - T_a)$
- $\varphi_{res}^{evap} = 1.7 \times 10^{-5}\varphi(5867 - P_a)$

The thermal losses terms in equation (4) above, are coming from bibliography (Gagge et al 2011, Enescu 2019, ISO 7730:2005, ASHREA 55:2017). For more details on heat flux density losses in equation (4), see **appendix E page 136.**

Figure 3 below shows the sensation of the subjects in relation to their thermal sensational votes (TSV).

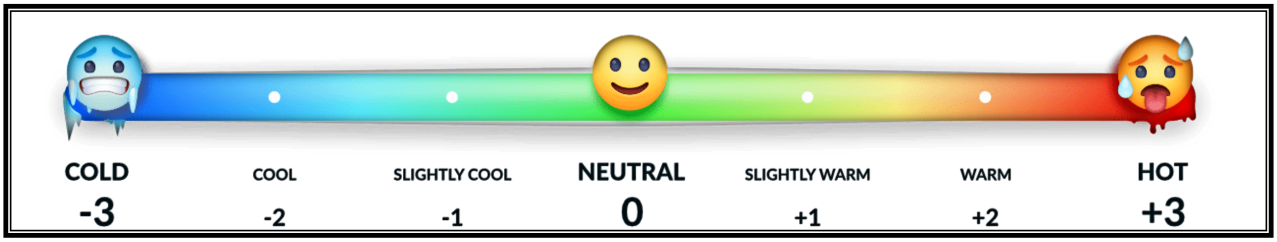

Figure 3 : Thermal Sensational scale (TSS) (source: www.simscale.com)

The predicted percentage of dissatisfied (PPD) index is a derivative of the PMV index, and gives information on the discomfort or dissatisfaction of the occupants. It predicts the number of people who feel too cool or too warm (thermally dissatisfied) among a large group of people in a given environment (ISO 7730:2005). The PPD was estimated based on studies comprising a group of 1300 subjects with 5% of them being the lowest percentage of dissatisfied that is obtainable when PMV is zero. The PMV and PPD indicators predict cold and warm discomfort for the body as a whole. The PPD equation is given below as:

$$PPD = 100 - 95e^{(-0.03353PMV^4 - 0.2179PMV^2)} \tag{5}$$

The diagram in Figure 4 depicts the relationship between the PMV and the PPD values. This will aid to making adequate judgment on the level of dissatisfaction permissible depending on the occupant’s requirements.

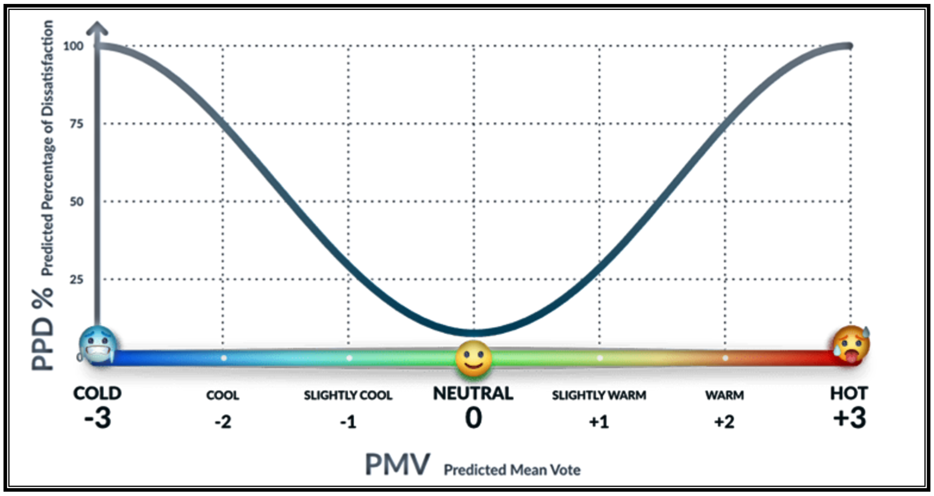

Figure 4: PMV-PPD thermal sensational scale (source: www.simscale.com)

Consequently, The PMV index is being considered as a reference index for buildings provided with HVAC systems in a moderate indoor thermal environment. The PMV index also appeared in the first edition of the Standard ISO 7730:1984, it was later accepted by ASHRAE, and it is currently used in various Standards such as ISO 7730:2005, EN 15251:2007, ASHRAE 55-2017, and ISO 17772-1:2017.

Other heat balance comfort models

The other heat balance models and indices includes the model of J. B. Pierce Foundation known as the (1) Pierce Two-Node Model, (2) the new standard effective temperature SET*, (3) the heat stress index HSI, (4) the Munich energy balance for individual MEMI, (5) the physical equivalent temperature (PET) and much more. Most of these models listed above, except the pierce 2-node model, express thermal comfort evaluations via equivalent temperatures. The pierce 2-node model evaluates the heat balance between the body core (consisting of the internal organs of the body) and the outer layer of the body (consisting the muscles, skin and blood vessels) using physiological parameters. Some of these parameters are not commonly used in engineering evaluations. For more details on these models and the parameters considered, refer to **Appendix F, page 143.**

Limitations of Fanger's comfort model

Based on the popularity and convenience of use of these models, the Fanger's model is predominantly being used for indoor space by thermal comfort professionals, engineers and researchers. This is because of its acceptability by the various standard organizations and the ease in evaluating its constituent parameters. However, the Fanger's result differs from field studies in warmer climates in buildings without air-conditioning, which revealed that the PMV model predicts a warmer thermal sensation than the occupants actually feel (Brager & de Dear, 1998). Thus, the ISO 7730, which is based on the heat balance model, was claimed to overestimates the occupant responses on the ASHRAE scale at high temperatures and underestimates them at low temperatures. Consequently, field studies in thermal comfort domain had pointed out 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. This implies that the adaptive quality of the human body is not a passive recipient of thermal stimuli as portrayed by heat balance model, but an active recipient interacting between the person and the environment conditions via multiple feedback loops. Thus, Fanger PMV model is actually not universal because of these fundamental discrepancies. Therefore, some adaptive thermal comfort models have been proposed.

1.3.2 Adaptive thermal comfort approach

Definitions of thermal adaptation

The term 'adaptation' can be broadly defined as the gradual decrease of the organism's response due to repeated exposure to a stimulus, involving all the actions that make this organism better suited to survive in their environment. In the context of thermal comfort, this may involve all the processes that people go through to improve the fit between the environment conditions and the occupant's requirements (Nikolopolou et al., 1999). Therefore, people are always interacting and reacting to the conditions of their environment, both consciously and unconsciously, with the aim of achieving comfort for themselves.

Evolution of the adaptive thermal comfort approach

The 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 but some key actors who have contributed immensely to this development, includes; Charles Webb (1959), a physicist and a field study thermal 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 where he observed that his subjects were comfortable at the mean temperature of their location which was different in Singapore, North India, Baghdad or North London. Hence, he concluded that they had adapted to their indoor climates (Webb, 1959). Nicol and Humphreys proposed in 1973 the idea that building occupants and their indoor climate were two parts of an integrated, self-regulating feedback system through the physiological adaptation (acclimatization) and behavioral 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.

Furthermore, Auliciems (1981) 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), behavioral (adjustment), psychological (expectation) and cultural factors. He showed that the combinations of past and current thermal experiences, cultural and technical practices are the determinant of thermal expectation. de Dear (1985) compared the adaptive approach with the heat-balance approach in a series of field experiments in Australia. 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. He 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). Also further studies carried out by de Dear and Auliciems (1988) in Australia, showed a disparity between the thermal perceptions and preferences of occupants of air condition buildings and those that were naturally ventilated. Hence the studies related thermal adaptation to cultural expectation and climatic conditions (de Dear et al., 1988).

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). Field studies also shows that people tend to make themselves thermally comfortable by changing their clothing, activity and posture (Nasrollahi, 2007). Also people can easily adapt to higher temperatures in naturally ventilated buildings than the prediction of PMV or the heat balance model (Olesen, 2004). Thus, to account for these adaptive factors in thermal comfort evaluations many field studies were explored by thermal comfort international organizations via numerous researchers.

Note*: There are three main international organizations that are well-known and are involved in the development of 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 55-2017: Thermal Environmental Conditions for Human Occupancy. (2) The European Committee for Standardization (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. (3) 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. Details of the evolution of field studies by comfort standard organizations is explained in* ***appendix G, page 151***

Thus, these adaptive factors can be grouped into two forms, this includes; (1) the physical adaptive factors and (2) the psychological adaptive factors. Consequently, these factors can be evaluated via a two approaches:

(1) Physical adaptive approach;

(2) Psychological adaptive approach.

In the subsequent sections, these approaches of evaluating adaptive thermal comfort were detailed.

1.3.2.1 The physical adaptive approach

The physical adaptive approach emphasizes on the physical changes a person makes, in order to adjust oneself to the environment, or alter the environment to his needs. These physical changes can be; (1) reactive and (2) interactive.

Reactive physical adaptation

The reactive adaptation refers to the changes that people make to their body or by their body both voluntarily or involuntarily to adjust themselves to the prevailing physical and environmental conditions. This reactive adaptation are also called behavioral adjustment since it is well associated with the conscious and unconscious behavior or action of human to adjust themselves to become more thermally comfortable. These behaviors includes personal changes such as altering one's clothing levels, posture and position, consumption of hot or cool drinks etc. according to Yau & Chew 2014, these Behavioral adaptations are commonly represented by (1) clothing insulation, and (2) activity level. Clothing plays an important role as one of the behavioral adaptations of humans. According to some researchers, the linear regression between clothing insulation and operative temperatures was developed as shown in the Table 1 below. The equations were developed from HVAC buildings, air-conditioned offices and free-running buildings, consecutively. Then Mui and Chan 2003 found a correlation between clothing insulation and outdoor temperature for offices in Hong Kong.

Table 1: linear regression of clothing and thermal conditions parameters

Linear Regression	Researchers
$\mathbf{Clo = -0.04T_{op} + 1.73}$	de Dear and Brager (1998)
$\mathbf{Clo = -0.0352T_{g} + 1.3875}$	Bouden and Ghrab (2005)
$\mathbf{Clo = -0.0075T_{ou}t + 0.9898}$	Bouden and Ghrab (2005)
$\mathbf{Clo = -0.04T_{op} + 1.76}$	Mui and Chan (2003)

Furthermore, consumption of cool or hot drinks can be viewed as an adaptive action, as it affects the individual's net metabolic heat, decreasing it by 10% or increasing it by 5% respectively (Baker et al. 1996). Also acclimatization and genetic heritage can be grouped as an inherent physical adaptation to the environment condition. However, there is a general consent that physiological acclimatization does not play a role in adaptive procedures (Fanger et al. 2002).

Interactive physical adaptation

This refers to the changes people make to their environment conditions in order to improve their comfort conditions, such as opening a window, turning a thermostat, creating a shade, *etc.* This behavioral adjustment is commonly represented by the air temperature and air velocity. People's adaptation to air velocity is different in air-conditioned buildings and naturally ventilated buildings. In air-conditioned buildings, people react to thermal comfort by adjusting the temperature set-point, while in naturally ventilated buildings, people adapt by closing or opening windows. Researchers such as de Dear and Brager (1998) and Mui and Chan (2003) found a relationship between air velocity and operative temperature in their field studies as shown in Table 2:

Table 2: linear regression of air velocity and thermal conditions parameters

Linear Regression	**Researchers**
$\mathbf{v = 0.03T_{op} - 0.56}$	Dear and Brager (1998)
$\mathbf{v = 0.02T_{op} - 0.35}$	Mui and Chan (2003)

Hence to take into account the physical adaptive factors in thermal comfort evaluations various models have been developed, these models will be elaborated in the following sections.

1.3.2.2 Physical adaptive thermal comfort models

Quantifying the physical adaptive factors may be somewhat complicated however its relative effect and influence on perception can be possibly weighed and evaluated. Most of the methods and models developed by researchers were in the order of the 'black-box' approach, such that the input factors and output parameters are known whereas the interactions between these parameters may not be clearly defined. Nevertheless, it is necessary to take into account these adaptive loads in thermal comfort analysis and evaluation.

Below are some of the models and indices generated by researchers to evaluate the physical adaptive comfort of occupants.

Relationship between outdoor and indoor temperatures

In Auliciems's research, there is a statistical relationship that states that indoor air temperature is influenced by outdoor temperature (Auliciems 1981). In the exploration of the adaptive model, it can be said that thermal comfort temperature (neutral temperature) is a function of outdoor temperatures. Hence, this adaptive approach also suggests that the people's satisfaction with an indoor climate is attained by matching the actual thermal environmental conditions at the existing time and space with their individual thermal expectations (de Dear et al. 2002). Therefore, to evaluate adaptation, physiological and behavioral actions must be integrated (N. E. Rowland 1996).

This form of model is based on the correlation between the outdoor air temperature and indoor neutral temperature. Note that neutral temperature is the operative temperature where a person neither feels cold or hot. In other words, it is that operative temperature where he doesn't have an urge to adjust himself to the environment and doesn't have the urge to adjust the environment conditions to suite himself. Some correlation has been proposed by researchers revealing the relationship between the outdoor air temperature and the indoor neutral temperature;

Mao Yan 2007 selected five different climatic zones in China as a typical representative of field thermal comfort studies, and established the implementation of climate adaptation method. He represented the relationship between indoor thermal comfort and major outdoor climate changes and finally proposed some climatic adaptation model based on different climatic regions as follows in Table 3 below.

Table 3: Climate Adaptation Model in China

Climatic regions	T_n	R
Severe cold regions	$T_n = 0.121 \times T_{out} + 21.488$	R=0.804
Cold regions	$T_n = 0.271 \times T_{out} + 20.014$	R=0.894
hot in summer and cold in winter regions	$T_n = 0.326 \times T_{out} + 16.826$	R=0.907
Hot summer and warm winter regions	$T_n = 0.554 \times T_{out} + 10.578$	R=0.973
Temperate regions	$T_n = 0.517 \times T_{out} + 11.166$	R=0.879

A study on adaptive model for building was carried out in sub-tropical Hong Kong by Mui and Chan 2003. The adaptive model was developed based on the measurement from 29 offices in summer and 26 offices in the winter. The result shows that the range of acceptable operative temperature for summer and winter are 20.8–25.0^{o}C and 19.5–21.5^{o}C, respectively. The neutral temperature from the study was 23.7^{o}C in summer and 21.2^{o}C in winter. A correlation of indoor neutral temperature and outdoor air temperature was developed by Mui and Chan 2003. Furthermore, some other researchers acquired data in various locations and derived similar linear regression as shown in the Table 4 below.

Table 4: Climate Adaptation Model in China

Location	Linear regression	Researchers
sub-tropical Hong Kong	$T_n = 18.303 + 0.158T_{out}$	Mui and Chan 2003
Pakistan	$T_n = 18.5 + 0.36T_{out}$	Nicol et al. 1999
Tunisia	$T_{n\text{-}Griffiths} = 0.518T_{out} + 10.35$	Griffiths
Asia	$T_n = 0.16T_{out} + 18.6$	Humphreys et al. 2007
Pakistan	$T_n = 0.534T_{out} + 12.9$	Humphrey & Nicol 2000

PMV expectancy factor: *e*

This adaptive comfort model desires to overcome the discrepancies between PMV and the average mean vote (AMV) in warm climates. Fanger and Toftum 2002, proposed an extended PMV model with an expectancy factor, 'e' being the factor explaining why PMV overestimates the thermal sensation of occupants in non-air-conditioned buildings in a warm climate. This is considered to widen the applicability of the thermal index of PMV derived from laboratory research based on conventional heat-balance theory. They considered the expectations of the occupants and the estimated activity as the two major reasons leading to the discrepancies between the calculated PMV and the actual thermal sensation vote in non-air-conditioned buildings. The expectancy factor e was estimated roughly to vary between 0.5 and 1. The e values have been classified by rough estimation of three groups corresponding to the ranges of high, moderate and low degrees of expectations. To evaluate the estimated e values and the hypotheses of the impact of estimated activities, they downloaded some data from the database of thermal comfort field study of de Dear 1998, by analyzing over 3200 sets of field study data from four cities with warm climates (Bangkok, Brisbane, Athens, and Singapore). As a result, an adaptive PMV model (PMVe) has been developed by multiplying the calculated PMV value with the expectancy factor for warm climate region. The expectancy factor e therefore serves as a correction factor to the PMV values which express the mean TSV of the occupants. The expectancy factor e, depends on how common air-conditioned buildings are available in the region and the duration of the warm climate as shown in Table 5.

In this way, it is possible to take into account the reduced expectation of thermal comfort by the occupants in the environments without HVAC (d'Ambrosio Alfano et al. 2011). PMV*e* is thus calculated via equation (6):

$$\mathrm{PMV}e = e \times \mathrm{PMV} \quad (6)$$

Where e = expectancy factor

Table 5: Expectancy Factors for the PMV Index (Fanger and Toftum, 2002)

No. of air-conditioned buildings	Classification of buildings	Expectancy factor *e*
Many	Non-air-conditioned buildings located in regions where air-conditioned buildings are common. Warm periods occurring briefly during the summer season.	0.9-1.0
Some	Non-air-conditioned buildings located in regions with some air-conditioned buildings. Warm summer season.	0.7-0.9
Few	Non-air-conditioned buildings located in regions with few air-conditioned buildings. Warm weather during all seasons	0.5-0.7

Adaptive Predicted Mean Vote (aPMV)

To improve on the adaptive comfort evaluation of occupant, Yao et al. 2009 considered the adaptation behavior of occupant by endeavoring to quantify the weight of the influence of some adaptive factors in relation to PMV. He was able to enumerate theoretically that Fanger's PMV was majorly a relationship between the physiological processes of the human body and the physical conditions of his environment, thereby omitting the adaptive and psychological factor influencing the thermal perception of the occupant. To buttress this, de Dear et al. 1998 revealed that psychologically adaptive self-regulation plays a significant role in determining human thermal sensations based on his research on occupant's thermal comfort in free-running buildings. Consequently, Yao proposed an adaptive comfort model called the adaptive predicted mean vote (aPMV). It is a 'black box' model built on the adaptive principle that, if any change occurs such as to produce discomfort, people react in ways which tend to restore their comfort (Nicol et al., 2002). Yao also postulate that, similar to the steady state theory, physiological response is contained within a 'Black Box', but psychological and behavioral response will give an ''Adaptive (negative) Feedback'' (Yao, 1997). This implies that the physiological component (X) that exist in the "black box" (G) responds proportionately to the effect of the load on the physical input factors δ. While the adaptive component (Y) in the "black box" acts adaptively contrary to the value of the physiological sensation, when weighed on the thermal sensational scale (TSS) (see Figure 5 and Figure 6 below). Thus, Yao proposed the following mathematical expression below to define this relationship:

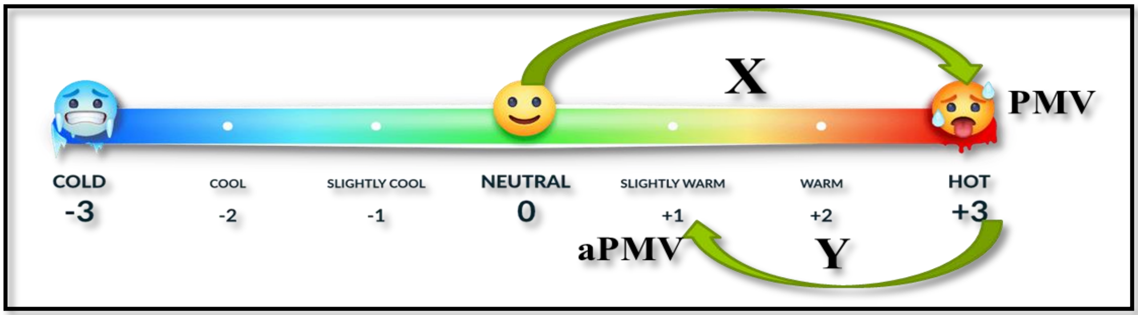

Figure 5: The adaptive component (Y) in the "black box" acts adaptively contrary to the value of the physiological sensation (X) when weighed on a thermal sensational scale

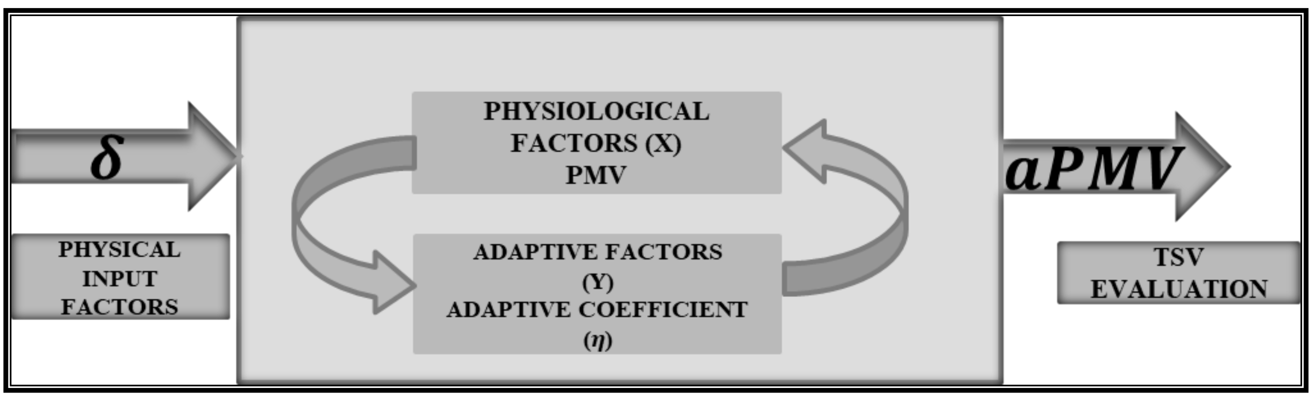

Figure 6: Components and reactions of the adaptive predicted mean vote model (aPMV)

$$aPMV = X - Y \tag{7}$$

where the physiological component has been written by Yao as follows:

$$X = G \times \delta = PMV \tag{8}$$

and the adaptive one has been written by Yao by introducing a psychological coefficient K_δ :

$$Y = G \times K_\delta \times aPMV \tag{9}$$

Yao defined the adaptive coefficient η as:

$$\eta = \frac{K_\delta}{\delta} \tag{10}$$

then combined equations (7)-(10) to obtain the following:

$$\mathrm{aPMV} = \frac{\mathrm{PMV}}{1 + \ \eta \times \mathrm{PMV}} \tag{11}$$

The Yao's model is thus useful to distinctly evaluate the physiological component (X) and the adaptive component (Y) of thermal perception via this "black box" model. The qualities of this model validate its suitability to be used to examine the effect and significance of each of the physical factors on the adaptive behavior of occupant. Nevertheless, this model can be enhanced to examine the influence of the psychological factors on the thermal perception of occupant, by evaluating the values and significance of the psychological coefficient K_δ.

Analysis and proposed modifications of the aPMV model

The physical input factor (**δ**) is the measure of the average thermal deviation from the neutral temperature. The neutral temperature is the operative temperature where a person neither feels hot or cold, such that he doesn't have the urge to adjust himself or his environmental conditions to feel thermally comfortable. At this point the thermal sensational vote TSV of the person is definitely zero. However, Yao et al. suggested that the weight of the physical input factor (δ) affecting the subject in the aPMV model is a function of the difference between the air temperature T_a and the neutral temperature T_{op}^n . According to Yao et al. δ is depicted as equation (12):

$$\delta = T_a - T_{op}^n \tag{12}$$

Hence, this equation above depict that the sum of the stimuli generated by the thermal condition is embedded in the air temperature (T_a). However this can only be acceptable with the assumption that the air temperature T_a is equal to the mean radiant temperature T_{mrt} with zero air velocity v_a. whereas this is not usually the case. Therefore the difference between T_a and T_{mrt}, and its respective heat transfer coefficient will definitely result to some deviations in the perception of the occupant. Thus, the operative temperature T_{op} is proposed to be a more relevant factor than the air Temperature T_a because it takes into account more physical factors from the thermal conditions influencing the stimuli of the human body. This is because the operative temperature considers the average weight of the mean radiant temperature T_{mrt}, air temperature T_a and the influence of the air velocity v. The operative temperature is defined as the weighted average of the air temperature and mean radiant temperature being multiplied by their respective coefficient of heat transfer. Thus, the stimulus ignited by these three physical factors is more reasonable than considering only air temperature. Thus we proposed δ as equation (13):

$$\delta = T_{op} - T_{op}^{n} \tag{13}$$

Observing the Yao's aPMV equation (11), it mathematically implies that when the value of PMV=0 then the value of aPMV=0. However this seems practically deficient because it is possible for individuals to perceive a different thermal perception other than zero when the calculated value of PMV is zero. The outcome of this argument can however be verified by performing experiments.

$$\mathrm{aPMV} = \frac{\mathrm{PMV}}{1 + \eta \times \mathrm{PMV}} \quad when\ PMV = 0, \qquad then \quad aPMV = 0,\ \ true\ or\ false?$$

1.3.2.3 Psychological adaptive approach

Human response to a physical stimulus is not simply a function of its magnitude, but also depends on the "information" that people have for a particular situation (Nikolopolou et al., 2003). Researches revealed that quantitative microclimatic parameters influences thermal sensations, but such approach only accounted for about 50% of the variation between objective and subjective comfort evaluation. The rest could not be measured by physical parameters. Therefore psychological adaptation seemed to become increasingly important because it accommodates the wide fluctuations in the physical environment, as thermal discomfort is being avoided (Nikolopoulou, 2003)

Psychological adaptation processes

The psychological processes refer to how various psychological factors combine its effects to influence the adaptive behavior and consequently the thermal perception of an occupant. This includes:

(i) Expectations and experience

Expectation refers to what the environment should be like, rather than what it is actually. This greatly influences people's evaluation. Experience directly affects people's expectations and can be differentiated into short-term and long-term experience. The short-term experience is related to the memory and seems to be responsible for the changes in people's expectations from one day to the next. In this case people seem to prefer temperatures which follow the profile of the preceding season (Nikolopoulou et al., 2007). Whereas the long-term experience is related to the schema people have constructed in their minds, determining a choice of action under different circumstances.

(ii) Perceived control

The perception of potential control is one of the most essential elements of thermal comfort. Paciuk (1990) affirms that unpleasant stimuli are less irritating when the subjects perceive that they can control them. It is widely acknowledged that people, who have a high degree of control over a source of discomfort, tolerate a wide range of variation of this discomfort and are less annoyed by it. However, people who are in a space to meet someone and did not have the option to leave whenever they wish, or the termination of their exposure to the thermal conditions was dependent on some external factors beyond their control, will feel more distressed and become less tolerant to the environment (Nikolopoulou &Lykoudis, 2006; Nikolopoulou & Steemers, 2003).

The duration of an experience also influences people's perception of control. A discomfort experience is not seen negatively if the individuals anticipate that its duration is going to be short, for example passing through a cold room to the next room. Thus, two different reasoning seem to influence this decision: the subjects' current thermal sensation and the subjects' short-term memory or thermal history.

(iii) Environmental stimulation

A satisfactory thermal comfort conditions have been regarded as those where occupants feel neither warm nor cold, where ambient conditions are "neutral", however environmental stimulation deviates from this assertion that thermal neutrality is a pre-requisite for thermal comfort (van Hoof, 2008).

To evaluate and validate the importance of environmental stimulation, it is interesting to note the variations between people's actual thermal sensation and thermal preferences (Aljawabra & Nikolopoulou, 2009). McIntyre (1980) showed that people who voted for the neutral temperatures in warm climates prefer to be cool and people in cold climates prefer to be warm. This is in line with the findings from the hot humid region of Taiwan, where people's preferred temperature was lower than the neutral temperature (Lin, 2009). Therefore this validate that, when a space offers different kinds of stimulation desirable by people, the people will have higher tolerances to these variant conditions in the space, provided these conditions are not threatening. Hence, psychologists that research on environmental psychology now argue that thermo-neutrality and thermal comfort are not identical (Satinoff, 1996).

(iv) The concept of place

Space is not the same as place. Space is the physical parameters that qualify an enclosure, area, volume or location while place is the perception of an individual due to the quality, characteristic and function of the space. Space is physical while place is psychological even when it is the same location. Therefore, the context of the space influences the perception of the subjects. Oseland proved that thermal comfort depends on the context of the space in question. He showed that the same group of people felt different comfort levels in three different spatial contexts; a climatic room, their work place and their home (becoming increasingly tolerant). He revealed that the people accepted a lower temperature of comfort of 3K in their houses than in the climatic room (Oseland, 1994).

1.3.2.4 Psychological adaptive models

Psychological adaptation is a modification of the perception of sensory information. This type of adaptation can be connected to the cognition, habituation, accommodation and representation concepts found in psychophysics. The notion corresponds to reduction of the intensity of feeling, due to the event of repeated exposures to the same environmental stress. Thermal perceptions depend directly on past experience and users expectations. Therefore, the parameters influencing people's psychological adaptation must be integrated into thermal comfort evaluation method.

In recent researches, some method and concepts have been developed and proposed to understand the behavior of psychological adaptation, this includes but not limited to;

(1) The phy-psy model (Lenzholzer et al,. 2020)

(2) The concept of place, Moderator and human response (Knez et al, 2009)

(3) The concept of relative influence of the psychological parameters (Nikolopoulou et al., 2003)

Note: A comprehensive details of the (2) and (3) above can be seen in **Appendix H, page 157**

The phy-psy model

Lenzholzer et al. (2020) developed a physical/physiological–psychological model Known as phy-psy model. This model differentiates between the long-term and short-term factors as well as the realms in which they manifest; this includes the physical/physiological and the psychological realm. As shown on the diagram in Figure 7, the regional climate and weather (boxes A and B) with its stable characteristics influences the typical microclimate in a location to a large extent (box D). At the same time, microclimate is also formed due to the local spatial characteristics (box C) such as the shapes of the buildings, type of spaces and building orientation (Oke et al., 2017). However, the spatial configurations of a space can result into micro-weather (Westerberg et al., 2003; Lenzholzer, 2010; Jacobs et al., 2015) (box E). Then micro-weather governs the human thermal sensation (box G) in a given space and time. "Thermal sensation" denotes the purely physiological part of thermal perception (Humphreys and Hancock, 2007; Knez et al., 2009). Additional momentary factors that influence this sensation amongst others are the clothing, a person's metabolism, and the length of exposure to the local microclimate (Parsons, 2003; Cheung and Jim, 2018) (box F).

Factors such as habituation, past experience and expectations are relevant for thermal perception. In the phy-psy model, this is summarized as the permanent personal preferences (box H). Knez et al. gave some hints on the spatial parameters that can influence thermal perception: "form (structure, openness), material (surface characteristics), naturalness (degree of artificiality), and location (space dimension)" (Knez et al., 2009). These are the spatial characteristics that influence the thermal perception (box I). Another major set of psychological factors identified were short-term influences (box J) that were first identified by Nikolopoulou and Steemers (2003) and then by others. These comprise a person's mood at a specific moment (Knez and Thorsson, 2008; Yin et al., 2012; Lindner-Cendrowska and Błażejczyk, 2018; Peng et al., 2019), whether or not a person is with company (Nikolopoulou and Lykoudis, 2006; Sharifi et al., 2016; Peng et al., 2019). Also the person could have perceived control over the microclimatic conditions due to the persons' intention within the space (Nikolopoulou and Lykoudis, 2006; Lin, 2009; Tung et al., 2014; Sharifi et al., 2016; Lindner-Cendrowska and Błażejczyk, 2018; Johansson et al., 2018. All these factors are summed up to be psychological factors that influence momentary thermal perceptions (box K).

Consequently, an accumulation of these momentary perceptions will evolve into long-term thermal perceptions for specific places (box L) and eventually distil into "mental schema" as indicated by Lenzholzer (2010). Thus "mental schema" is known to serve as a psychological mechanism to assess unknown situations and a similar process.

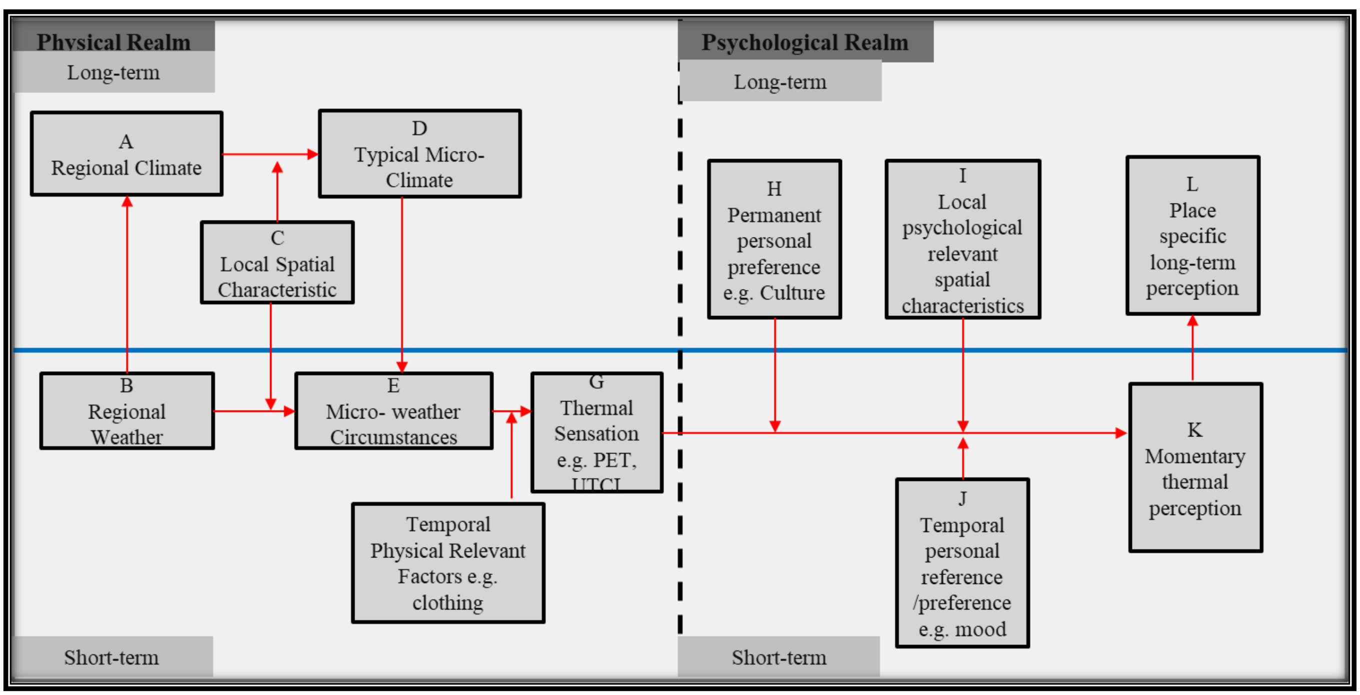

Figure 7: The Phy-Psy model to describe thermal perception. (Lenzholzer et al., 2020)

Schema are cognitive structures that represents organized knowledge about a given stimulus—that is, a person or situation—as well as rules that direct information processing. In essence, schema provides observers with a knowledge base that serves as a guide for the interpretation of information, actions, and expectations (Lord et al., 1986). Weick (1979) defined schema is an abridged, generalized, corrigible organization of experience that serves as an initial frame of reference for action and perception. It therefore serves as the tools that people use to extract the maximal useful "information" from an environment using the least amount of effort (Rosch, 1978). The concept of schema implies that information about some stimuli has been categorized or organized and the result of this organization is a discernible pattern which may be used as a basis for future judgments, decisions, inferences, or predictions (Markus, 1977). More details on the concept of schema can be accessed in **appendix I, page 163.**

Proposed phy-psy model

The phy-psy model is a psychological model in thermal comfort that expresses the chain of actions, reactions and inaction of a person, starting from the physical and physiological realm then to the psychological realm. However some psychological details in the concept of schema were not fully identified. Hence we went further to includes some of these schema concept and consequently modified some of the psychological processes indicated in the phy-psy model.

Figure 8 below is a proposed version of the phy-psy model; the model commences with the interaction between the micro-climate factors and the spatial factors as well as the occupants in the indoor environment. Hence, the thermal comfort evaluation in this physical realm will result into (physiological) thermal sensation (E). Furthermore this thermal sensation transmits the effect of the stimuli into the psychological realm so that it can be comprehended and organized via the person's schema (F). Therefore the first form of schema encountered by the incoming stimuli can be referred to as the perceptive schema (G). This schema is sourced from the permanent schema and it does not propel physical behaviors, but only cognitive and perceptive processes and interpretations. It however reacts with place factor (H) (e.g. restaurant, bedroom) and some temporary psychological factor (J) (e.g. mood and emotions) to result into some perceptive representation (I) which is expressed by perceived control, attitude etc. However if the thermal stress persist or increases, the behavioral schema (K) will be activated by referencing some behavioral representations which could result into actions, reactions and in-actions (P) (Nicol et al., 2002). Hence with further thermal stress beyond the threshold of these behavioral schemas, psychological factors such as habituation (Q), tolerance and copping will be ignited to withstand this stimuli. Note that the momentary interpretations generated by these schemas are the representations (I,R); they are initially activated in the short-term memory. Repetition of related or non-discrepant representation will strengthen the weight of the information structures in the short-term memory which will eventually distil into the permanent schema (S) and stored in the long-term memory. This consequently becomes the evolution of information processing, organizing and interpretation in a person's mental system.

Thus, the knowledge of schema may be a suitable concept for weighing and quantifying the information processed and organized in an individual, so that the resultant psychological parameters may be empirically introduced into thermal comfort evaluation instead of the "black box" approaches.

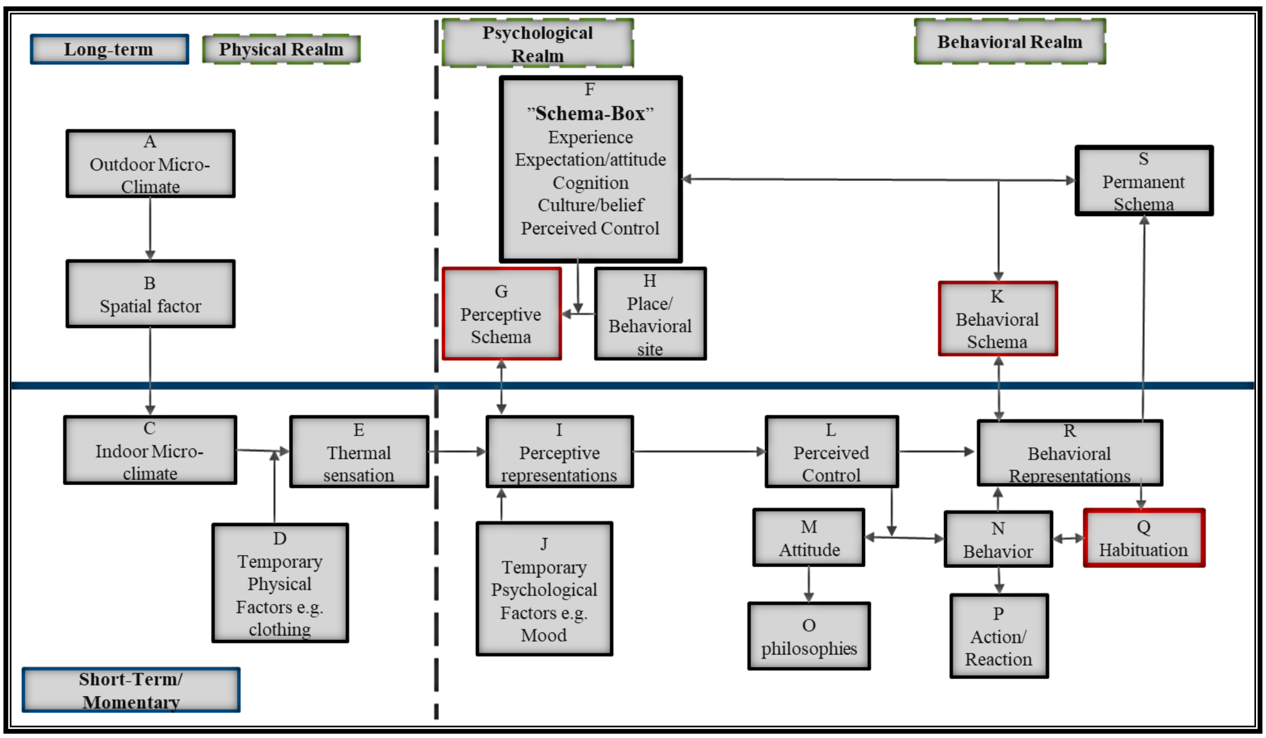

Figure 8: The psychological evolution of the proposed Phy-Psy model

The next chapter intends to develop a model-experiment methodology that can evaluate the psychological adaptive component of occupants' perceived comfort. This can be explored by considering the factors studied in this chapter.

1.4 Chapter Conclusion

In this chapter we were able to explore the definitions of thermal comfort while considering the fundamental criteria required for occupant perceived comfort. We further enumerated and reviewed the factors affecting thermal comfort by grouping them into their respective domain. Some of these factors were subjective factors while others were objective factors. Also some of them were physical factors and others non-physical or cognitive factors. Hence to synchronize these factors from different domain into a single evaluation could be a complex endeavor. We further studied and explore the various approaches developed by researchers to evaluated and predict thermal comfort. These approaches were grouped into the heat balance approach and the adaptive comfort approach. Considering the models and methods developed via this approaches, the adaptive thermal comfort approach was suitable for this research because it considers the psychological, socio-cultural and other physical adaptive factors as parameters required for the evaluation of thermal comfort. Among the adaptive comfort models studied, the adaptive predicted mean vote (aPMV) of Yao was adopted due to its relevance to the research objectives. The principles and equations of the models were able to distinctly evaluate the physiological component and the adaptive component of thermal comfort and then integrate them into a single evaluation. Based on our interest in this model, it was reviewed and some of its parameters were modified and ameliorated to improve its accuracy and functionality. Thus, the aPMV model has the prospect to evaluate the psychological component of thermal comfort. This psychological component may be related to the thermal stimuli experienced by the occupants and the "information" in their memory system.

CHAPTER 2

2 PROPOSED MODELING-EXPERIMENTATION METHODOLOGY FOR EVALUATING THERMAL ADAPTATION

This chapter presents the relationships between the model equations based on the proposed modification made on the Yao's model. It also states the known and unknown variables within the equations so that we can use the derivatives in determining the order and the operations of the model. Consequently, to determine some of the unknown variables in the equations, some experiments were proposed and designed. Hence, the factors and methods considered in these experiments were explained in this chapter.

The chapter is made up of 4 main sections; the analysis of the proposed model, the model operations, the design of experiments (DOE) and the evaluation of data.

2.1 Analysis of proposed model

The aim of this research is basically to investigate the magnitude of adaptation due to the influence of thermal conditions on the perceived comfort of occupants. This entails examining the psychological factors and comportment of the occupants and possibly quantifying these psychological factors to incorporate them into thermal comfort evaluations, standards, and indices.

By studying adaptive comfort evaluations and models, the Yao's aPMV model was identified as having specific characteristics that make it suitable to analyze perceived comfort.

The aPMV model is capable of effectively analyzing both the physiological and psychological components of thermal comfort. According to Yao, the aPMV model represents the relationship between physiological load and counter psychological feedback. Similar to the steady state theory, Yao postulates that the physiological response is contained within the "Black Box" (of the aPMV model), while psychological and behavioral representation provides an ‘‘Adaptive (counter) Feedback” (Yao, 1997). Therefore, it becomes possible to evaluate the physiological component separately from the psychological component of thermal perception, and finally integrate the two contrasting components.

According to Yao’s aPMV model, the PMV value represents the overall physiological weight of thermal comfort evaluation. The psychological component can be derived by evaluating the interaction between the adaptive coefficient, psychological coefficient, and the physical input factors or stimuli experienced by the subject. Thus, the PMV determines the physiological aspect while the adaptive feedback analysis determines the psychological aspect of the evaluation, ultimately contributing to the perceived comfort of the subject.

Yao proposed that the weight of the stimuli experienced by the subjects due to thermal conditions corresponds to the deviation of the air temperature from the neutral temperature, as explained in section 1.3.2.2. However, we differ on this proposition because it does not account for the influence of the mean radiant temperature, air velocity and humidity. Therefore, to complete Yao’s model, we have opted for an expression of the physical input factors or stimuli δ (°C) based on the concept of operative temperature instead of solely relying air temperature as suggested by Yao. This modification considers both radiative and convective thermal exchange stimuli of the human body from the surrounding environment, expanding beyond convective exchanges alone.

According to equation (13) the proposed physical input factor:

$$\delta = \mathrm{T_{op}} - \mathrm{T_{op}^{n}}$$

Where the neutral temperature $\mathrm{T_{op}^{n}}$ is the value of operative temperature $\mathrm{T_{op}}$ when aPMV=0 namely:

$$\mathrm{T_{op}} = \mathrm{T_{op}^{n}} \Leftrightarrow \mathrm{aPMV} = 0$$

Furthermore, in Yao’s experiments conducted in the classrooms of Chongqing University, the adaptive coefficient η was the only outcome derived from the data collected. Yao did not go further to investigate the parameters of the psychological coefficient K_{δ}, which is also an important aspect in analyzing the adaptive behavior and perceived thermal comfort of occupants. However, in our study, we wanted to investigate and evaluate both the psychological coefficient

K_δ and the physical input factor δ, and subsequently calibrate them with the physical thermal parameters of occupant's thermal comfort.

Thus, the objective of this modeling-experimentation methodology is twofold: first, to be able to evaluate the psychological coefficient and secondly, to examine its effect on the thermal adaptation and the perceived comfort of the subjects. The psychological coefficient can be related to the subject's perceptive schema, behavioral schema and habituation schema as explained in section 1.3.2.4 of course, this will requires the concept of weighing the information embedded in the long-term memory of a subject.

The experiment model is initiated from equation (11) of Yao's model expressed as:

$$\mathrm{aPMV} = \frac{\mathrm{PMV}}{1 + \eta \times \mathrm{PMV}}$$

Where PMV can be expand via equation (3) as:

$$\mathrm{PMV} = (0.303\mathrm{e}^{-0.036\,\varphi} + 0.028) \times (\varphi - \mathrm{L})$$

Then we detailed the human body heat losses L (W/m^2) as expressed in equation (4), **page 17** of chapter 1 as follows:

$$L = \varphi_{sk}^{Conv} + \varphi_{net,cl}^{rad} + \varphi_{sk}^{Sw} + \varphi_{sk}^{Diff} + \varphi_{res}^{Conv} + \varphi_{res}^{evap}$$

Where:

- $\varphi_{sk}^{Conv} = F_{cl} h_c (T_{cl} - T_a)$
- $\varphi_{net}^{rad} = h_r f_{cl} (T_{cl} - T_{mrt})$
- $\varphi_{sk}^{Sw} = 0.42[(\varphi - w) - 58.15]$
- $\varphi_{sk}^{Diff} = 3.05 \times 10^{-3}[5733 - 6.99(\varphi - W) - P_a]$
- $\varphi_{res}^{Conv} = 0.0014\varphi(34 - T_a)$
- $\varphi_{res}^{evap} = 1.7 \times 10^{-5}\varphi(5867 - P_a)$

Where F_{cl}= clothing factor, h_c= convective heat transfer coefficient, T_{cl} = clothing temperature, T_a = air temperature, P_a= vapor pressure

The thermal losses in equation (4) are based on bibliography (Gagge et al, 2011; Enescu, 2019, ISO 7730:2005; ASHREA 55:2017). For more details on heat flux density losses in equation (4), see **appendix E page 136.**

Hence, Yao defined the adaptive coefficient η in equation (10) as:

$$\eta = \frac{K_\delta}{\delta}$$

Thus, in the modeling of the physical stimuli δ in equation (13) we chose to consider:

$$\delta = \mathrm{T_{op}} - T_{op}^{n}$$

where the neutral temperature T_{op}^{n} is the value of operative temperature $\mathrm{T_{op}}$ when aPMV=0, namely:

$$T_{op} = T_{op}^{n} \Leftrightarrow aPMV = 0$$

Note that in equations enumerated above there are six unknown variables but five equations, namely aPMV, PMV, L, η, K_δ, δ. Thus, obtaining the 6th equation for closure is necessary; this "closure equation" will be obtained by performing experiments, in an indoor environment where the convective and radiative parts of the thermal conditions will be adjustable. This equation formulates the relation between the psychological coefficient $\mathrm{K_\delta}$, the experimental conditions values and the human subject adaptation.

2.2 Model operations

The operation of this model explores the transition of thermal load on occupants, commencing from the *thermal conditions* in their environment, then traversing through the *physiological processes* within the human body, and ultimately ending in the *thermal perception* experienced by the occupants. Hence the chronological stages of the model operation will be explained next:

- Therefore **the first stage** of the operation is to create or adapt some scenarios of experiments in an enclosure where the magnitude of the physical thermal factors can be altered and modified in the presence of the subjects.
- In **the second stage**, the physical environmental load will transit into physiological stress through the heat exchange medium. This includes the convective, radiative, evaporative

and conductive medium as the body aim to attain thermal equilibrium. Of course this will be evaluated via the heat balance principle of the PMV model. Therefore the PMV values are evaluated based on the magnitude of the physical thermal factors measured and the heat exchange load calculated (see equation (3) and (4)).

$$\mathrm{PMV} = (0.303e^{-0.036\,\varphi} + 0.028) \times (\varphi - \mathrm{L}) \quad (3)$$

Then the heat losses L (W/m^2) as expressed in equation (4) as follows:

$$L = \varphi_{sk}^{Conv} + \varphi_{net,cl}^{rad} + \varphi_{sk}^{Sw} + \varphi_{sk}^{Diff} + \varphi_{res}^{Conv} + \varphi_{res}^{evap} \quad (4)$$

- **The third stage** includes obtaining the values of aPMV which is the actual thermal sensational vote TSV of the subjects. This is acquired by evaluating the response of the subjects from the questionnaires. The results of the questionnaires will be accurately weighed into TSV based on the standards of ASHRAE 55 and ISO 7730.
- Furthermore, **the fourth stage** of the operation is the evaluation of the adaptive coefficient. In equation (11) shown below, comprises of three variables which includes the aPMV, the PMV and the adaptive coefficient η. Hence the values of PMV and aPMV are obtainable via evaluating the measurements of the experiments. Therefore, the value of the adaptive coefficient η can be evaluated by calculations and statistical relationships between PMV and aPMV. The diagram below (Figure 9) shows the transition of thermal factors from the input physical factors to the final output perception.

$$\mathrm{aPMV} = \frac{\mathrm{PMV}}{1 + \eta.\mathrm{PMV}} \quad (11)$$

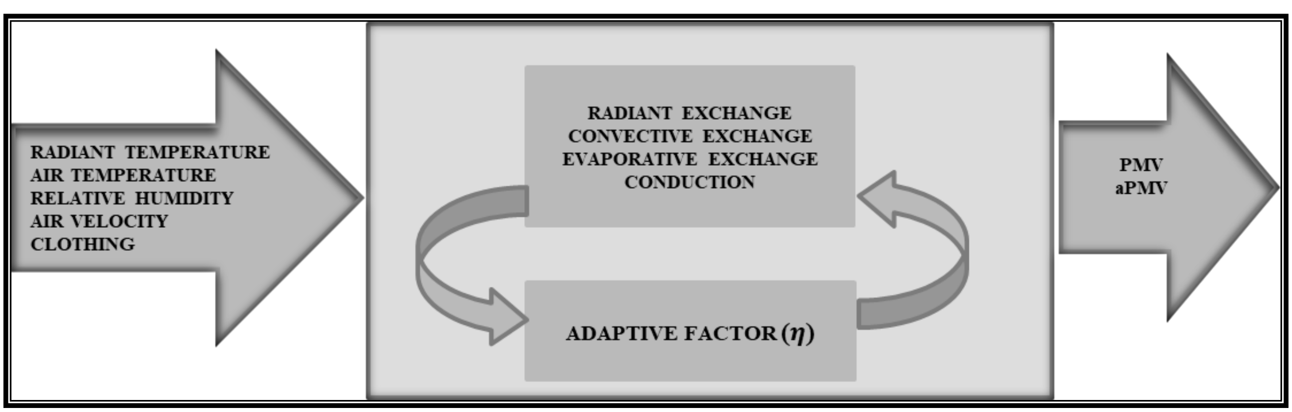

Figure 9: Input and output factors of the proposed model

- **The fifth stage** of the operations involves evaluating the physical input factor δ. It is important to note that the physical input factor and the physical thermal factors are not the same. The physical thermal factors encompass the influence of thermal conditions, such as air temperature and radiant temperature, on the environmental load surrounding an individual. While physical input factors represents the weight of stimuli experienced by the subject due to the magnitude of these physical thermal factors.

  To evaluate the physical input factor or stimuli, the deviation of the operative temperature from the neutral temperature is evaluated. Neutral temperature refers to the operative temperature where subjects do not feel hot or cold; it is also the operative temperature at which subjects does not have any urge to adjust themselves or their environment due to any form of discomfort. Therefore, operative temperature higher or lower than this neutral temperature can be used to assess the magnitude of the physical stimuli experienced by the subjects.

  To evaluate the physical input factor in this study, it is necessary to determine the neutral temperature of the subjects based on the thermal sensational vote (TSV) provided during experiments. In this study, neutral temperature is defined as the operative temperature at which $aPMV$ equals to 0. Thus, physical input factor is expressed in equation (13) below.

  $$\delta = \mathrm{T_{op}} - T_{op}^{n} \qquad (13)$$

- **The sixth stage** of this model's operations involves evaluating the psychological coefficient using the relationship depicted in equation (10). This equation expresses the relationship between adaptive coefficient η, physical input factor δ and psychological coefficient K_{δ}. As the adaptive coefficient and physical input factor have already been evaluated in the prior stage, the relationship between these two variables can be used to determine the psychological coefficient by calculation and statistical methods. Figure 10 below shows input and output parameters influencing psychological and thermal perception of subjects.

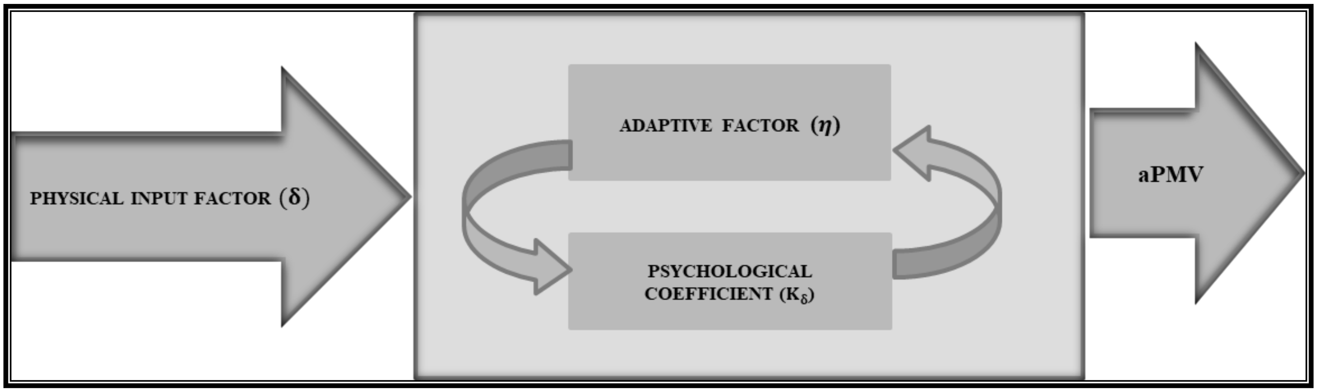

Figure 10: Adaptive and psychological transition in the proposed model

2.3 Design of Experiments (DOE)

Based on the choice of model adapted for this research, some experimental procedures will be necessary to examine the adaptive component in aPMV model and then go further to investigate the evolution of psychological coefficient in relations to stimuli or physical input factor. Therefore, objectives of the experiments include:

(1) To create an enclosure or indoor space with precise geometric specification and measurable surface characteristics such as lengths, heights, emissivity, view factor, temperature etc.;

(2) To be able to modify the magnitude of physical thermal factors in the enclosure, especially the radiant heat emitted, reflected and absorbed by surfaces of the enclosure and subjects;

(3) To determine suitable measurement instrumentation that can capture the required parameters;

(4) To be able to obtain information about thermal perception, sensation and physiological information of subjects;

(5) To obtain some information relating to schema and psychological comportment of subjects;

(6) To observe some consistencies in behaviors of subjects that participated.

To commence the experiment operations, it is paramount to design the experiments with elements, conditions and systems that will achieve the research objectives. This will enable the researcher to acquire experimental data that are accurate. The design consideration for these experiments can be grouped into three domains, which are; (1) the design and operation of experimental-cell; (2) the design of experimental conditions and scenarios and; (3) the design of the questionnaires

2.3.1 Design and operation of experimental-cell

Design of experimental-cell

The experiments was to be executed in a location that is easily accessible to the participants so as maximize the numbers of subjects. At this location a large space is required so that the experiment cell can be constructed within. Hence the experiment cell is expected to be constructed with materials that allows for heat transfer conductively, radiantly and convectively so as to enable temperature modification within the cell. Also the precision of the geometry of the cell is quite important especially in the evaluation of the radiant heat transfer within the cell.

The experimental cell was conveniently located in the research laboratory of Ecole Nationale Supérieure d'Arts et Métiers (ENSAM) Bordeaux, ensuring easy accessibility for the participants and promoting their active participation. The experiments were carried out in a selected enclosed room with a rectangular floor area of 45 m^2 floor space and an air volume of approximately 100 m^3. Within this room, a 2.55 m × 4 m experimental cell was built, as depicted in in Figure 11 and Figure 12. The experimental cell was simplified to a simple cuboid shape with a rectangular flow area of 10m^2. The simplified shape facilitated precise calculations of the geometry and view factors, enabling accurate assessment of the radiant heat transfer between the enclosure surfaces and the human subjects inside.

The experiments were carried out in an enclosed experimental-cell built with externally heatable materials. The heat generated externally was conducted to the internal surface of materials, which then emitted radiant heat into the indoor space, allowing the subjects within the cell to perceive it. The material used for constructing the walls of the cell is strong sheet steel. This material was selected due to its ability to efficiently conduct heat from the external surface to the internal surface. Additionally, strong sheet steel possesses high emissivity value above 0.80, which is suitable for the experiment’s goals. Other advantages of using steel include its structural strength, ease of coupling and dismantling the cell, mobility, flexibility and adjustability as a permanent structure. Moreover, steel structures have a long life span, making them suitable for numerous experiments.

All surfaces of the enclosure, including the floor and ceiling, were uniform and had homogenous emissivity. The walls were made up of steel sheets, while the ceiling and the floor was made up of gypsum board and terrazzo floor finish, respectively. These surfaces were carefully chosen for their high emissivity values. The emissivity of the steel sheet wall surface, ceiling and floor surface was 0.8, 0.9, and 0.9, respectively.

The experiment focused specifically on investigating the influence of long wave radiation, which is prevalent in indoor spaces. To ensure accurate measurement of radiant load, direct solar radiation (which includes short wave radiations) was not allowed to enter the experimental. Transparent openings to the outdoor environment were absent in the design. Ventilation within the cell was provided by electric fans, compensating for the lack of natural air circulation.

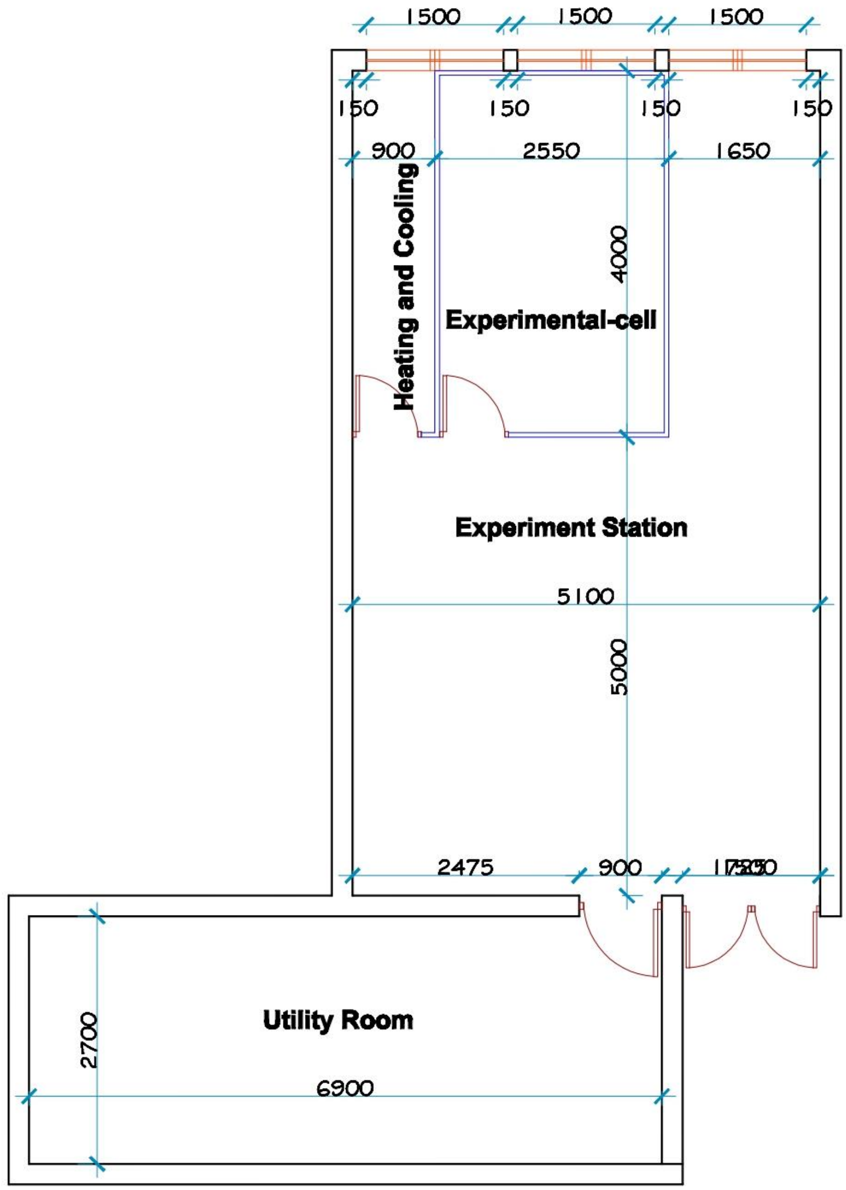

Figure 11: Diagram showing the demarcation of space at the experiment station

Figure 12: Pictures showing the stages of constructing the experimental-cell

Operations of the experimental-cell

Operations of the experimental cell involved simulating a realistic office environment by heating and cooling the walls, replicating the solar gains experienced in typical buildings. To achieve this, one of the steel walls of the cell was either externally cooled (ranging from 20-0°C) or heated (ranging from 20-40°C) using radiators for heating and ice-blocks for cooling. The temperature was modified till a uniform cool or hot temperature was attained. Concurrently, each subject entered the experimental cell and filled out the questionnaire.

Surface temperature sensors were placed on each wall, as well as the floor and ceiling surfaces. Additionally, a meteorological acquisition station was set around the human subject to measure the air temperature, relative humidity, air velocity, and black globe temperature. The surface temperatures and the data collected from the meteorological acquisition station were recorded on a computer for further evaluation and analysis.

For these experiments two main aspect of physical measurement was done, which includes the measurement of the (1) microclimate of the experimental cell, (2) the surface temperature of the experimental cell and the clothing of the subjects. The microclimate of the indoor space was measured with the HD32.3TC of DELTA OHM (see Figure 13). The HD32.3TC has the capacity to measure air temperature, air velocity, radiant temperature and relative humidity concurrently. The equipment is characterized with high accuracy and quite durable for short-term and long-term measurements. It's a device which admits many probes depending on the microclimate elements to be measured. Therefore, for these experiment three (3) major probes was used which includes (1) the HP3217.2R which is a combined relative humidity and temperature probe, (2) TP3276.2 which is the globe thermometer probe; and (3) the AP3203.2 which is the omnidirectional hot wire air speed probe. The characteristics of the listed probes are detailed in Table 6 below.

Table 6: Characteristics of HD32.3TC probes used for the experiments

HD32.3TC of DELTA OHM						
Probes	**parameter**	**Dimension**	**Temp. range**	**Resolution**	**Accuracy**	**Temp. drift**
HP3217.2R	Surface temperature	150mm long 14mm diameter	-40 to 100°C	0.1°C	1/3DIN	0.003%/°C
HP3217.2R	Relative humidity	150mm long 14mm diameter	0% to 100%	0.1%	±1.5%.	0.003%/°C
TP3276.2	Globe thermometer	170mm long 50mm diameter	-30 to 120°C	0.1%	1/3DIN	0.003%/°C
AP3203.2	Air Speed	230mm long 8mm diameter	0.02-5 m/s / 0-80 °C	0.1%	± 0.05%	0.06 %/°C

The second aspect of the measurement is the measurement of the surface temperature of the enclosure with the GL840 of GRAPHTEC (see Figure 13). It has Pt100 temperature sensor that can measure temperatures between the ranges of -200°C to 100°C with an accuracy of ±0.6°C. It has 20 input channels for connection of thermocouples. The connected thermocouples were padded with cotton fiber before being placed on the surfaces of the enclosure. Then, thermocouples are attached firmly to the wall surface by a reflective tape to avoid the absorption of radiant flux by the thermocouples. Hence, GL840 was used to measure temperature of the wall surfaces, the ceiling, the floor and the clothing surface of subjects. The time-step for all data logger during the experiment was configured for one minute per log so that they can be uniformly synchronized during data collation and analysis.

Figure 13: Delta Ohm HD32.3TC captured indoor micro-climate

Figure 14: Graphtec GL840 captured the surface temperatures

Additionally, physical measurements were conducted, including the evaluation of clothing insulation and metabolic rate of the subjects. These measurements were carried out in accordance with standards and specifications outlined in ASHRAE 55-2017. The clothing insulation was assessed in clo units, taking into account the combination of clothing ensembles worn by the subjects, as depicted in the ASHRAE clothing list. The metabolic rate was determined based on the activity level of subjects, as specified in ASHRAE standard. However, since the subjects were instructed to engage in sedentary activity, the metabolic rate was uniform across all subjects.

2.3.2 Design of experimental conditions and scenarios

Furniture within the experimental cell was intentionally kept to a minimum to reduce the dispersion of radiation caused by the complex shapes, sizes and geometry of furniture items. Consequently, only one seat was present in the room, ensuring direct interaction between the subject’s body surface and the surrounding surfaces without any obstruction or interference from additional furniture. The microclimate measuring equipment was placed at a distance of 1 meter from the subject’s seat, based on standard procedures.

For cold session, the process commences in the morning by attaching ice-blocks to one of the external walls for about 2 hours before allowing the subjects into the cell. The subjects were expected to feel cool. For hot session, walls were heated with radiator affixed to one of the external walls, generating warmth and hot thermal sensations for the subjects to perceive.

The subjects were instructed to wear lightweight clothing dark or black colors to facilitate the measurement of their clothing insulation. Also, the choice of dark colored clothing allowed for the estimation of clothing emissivity based on the materials and color. The use of dark colored clothes in the experiments was specifically aimed at ensuring that the emissivity of the subjects’ clothing fell within the range of 0.9-1.0

Program of Experiment

The procedures started by inviting and sending mails to prospective participants explaining to them the aim and objectives of the experiment, of which many participant responded positively and came on the scheduled dates. The experiment consists of four stages of operation for each participant, which are as follows:

1. pre-experimental period;
2. waiting period;
3. questionnaire period;
4. Post-experiment period.

- During the **pre-experimental period**, the researcher collects personal information from the subjects such as name, age, weight and current thermal sensation. This period lasts for 10 minutes and takes place outside the experimental cell.
- In the **waiting stage**, which also lasts for 10 minutes, the subject enters the experimental cell and is instructed to sit and wait. This allows the subject to acclimate to the thermal conditions within the enclosure.
- The **questionnaire stage** involves the subject being attentive to the sensations induced by their environment. The subject proceeds to answer the provided questions and indicate their perceptions and thoughts about their thermal situation and comfort. The completion of the questionnaire typically takes around 10 minutes.
- The **final period** involves a brief discussion with the subject about their experience in the test room and gathering additional details about their background and past experiences.

2.3.3 Design of Questionnaires

Questionnaire is a structured and standardized technique for collecting subjective information or data. It is generally a series of written questions for which the respondents has to provide the answers (Bell et al., 2012). Questionnaires may be qualitative or quantitative and can be conducted online, by phone, on paper or face-to-face. It consists of open and/or closed ended questions and most of the times a mixture of both to avoid the repetitive and boring aspect of the questionnaire. Thus, the open-ended questions enable respondents to answer in their own words in as much detail as they desire but it takes longer to answer, which may discourage respondents. Closed questions provide respondents with a series of predetermined responses they can choose from and takes less time to respond. Closed-ended questions are easier to code and analyze, than open-ended questions which requires content as opposed to statistical analysis.

In this research, both quantitative and qualitative data are essential for analyzing human thermal perception. Therefore, a mixture of the closed-ended and open-ended questions was employed in the surveys. Closed-ended questions are particularly useful for statistical analysis, while open-ended questions complement the results acquired from the analysis of closed-ended questions. Additionally, open-ended questions provide opportunities for the discovery and formulation of new theories during analysis process.

The questions used in the survey were designed to obtain data that can be applied to the aPMV model, PMV model, phy-psy model and the Schema principles of human perception and mental reasoning. These questions aimed to gather information on the subject's thermal sensational votes (TSV), thermal perception, thermal satisfaction or comfort level, thermal preferences, thermal tolerance, and thermal acceptability, as well as the underlying schema structure embed in the thought patterns and behavior. The answers were weighed using the thermal sensational scale (TSS), Linkert scale and other scale suitable for the analysis of the acquired data. The questionnaire was also formulated and structured in accordance to the ASHRAE 55 and EN 15251 standards, incorporating recommended terminology from thermal comfort standard organizations. This approach facilitated comparative investigations and ensured relevance to existing thermal comfort evaluations and standards. The ultimate objective was to relate the evolution of occupants' adaptation to psychological coefficient of the model.

Questionnaire was divided into two main sections. The first section focused on collecting the subjects' personal information, including their name, age, height, weight, country of origin, and more. The second section of the questionnaire focuses on the subjects' thermal sensation, thermal perception, adaptive behaviors, and schema information. This section includes a combination of the closed-ended and open-ended questions to acquire both qualitative and quantitative data aligned with the research objectives.

The questionnaire was prepared to determine the thermal perception, preferred perception, comfort level, perceptive schema and the level of tolerance of the subjects. For example, the questions relating to their preferred perception wishes to determine the difference and intersection between the subject's actual perception and his/her preferred perception. Just as Brager et al. (2003) explained that occupant satisfaction can be determined by the complex perception resulting from the intersection between objective *stimuli* with cognitive and emotional processes. Other qualitative questions were closely related to the long-term memory or schema of the subjects. This has to do with their past experience and expectations, perceived control, level of tolerance etc. The details and reasons for the questions administered via the questionnaire are explicitly elaborated in **appendix J in page 169.**

2.4 The evaluation of data

The method for experimentation and data collection in this research was the mixed method approach. This approach combines quantitative and qualitative research techniques, methods and concepts. The quantitative methods are useful in dealing with precise and systematic measurement of verifiable quantities, such as climate data (Groat & Wang, 2013). While the qualitative methods are used to reinforce the interpretations generated from the quantitative methods. Therefore, to achieve the objectives of this research work, two steps was taken which includes the data acquisition and the data analysis.

Data acquisition

In these experiments, there are two forms of data collected; physical data and subjective data. Physical data are related to the physical component of experiments and the environmental thermal conditions. These components include characteristics of the cell and subjects, some of which are measured directly while others are evaluated based on standards like ASHRAE 55.

Subjective data were obtained directly from the subjects, based on their sensation, perceptions or opinion of their thermal experience in the experimental cell.

Data analysis

Data analysis in this study involved three types of data: *input* data, *intermediate* data and *output* data. Input data signifies all data directly acquired from the experimental procedure. Intermediate data is derived from calculations performed on the input data and output data represents the resultant data from the evaluation of the input data and intermediate data. The parameters in each type of data are enumerated in Figure 15.

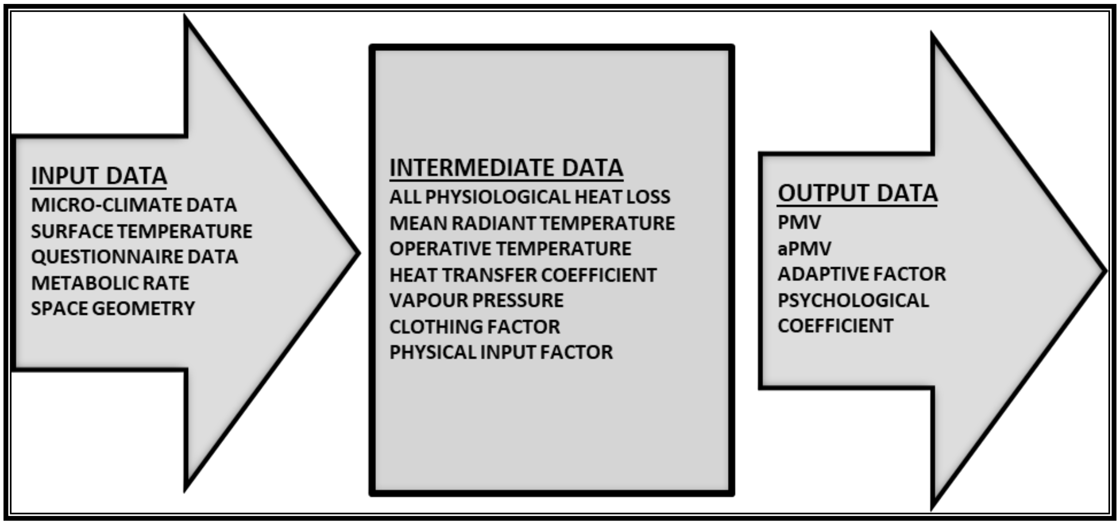

Figure 15: Types of data evaluated during the data analysis

The input data from these experiments includes (1) micro climate data, (2) surface temperature data and (3) questionnaire data. The analysis of the quantitative data collected in this study began with the compilation, and computing of the different raw data obtained from the data loggers and questionnaires. The data were then sorted and summarized into a dataset suitable for computer analysis. First, the data from the data loggers was imported into an excel spreadsheet and organized appropriately. Next, questionnaire data was synchronized with the physical data via their corresponding time step. The time step of the data loggers was one minute. Hence, the Google sheet automatically registered the time at which the questionnaires were submitted.

After the data was properly synched together and compiled, the intermediate data calculations began. These are the calculations resulting from the evaluation of the diverse heat loss from the body. After which some of the output data were calculated by evaluating the intermediate and input data, such as PMV and adaptive factor η. Thus, the values obtained from these calculations were further analyzed statistically to deduce some significance. These statistical techniques include: (1) descriptive and (2) inferential statistical techniques.

Descriptive statistical analysis

Descriptive statistical analyses are used to describe the basic features of the data. They provide simple summaries about the sample and graphical representations of the data to facilitate quantitative analysis. It is used to present quantitative descriptions in a manageable form, especially when we have many measures. However, it does not allow for drawing conclusions beyond the analyzed data or making inferences about hypotheses.

Common statistical measures used in descriptive analysis include measures of central tendency, frequency distribution, and measures of dispersion. Measures of central tendency, such as the mean, median, and mode, describe the central position of the data. Measures of dispersion, such as the standard deviation and range, indicate the spread or variability of the data.

The mean is the average value of the data set, calculated by dividing the sum of all values by the number of values. The median represents the middle score when the data is arranged in order of magnitude, and it is less influenced by outliers or skewed data. The mode is the most frequently occurring value in the data set.

Frequency distribution summarizes the distribution of individual values or value ranges for a variable. It can be presented in tabular or graphical form. Dispersion measures the spread of values around the central tendency. The range is calculated as the difference between the highest and lowest values, while the standard deviation measures the spread of scores within the data set, taking into account the distance of each value from the mean.

Inferential statistical analysis

Inferential statistics are techniques that allow us to use samples to generalize about populations from which samples were drawn. It uses various analytical tools to draw inferences about the underlying distribution of the population. The accuracy of the inferences relies on the sample's representation of the population (Upton, & Cook, 2008). Sampling techniques like simple random sampling, stratified sampling, cluster sampling, and systematic sampling are commonly used to ensure accurate representation.

Note that the inferential statistics usually suggest but cannot absolutely prove an explanation or cause-and-effect relationship. It frequently involves estimations (i.e., guessing the characteristics of a population from a sample of the population) and hypothesis testing (i.e., finding evidence for or against an explanation or theory). There are two main types of inferential statistics: (1) hypothesis testing and (2) regression analysis. The regression analysis is used to quantify how one variable will change with respect to another one. There are many types of regressions available such as simple linear, multiple linear, nominal, logistic, and ordinal regressions. Linear regression is the most commonly used regression technique in inferential statistics, examining the effect of an independent variable on a dependent variable based on unit changes.

Statistical analysis of the experiments

Statistical analysis of this research efficiently used both descriptive and inferential statistical analysis methods to evaluate experiments data. Descriptive data was applicable to summarize subjects' personal information (age, gender, etc.), experiments physical factors (air temperature, air velocity, humidity, and radiant temperatures, metabolic rate and clothing insulations). Descriptive analyses also graphically represented heat losses, including convectional, radiant and evaporative heat loss from the subjects' body. This analysis provided a simple and clear depiction of data characteristics. The other part of the analysis were evaluated and expressed through inferential analysis. This includes the relationships between PMV and physical thermal parameters, adaptive and psychological coefficient evaluation, relationships between physical input factors and psychological coefficient as well as determination of neutral temperature. Thus, these statistical techniques were used to generate various relationships, predictions and probabilities in this research.

2.5 Chapter Conclusions

In this chapter, we were able to proposed and analyze the model equations for the evaluation of occupant's thermal adaptation. However these equations generated the model operation and consequently the experimentation design. The model operations were strategized to follow a sequence that unveils the unknown variables of the model. Based on this model operation, the experimental protocol and scenario was designed. The experimental protocol determined the choice and characteristics of the construction materials, the qualities of the indoor surfaces, the geometry and dimension of the cell and the location or accessibility of the experiment site. It also determined the heating and cooling system of the experiment cell as well as the type of measuring devices and equipment that was used to collect the experiments data.

Two types of experiments were proposed; the "hot" experiments and the "cold" experiments. The hot experiments were related to the summer season while the cold experiments were related to the winter period of the year. This could be an important concept, because the perception of the thermal conditions by the subjects could vary in different climate period even if the temperatures are the same. This behavior could be due to the physical and psychological adaptation of the subjects and it will be necessary to evaluate the magnitude of these adaptations.

Thus the questionnaire were designed to collect the subjective data of the subjects such as their actual perception, preferred perception, level of tolerance, their past experiences and expectations. The quantitative and qualitative data of the experiments were to be synchronized and evaluated based on the model equations and operations enumerated. These evaluations were expected to determine the values of the adaptive factor and psychological coefficients of the subjects. Thus, the next chapter is the detail evaluation and analysis of the acquired data.

CHAPTER 3

3 DATA ANALYSIS FOR THE EVALUATION OF THE ADAPTIVE AND PSYCHOLOGICAL COMPONENT OF PERCEIVED COMFORT

This chapter explained the step by step process of evaluating and analyzing the experiment data. The chapter is outlined into two main sections of data analysis: cool and cold experiments conditions and hot experiments ones.

3.1 Cool and cold experiments

Two forms of experiments were carried out during this period. This includes (1) cool experiments and (2) cold experiments. The "cool experiments" was carried out in early winter period when outdoor temperatures were moderately low, ranging from 14^0C to 25^0C. These experiments were held on the 20^{th}-26^{th} October 2022. Then the "cold experiments" were carried out in mid-winter period when outdoor temperatures were low, ranging from 0^0C to 15^0C. These experiments were held on the 30^{th} January -3^{rd} February 2023. Thus, a comparative and integrated analysis of data acquired for both form of experiments will be expounded. The physical, physiological and the psychological factor were statically characterized hence.

Sample size and characteristics of subjects

The "cool experiments" and "cold experiments" were carried out when outdoor climate condition was cold and indoor microclimate was respectively moderately cool and cold. However, indoor thermal condition was modified via one of the walls, which emit radiant heat into the cell as explained in the experimental-cell designed section. Hence, this experimental setup was intended to produce an outcome of thermal sensational votes (TSV), ranging from -3 to +2.

The experimental setup for cool and cold experiments was carried out with the objective of creating environmental conditions where participants can fully deploy their adaptive characteristics and capacity. Therefore, experiment duration for each participant was 40 minutes. Thus, adaptation in thermal comfort was expected to be deployed by subjects due to their long-exposure to indoor environmental conditions. A total of 24 subjects participated in “cool experiments” consisting 18 males and 6 females while a total number of 29 subjects participated in “cold experiments’” consisting of 17 males and 12 females. The age range was 21-51 years old; highest population age range was 21-31 years. Most of participants were from French origin, although participant from other countries includes Spain, Morocco, Vietnam, Algeria, USA, and Philippines.

Other data estimated based on thermal comfort standards are metabolic rate and clothing insulation. Metabolic rate was the same for all the participants because it was based on metabolic standard for subjects’ activity level. Since subjects were required to fill-in their questionnaire on their laptops or on their phones, their activity level for being seated, quiet and reading was 1met or 58.2W/m^2. Thus, it was assumed to be uniform for all the subjects. Clothing insulation varied slightly among subjects, although we proposed a dress code that will make them more sensitive to the thermal conditions. Clothing insulation ranged from 0.3-1.0 clo, although most of the subjects clothing were estimated to be 0.45 clo.

3.1.1 Characterization of the physical thermal factors

Based on data downloaded from data logger, air velocity was uniformly constant throughout the experiments, not exceeding 0.1m/s. However, magnitude of the other physical thermal factors changed due to the change in internal surface temperature of the cell walls, ceiling and floor (independent variable for the experiment). Thus, some evolutions were observed in mean radiant temperature, air temperature and relative humidity. Figure 16 and Figure 17 show an evolution of these physical thermal factors and that an increase in mean radiant temperature led to a proportionate increase in air temperature as well as a proportionate decrease in the relative humidity. It is important to note that the thermal load applied to the experimental cell was generated by radiant heat modified on one of the walls. Hence, this radiant heat influenced other physical thermal factors, except the air velocity. Change in air temperature can be accounted for by considering the radiant heat absorbed by air particles and water vapor in the air. Another factor includes natural convection between air and the heated or cooled surfaces of the cell. Thus, we can observe that radiant heat can influence air temperature magnitude, and can moderately affect the magnitude of relative humidity in cold thermal conditions. Figure 16 and Figure 17 depict the relationship between mean radiant temperature and air temperature in indoor space resulting from indoor radiant heat modification. The graphs in both cases showed that a unit increase in mean radiant temperature led to a unit increase in air temperature.

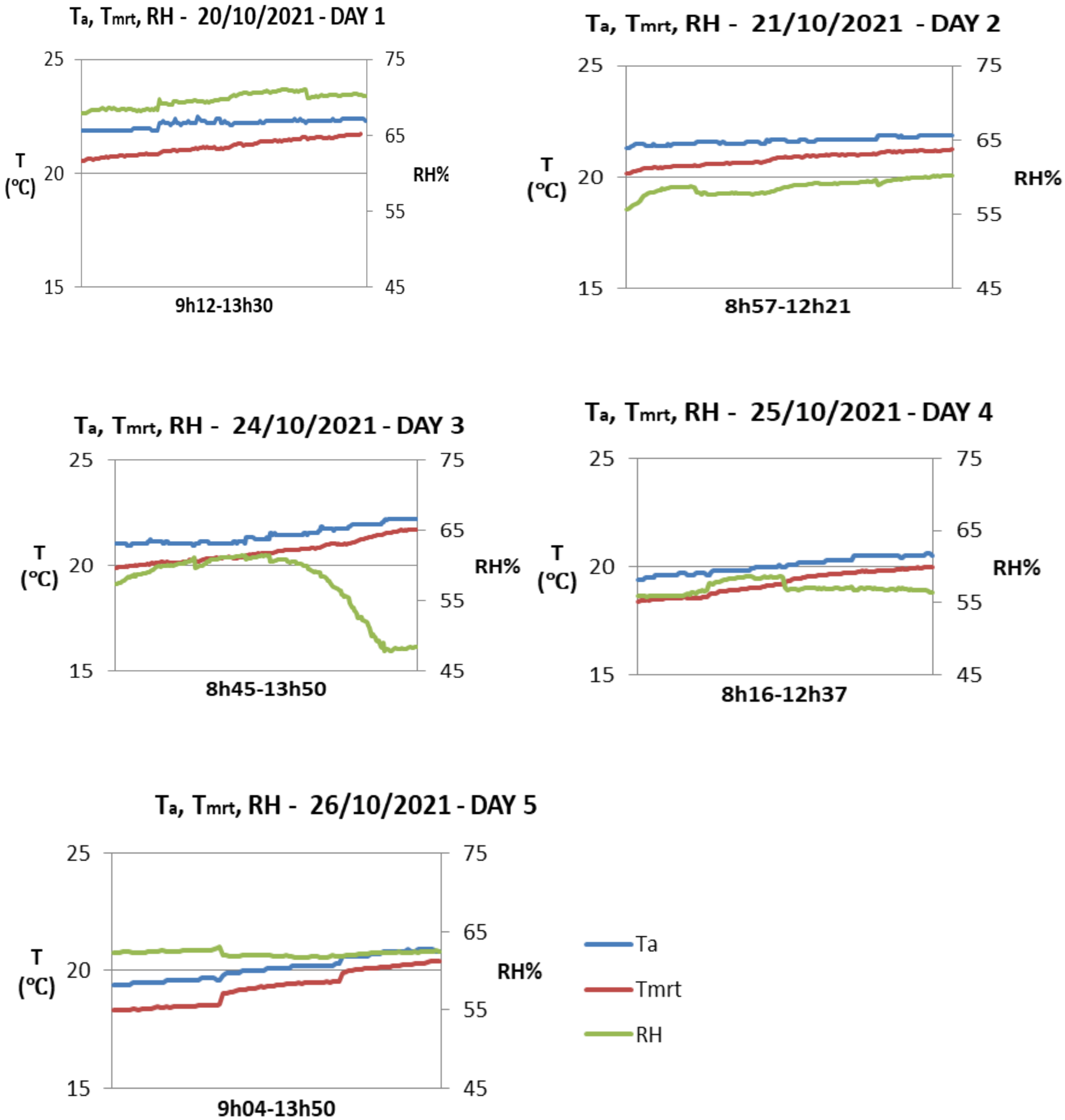

Figure 16: Evolution of the physical thermal factors in experimental-cell (cool conditions)

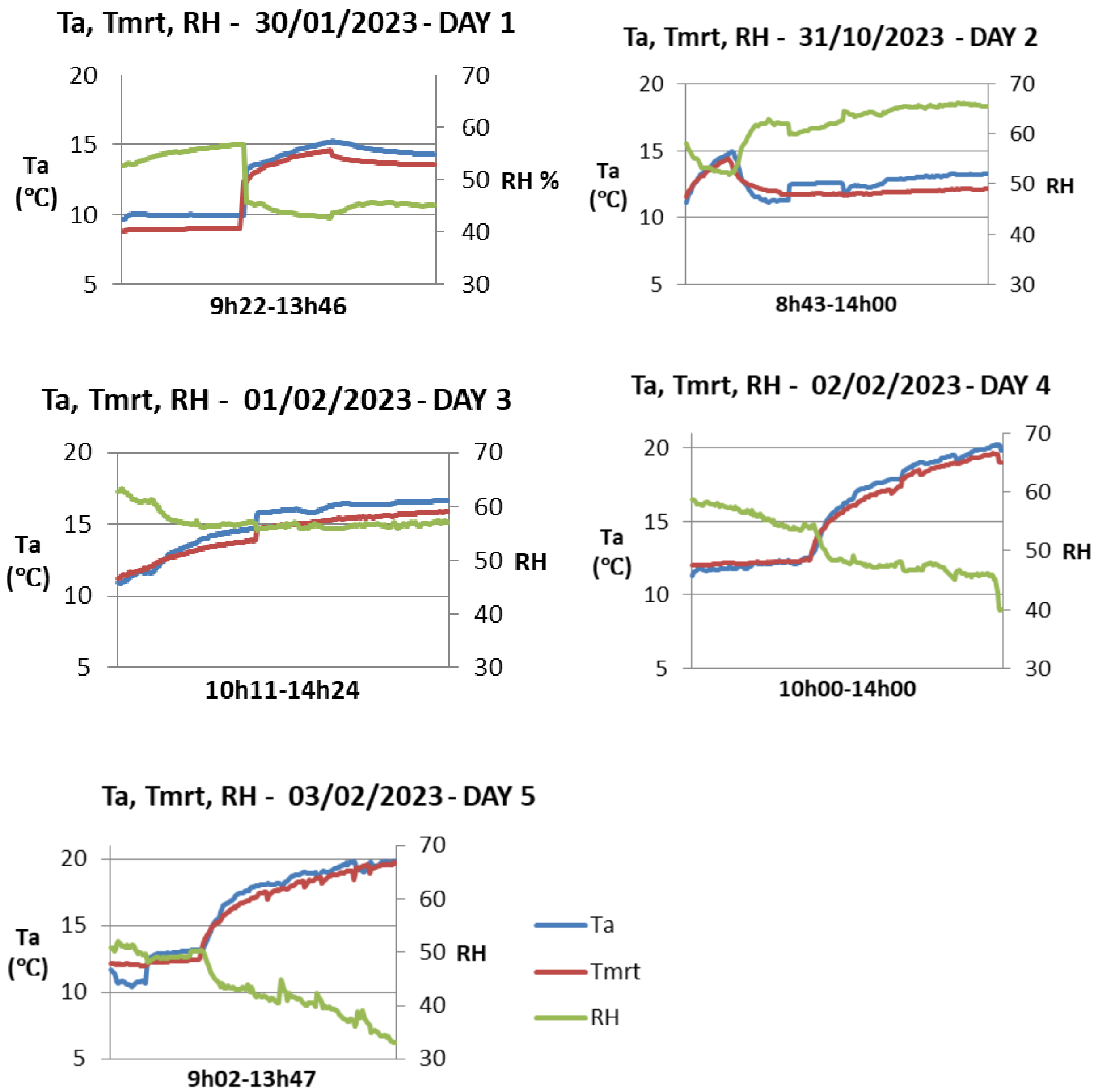

Figure 17: Evolution of the physical thermal factors in experimental-cell (cold conditions)

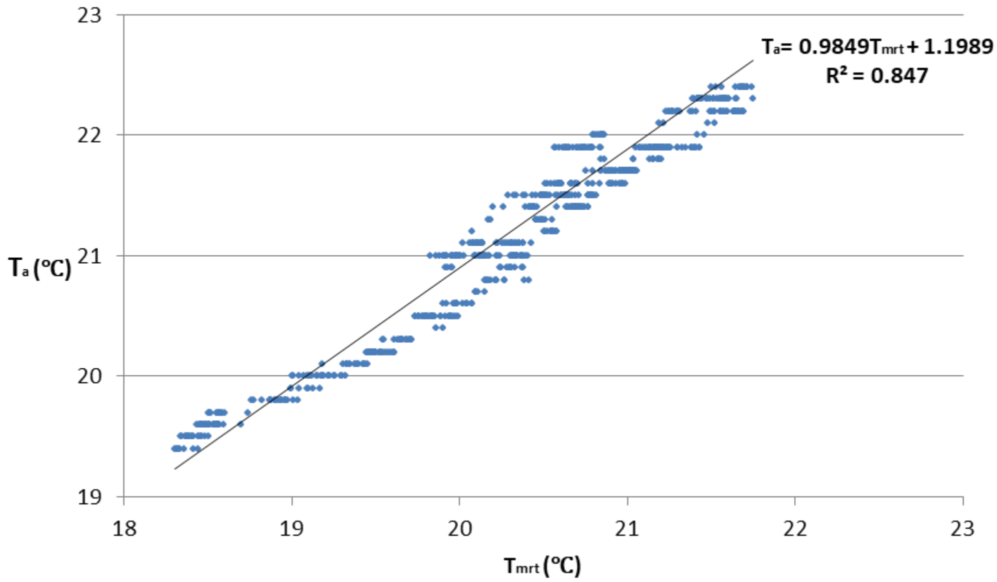

Figure 18: Correlation of air temperature and mean radiant temperature (cool conditions)

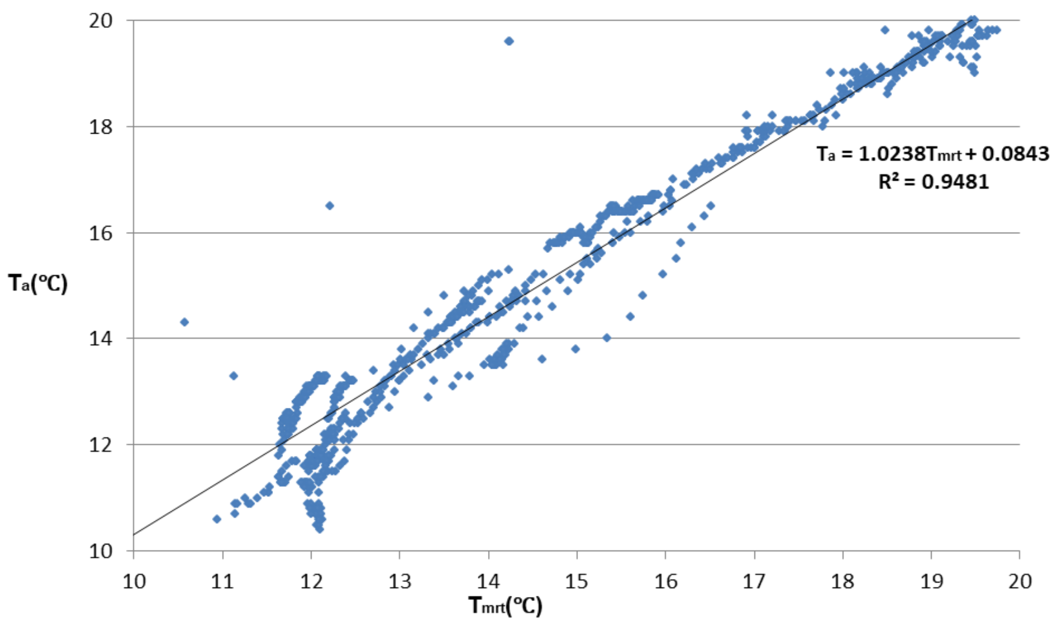

Figure 19: Correlation of air temperature and mean radiant temperature (cold conditions)

3.1.2 Characterization of the physiological factors

Figure 20 and Figure 21 below depict the trends of heat losses from subjects' body as their body aim to achieve thermal balance with environmental condition in experimental cell. This analysis expresses, in graphical form, average heat losses from all subjects' body, specifying the processes at which this heat is being exchanged with their thermal environment for cool thermal conditions.

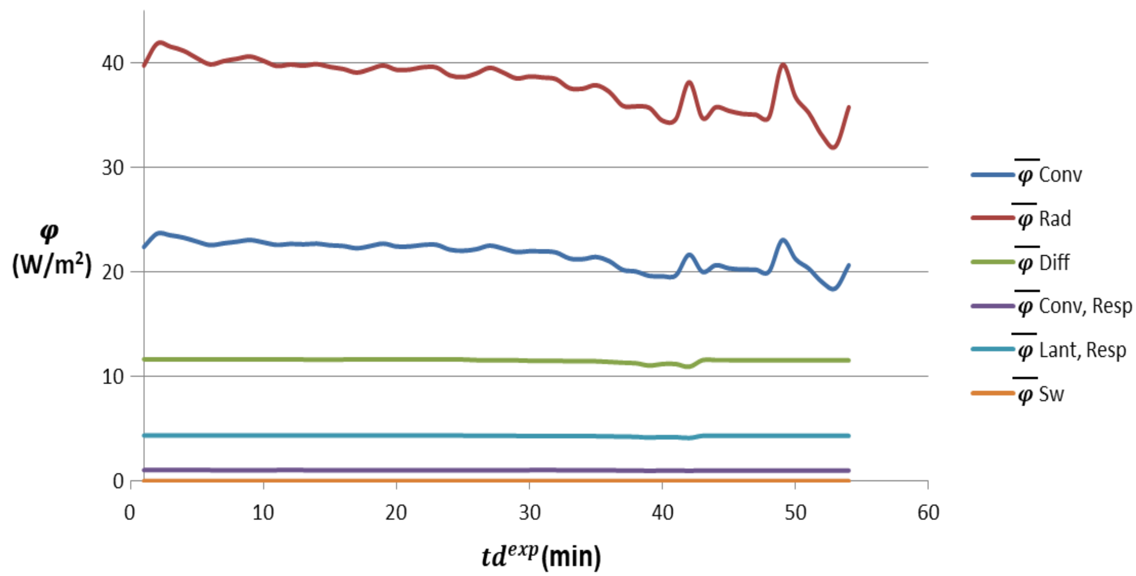

Figure 20: Trends of heat losses by subject's body (cool conditions)

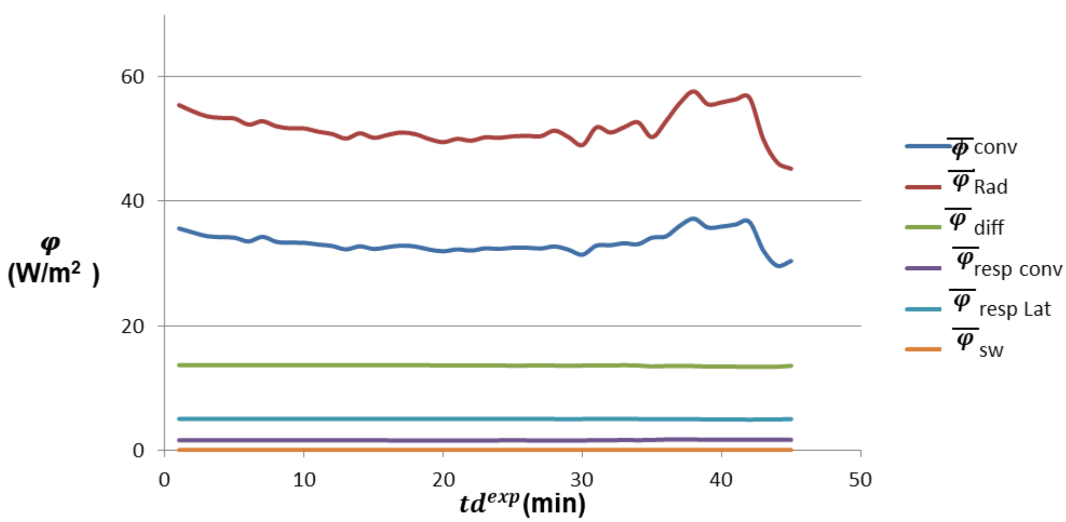

Figure 21: Trends of heat losses by subject's body (cold conditions)

From the analysis above, average heat losses (via various processes of heat loss) from subject's body were plotted on vertical axis while experimentation duration was plotted on the horizontal axis. The analysis can be mathematically represented by the equation below:

$$\overline{\varphi^*} = \frac{\sum_{i=1}^{N_{exp}} \varphi_i^*(t)}{N_{exp}(t)} \tag{14}$$

Where φ^* is φ_{cl}^{Conv}, φ_{cl}^{rad}, φ_{sk}^{Sw}, φ_{sk}^{Diff}, φ_{resp}^{Conv}, φ_{resp}^{Lant} and exp mean experiments

Hence, it can be observed that convectional and radiant heat losses from body surface were the prominent heat loss as seen on the graphs above. Average radiant heat loss ranged from 31 to 60 W/m^2 while average convective heat loss ranged from 18 to 38 W/m^2. Heat losses by body surface via radiation and convection followed the same trend based on temperature change within cell. This indicates that as air temperature and radiant temperature decreases, convectional and radiant heat loss increased respectively and vice versa. Heat loss by sweating was uniform and low throughout experiment because each subject activity level was uniform. This activity level was based on ASHRAE standard for subjects that are sedentary, seated and quiet. Also, heat loss by diffusion from skin surface was relatively uniform and respiratory latent heat loss by subject's body was also uniform and negligible compared to other forms of heat losses enumerated.

Body thermal sensation is primarily influenced by the magnitude of body heat loss, with convectional and radiant heat losses from the body surface playing a significant role. Consequently, the findings of these investigations emphasize the importance of considering operative temperature as a key parameter in evaluating subjects' thermal sensation. Operative temperature combines the effects of air temperature (which is inherently convective) and means radiant temperature, along with their respective heat transfer coefficients. By considering operative temperature, we can better define the stimuli sensed by the subjects' bodies. Moreover, the use of operative temperature may provide a simpler approach for evaluating and predicting occupants' thermal sensations.

A further analysis, shown in Figure 22 and Figure 23, was explored to determine the percentage weight of heat loss from human body. This was done by calculating the percentage of the sum of the average heat losses for each heat loss process. It can be expressed with the equation below:

$$\varphi^*_{\%} = \frac{\int_0^{td^{exp}} \overline{\varphi^*}(t)dt}{\int_0^{td^{exp}} \overline{L}(t)dt} (\%) \tag{15}$$

Where φ^* mean φ_{cl}^{Conv}, φ_{cl}^{rad}, φ_{sk}^{Sw}, φ_{sk}^{Diff}, φ_{resp}^{Conv}, φ_{resp}^{Lant} exp mean experiments

Figure 22 and Figure 23 show that about 50% of total heat loss from human body in the cell during the cold experiments was radiant heat loss. Therefore, radiant heat loss can define 50% of thermal sensation experienced by the subjects. It can therefore be concluded that in physiological realm, radiant heat loss is the most significant determinant of subject's thermal sensation. However, convective heat loss is another prominent influencer of thermal sensation because it makes up about 30% of the total heat loss from subjects body. Thus, a combined influence of radiant and convective heat losses, equaling about 80% of total heat loss by subjects, will indicate an estimate of thermal sensation experienced. Therefore, concept of operative temperature can be adopted as a significant parameter in thermal comfort evaluations

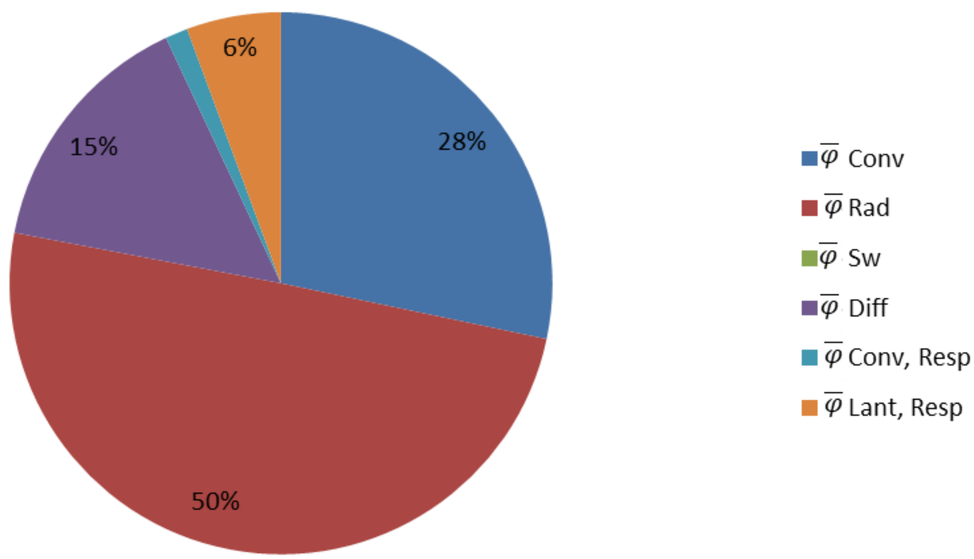

Figure 22: Percentage of total heat loss by various heat loss process (cool conditions)

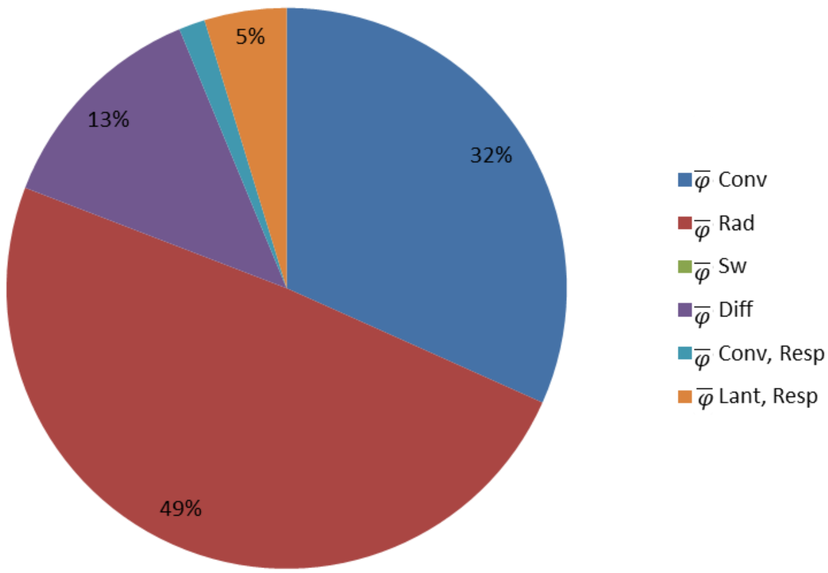

Figure 23: Percentage of total heat loss by various heat loss processes (cold conditions)

To further investigate the significance of the radiant heat loss, a graph of PMV against subject radiant heat loss was plotted as shown in Figure 24. Subjects cold thermal sensation proportionately becomes colder (as PMV tends to -3) when radiant heat loss increased. The graph also shows that when PMV=0 radiant heat loss is about 28 W/m^2. This signifies that radiant heat loss of about 28 W/m^2 is required by the body to make it thermally comfortable when the body is at rest.

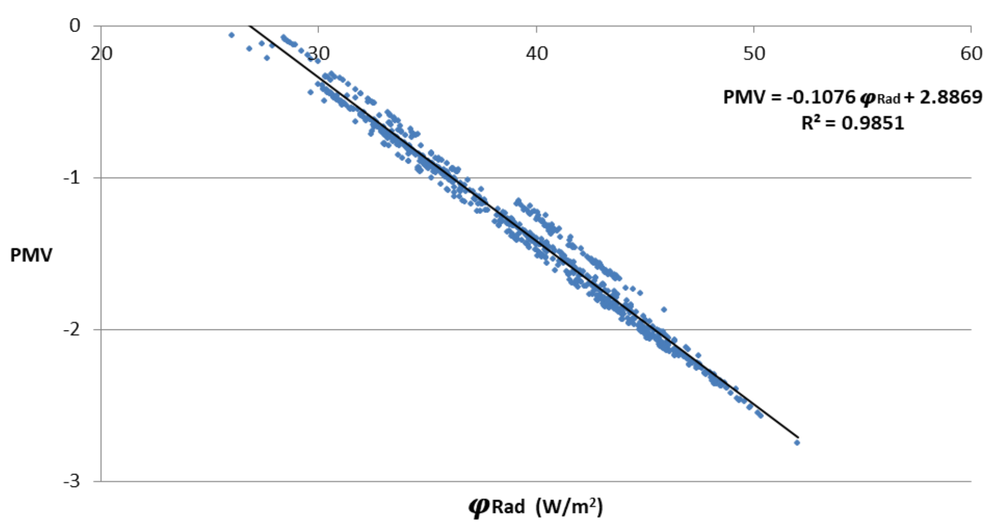

Figure 24: Relationship between thermal sensation and radiant heat loss (cool conditions)

Heat balance is attained when the sum of body heat loss is equal to the value of heat gained by subject's environment. However, discomfort emanates when there is a disparity between the required body heat loss and the actual heat loss. Consequently PMV is directly propelled by the physiological component of thermal perception in thermal comfort evaluation. Figure 25 below shows the trends of the subjects total heat loss and their PMV. We can observe that the total heat loss increase, the thermal sensation becomes colder. We can also deduce that when the body is at rest a total heat loss of 58 W/m^2 is required by the body to be thermally comfortable (where PMV=0).

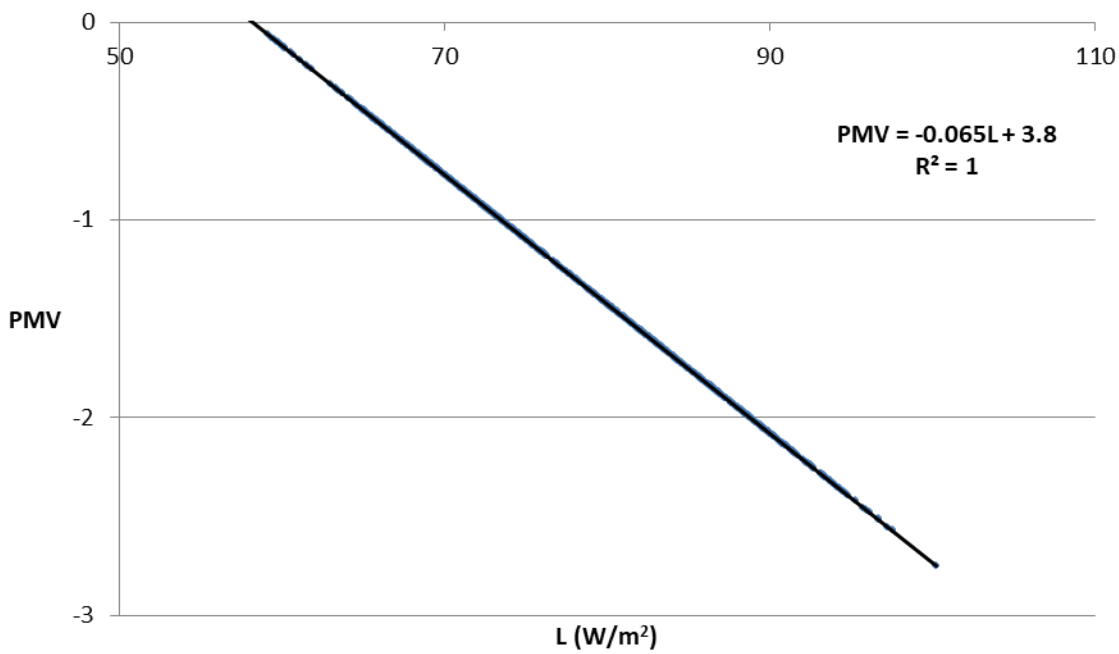

Figure 25: relationship between PMV and total heat loss (cold conditions)

3.1.3 Characterization of the adaptive and psychological factors

The difference between the evaluated PMV values and actual thermal perception of occupants can be attributed to the presence of physical and psychological adaptive factors. One of the objectives of this analysis is to examine the magnitude of these differences and calibrate the factors that contribute to the variations. By considering these factors, we aim to develop a suitable model.

During the experiment, the subjects' actual sensational vote (ASV) was collected via a questionnaire. Disparities were observed between the calculated PMV and ASV data obtained from the experiments. To address this, Yao proposed the adaptive predicted mean vote (aPMV), which incorporates the physical input factor (stimuli), adaptive coefficient, and psychological coefficient.

Since the values of PMV are calculated and the values of aPMV (ASV of subjects) are obtained from the subject's questionnaire, we can determine values of adaptive coefficient η via the equation (16) below. According to Yao's findings, adaptive coefficient values were two constant values; one for hot thermal sensation and the other for cold thermal sensation. Experiments data obtained were substituted into Yao's equation to derive values of adaptive coefficient for each thermal sensational vote perceived by subjects. Although the calculated adaptive coefficient values were not consistently constant like Yao's result, they can still be used to evaluate the psychological coefficient once the neutral temperature is determined. Thus, adaptive coefficient was calculated via equation (16) below:

$$\eta = \frac{\mathrm{PMV} - \mathrm{aPMV}}{\mathrm{aPMV} \times \mathrm{PMV}} \tag{16}$$

The relationship between adaptive coefficient η, physical input factor δ and psychological coefficient K_δ has to be investigated because this will aid in determining the statistical behavior of subjects psychological response.

Characterization of the psychological coefficient

The psychological coefficient can be derived from equation (17) below. However, the values of physical input factor δ or stimuli can be evaluated after the neutral temperature is determined. The physical input factor δ measures the magnitude of deviation of operative temperature $\mathrm{T_{op}}$ from neutral temperature T_{op}^{n} as depicted in equation (13). The neutral temperature is the operative temperature where subjects feel neither hot nor cold and they have no urge to adjust their environment or themselves to become more comfortable. It is therefore operative temperature when the aPMV (ASV of the subjects) is equal to zero. Therefore, two methods where applied in this context. The first was to determine operative temperatures average value when subjected voted aPMV=0. The second method was to plot aPMV values against corresponding mean operative temperature and then define the regression line between the two variables. This will aid to consider subjects whole behavior. Therefore, with a linear regression and high correlation coefficient, operative temperature value where aPMV=0 was considered to be the neutral temperature as shown in Figure 26 and Figure 27. Through this method, we can account for subjects' overall perception and their corresponding operative temperatures. The result of both methods for the neutral temperature was 21^{0}C for cool experiments and 18^{0}C for cold experiments. Thus, physical input factor δ value of each subject was evaluated as the difference between T_{op}^{n} and its corresponding operative temperature as enumerated in equation (13).

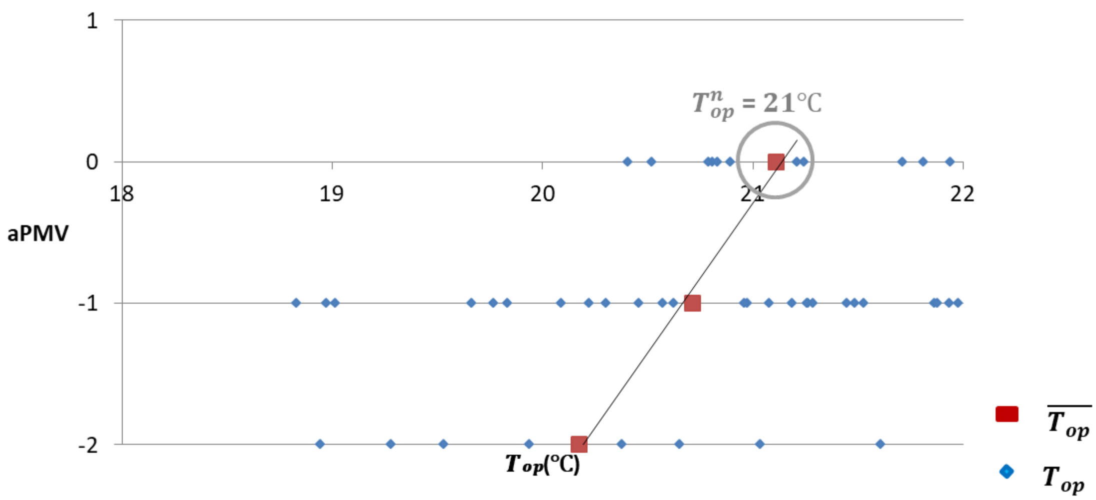

Figure 26: Correlation of aPMV and operative temperature $\boldsymbol{T_{op}}$ for cool thermal conditions

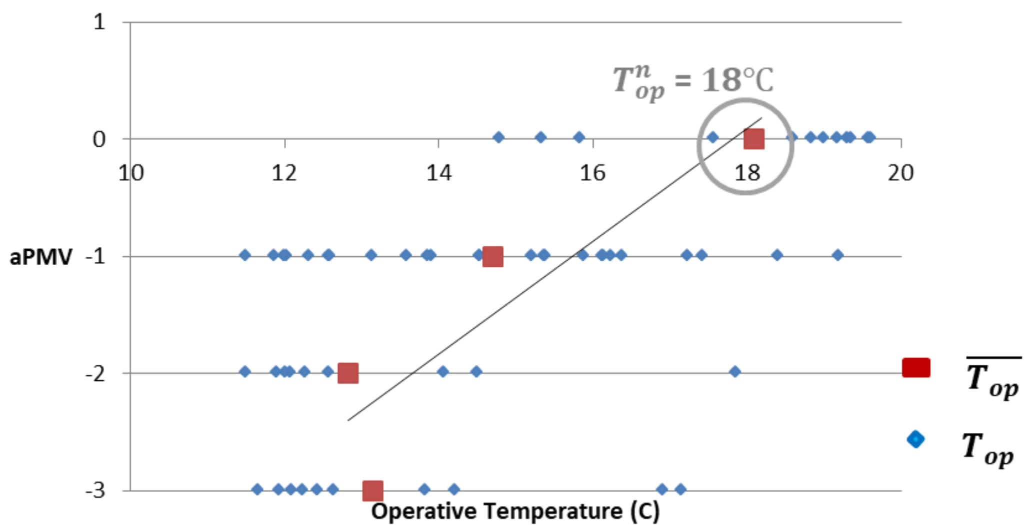

Figure 27: Correlation of aPMV and operative temperature $\boldsymbol{T_{op}}$ for cold thermal conditions

Having evaluated values of two variables (adaptive coefficient η and physical input factor δ), it is possible to calculate the psychological coefficient values using the equation below.

$$K_\delta = \delta \times \eta$$

Therefore:

$$K_\delta = \frac{\left(\mathrm{T_{op}} - T_{op}^{n}\right) \times (PMV - aPMV)}{aPMV \times PMV} \tag{17}$$

Thus, psychological coefficient values were evaluated via equation (17). Then, the evolution of psychological coefficient K_δ versus physical input factor δ of subject was examined in Figure 28. Psychological coefficient K_δ vis-a-vis the radiant heat exchanges from subject's body, mean radiant temperature and operative temperature will be examined subsequently.

Figure 28 below shows the graphical representation of the relationship between psychological coefficient values and physical input factor of cool experiments. The correlation coefficient was very low and the regression line passed through the (0,0) point of the graph. Hence, the regression equation of this graph can be related to equation (10). Thus the regression equation is:

$$K_\delta = -0.125 \times \delta$$

Therefore:

$$\eta = -0.125$$

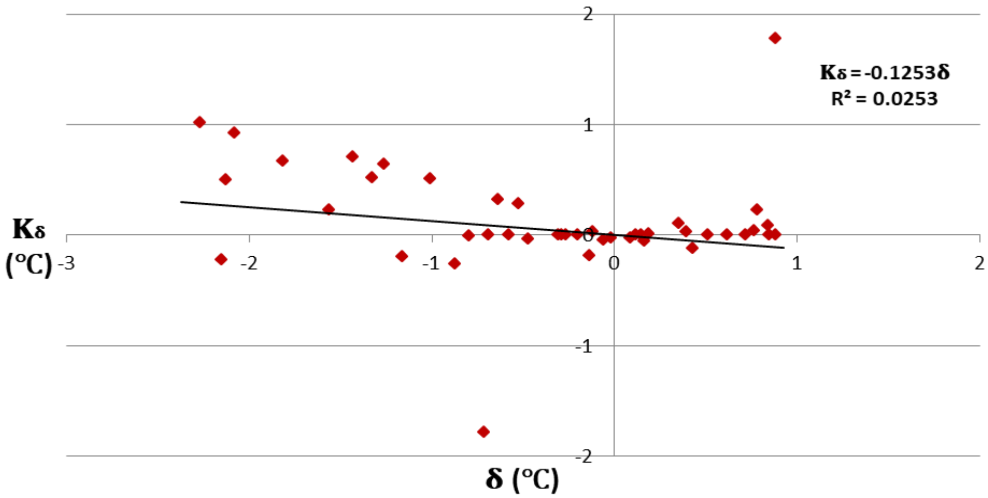

Figure 28: Correlation of psychological coefficient and physical input factor (cool)

3.1.4 Further modifications of Yao's aPMV model

Yao model equation generated some questions that could not be accounted for by the experiment data and by data acquired evaluation. In equation (11), Yao's equation is thus:

$$\text{aPMV} = \frac{\text{PMV}}{1 + \eta \times \text{PMV}}$$

The questions generated by Yao's equation are:

(i) When PMV is equal to zero will aPMV always equal zero?

(ii) When aPMV is equal to zero will PMV always equal zero?

$$\text{PMV} = 0 \Leftrightarrow \text{aPMV} = 0\ ?$$

Looking at the equation above, the value of aPMV cannot be accounted for when PMV=0. Note that due to adaptation when PMV is zero, aPMV may not be the same perception. Therefore the model equation could not accurately account for aPMV when PMV is zero and vice versa. It therefore assumes that aPMV is equal to zero when PMV value is equal to zero. However, this assumption is not true, based on the data obtained from these experiments because there were numerous data depicting that when PMV was approximately zero, aPMV was not equal to zero and vice versa.

Therefore, some modifications of Yao's model had to be explored and proposed to account for these anomalies. In addition, this proposed model is required to be a statistical derivative with a high correlation coefficient, so that the derived equations can be used in thermal comfort evaluation with more certainty. Hence, the proposed model starts with an expression for Yao's postulation. The postulation state that physiological response exist in the "black box" but the psychological and behavioral response will propel an "Adaptive (contrary) Feedback" (Yao et al. 2009). Thus:

$$aPMV = PMV - \eta \tag{18}$$

It has been established that PMV value of the subjects is the proportionate physiological response to thermal load posed by physical thermal factors. While adaptive factor η acts as the counter feedback to this physiological response as a result of interaction between the stimuli and the psychological factors affecting human thermal perception. This phenomenon can be expressed on the thermal sensational scale as illustrated in Figure 29

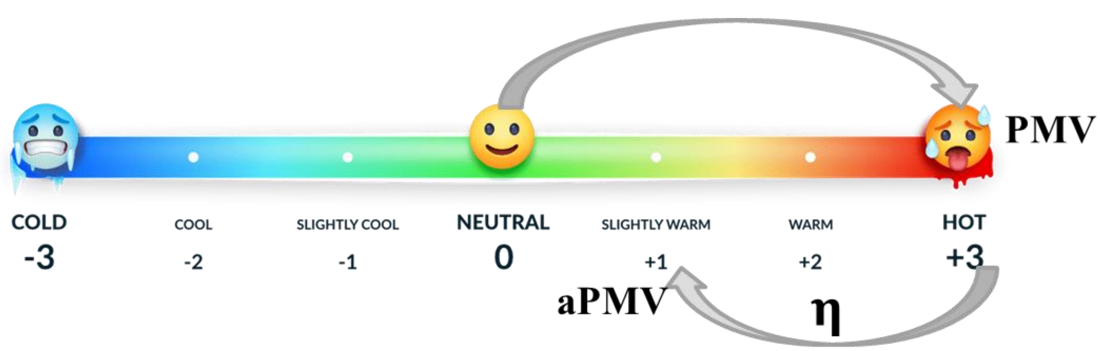

Figure 29: Evolution of PMV and adaptive feedbacks η in human thermal perception

Thus, based on equation (18) above, adaptive factor η exist for a cool or cold thermal conditions when;

$$PMV - aPMV < 0$$

Consequently, adaptive factor η exist in a warm or hot thermal condition when

$$\mathrm{PMV} - \mathrm{aPMV} > 0$$

This concept is expressed in Figure 30 below. The concept implies that most subjects' adaptive and psychological responses and behaviors are voluntary and therefore require innate permission of the person to respond to stimuli. This is usually based on the person's adaptive and psychological capacity. It is unlike physiological responses that are involuntary, because heat loss processes of human physiological systems are automatically coordinated by body thermoregulatory system. Therefore a subject can chose to apply his adaptive process or not, depending on his capacity and environmental context. For example, a person may deploy more adaptive or psychological capacity in a public hall where he cannot control thermal conditions than in his bedroom. Thus, an individual can be adaptive or contra-adaptive depending on his adaptive capacity and environmental context.

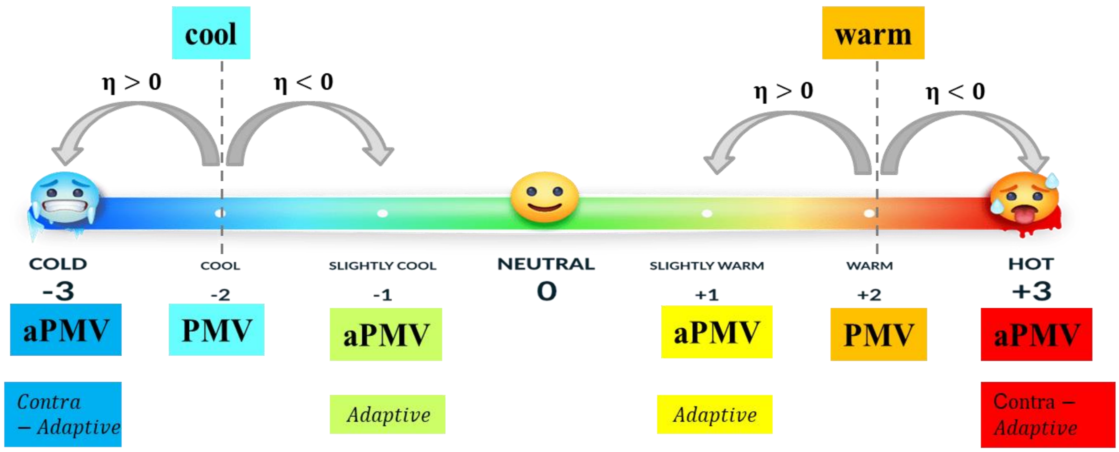

Figure 30: Evolution of PMV and adaptive feedbacks **η** on human thermal perception

Furthermore, the proposed model also aligns with Yao's postulation that adaptive factor η is a function of psychological coefficient K_δ and physical input factor δ:

$$\eta = \frac{K_\delta}{\delta} \tag{10}$$

Thus, the model equations and operation can be stated thus:

$$\mathrm{aPMV} = \mathrm{PMV} - \eta \tag{18}$$

$$\mathrm{PMV} = (0.303e^{-0.036\,\varphi} + 0.028) \times (\varphi - \mathrm{L}) \tag{3}$$

$$L = \varphi_{cl}^{Conv} + \varphi_{cl}^{rad} + \varphi_{sk}^{Sw} + \varphi_{sk}^{Diff} + \varphi_{res}^{Conv} + \varphi_{res}^{evap} \quad (4)$$

$$\eta = \frac{K_\delta}{\delta} \quad (10)$$

$$\delta = \mathrm{T_{op}} - T_{op}^{n} \quad (13)$$

Figure 31 show subjects adaptive behavior during the cold experiments. In these thermal conditions, adaptive factor η lesser than zero ($\eta < 0$) indicate that the subject is adaptive while adaptive factor greater than zero indicate that subject is contra-adaptive (this is in accordance to equation (18) above). The non-adaptive subjects did not deploy their adaptive capacity during the experiment; therefore their values may not be relevant in this evaluation. Hence, the values generated by adaptive subjects were selected for the evaluations in this model. Therefore, a systematic or purposeful statistical sampling method was applied in this case because of research objective.

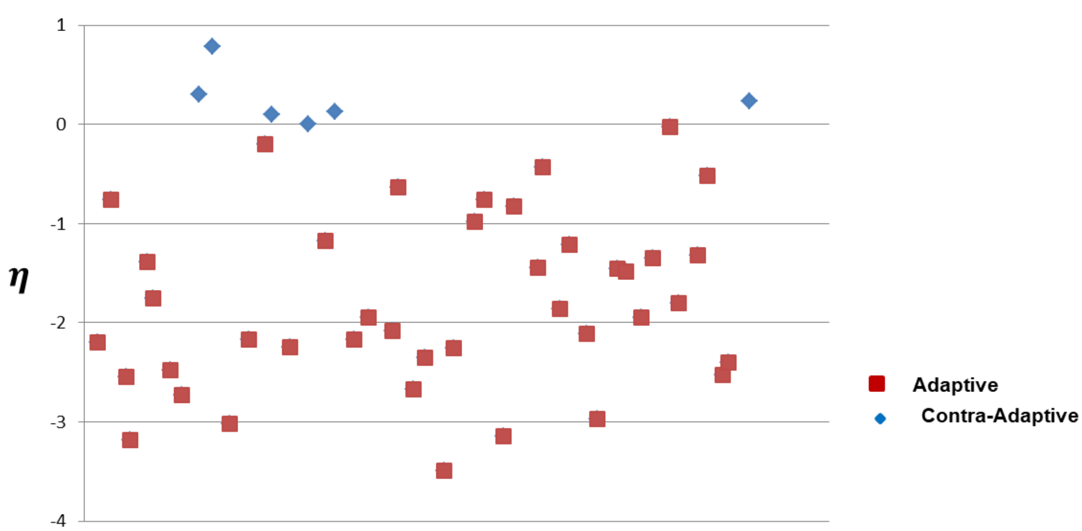

Figure 31: Adaptive and contra-adaptive behavior of subjects during cold experiments

Figure 32 and Figure 33 below are the graphical correlations of psychological coefficient values K_δ versus physical input factor δ. This is aimed at calibrating the behavior or determining function of adaptive factor η as represented in equation (10). According to the graph below, red plots depict adaptive subjects while blue plots were contra-adaptive subjects. Thus, regression equation from the graphs below expresses a high correlation coefficient. Therefore, subject adaptive factor can be determined or calibrated. The regression is thus:

$$\eta = \frac{K_\delta}{\delta} \tag{10}$$

$$K_\delta = -0.7 \times \delta \qquad R^2 = 0.7 \tag{19}$$

In accordance to equation (18):

$$aPMV = PMV + 0.7 \tag{20}$$

The above equation infers that adaptive factor η is -0.7 and equation (19) is the closure equation for cool thermal conditions.

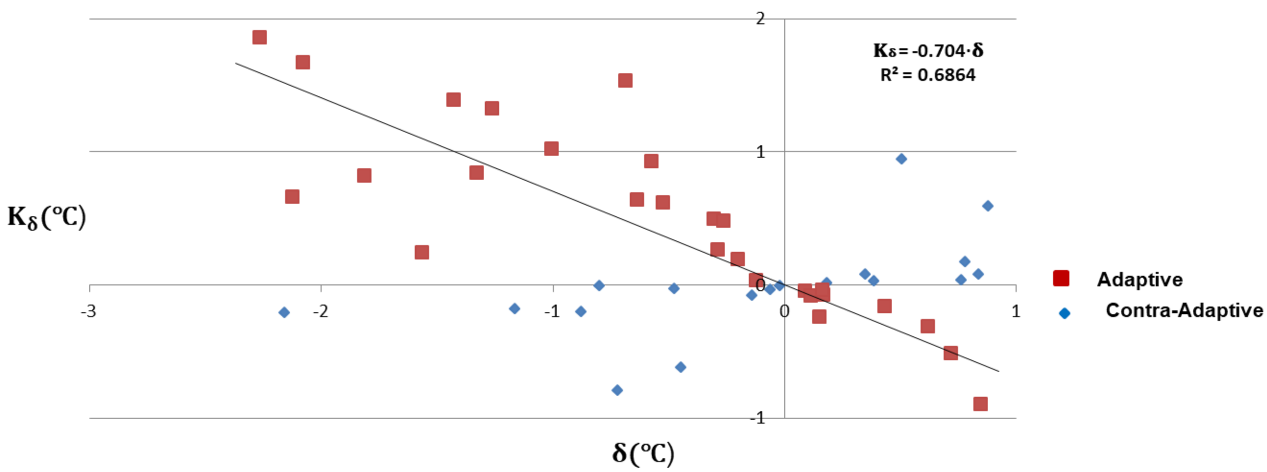

Figure 32: Correlation of psychological coefficient and physical input factor (cool)

The regression for cold experiment in mid-winter period is thus:

$$K_\delta = -1.4 \times \delta \qquad R^2 = 0.6 \tag{21}$$

In accordance to equation (18):

$$aPMV = PMV + 1.4 \tag{22}$$

The adaptive factor η is -1.4 and equation (21) is the closure equation in cold thermal conditions.

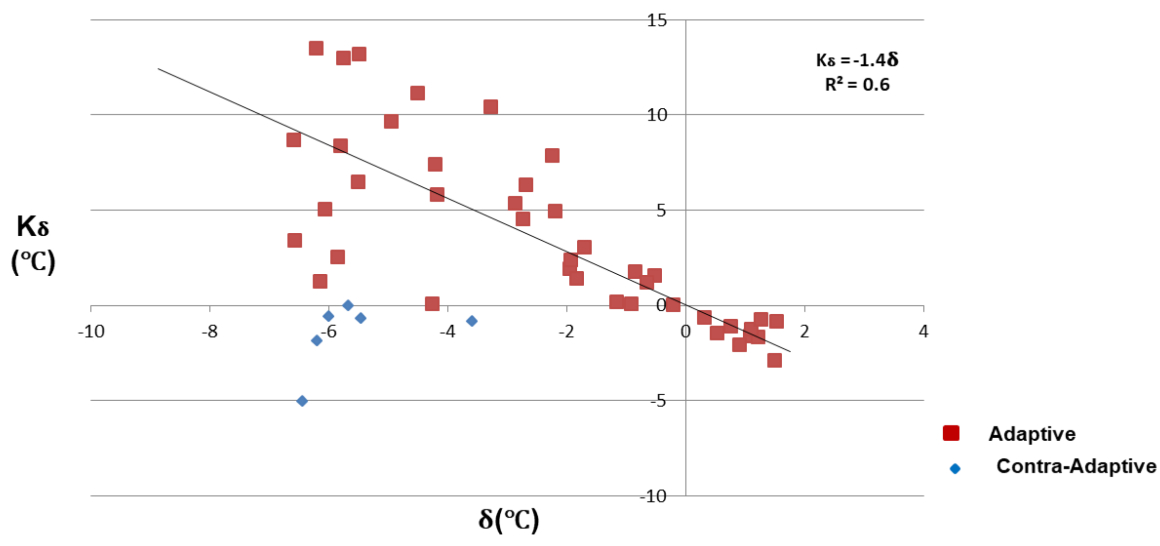

Figure 33: Correlation of psychological coefficient and physical input factor (cold)

The above graphical representations and their corresponding regression has shown that adaptive factors for cool experiments and cold experiments where different and the difference between them is obviously due to the difference in outdoor temperatures when the experiments were conducted. This outdoor temperature difference also resulted into the alteration in subject's neutral temperature T_{op}^{n} .

Therefore, the relationship between outdoor temperature and neutral temperature was proposed. This relationship is graphically expressed in Figure 34 below in the graph of neutral temperature T_{op}^{n} versus outdoor air temperature T_{out}. Data used for this relationship includes data of cool, cold and hot experiments. This includes both winter and summer period. The regression equation is expressed in equation (23) below.

$$T_{op}^{n} = 0.36 \times T_{out} + 15.4 \qquad R^2 = 0.8 \qquad (23)$$

Thus, this equation can be used to determine the neutral temperature when outdoor air temperature is known. Also, this neutral temperature equation above can be substituted into aPMV equations (18) and (10) as shown in equation (24) below. Equation (24) suggests that subjects' thermal perception and adaptive factor η is a function of outdoor air temperature, indoor operative temperature as well as subjects psychological coefficient.

$$\text{aPMV} = \text{PMV} - \left(\frac{K_\delta}{T_{op} - 0.36 \times T_{out} - 15}\right) \tag{24}$$

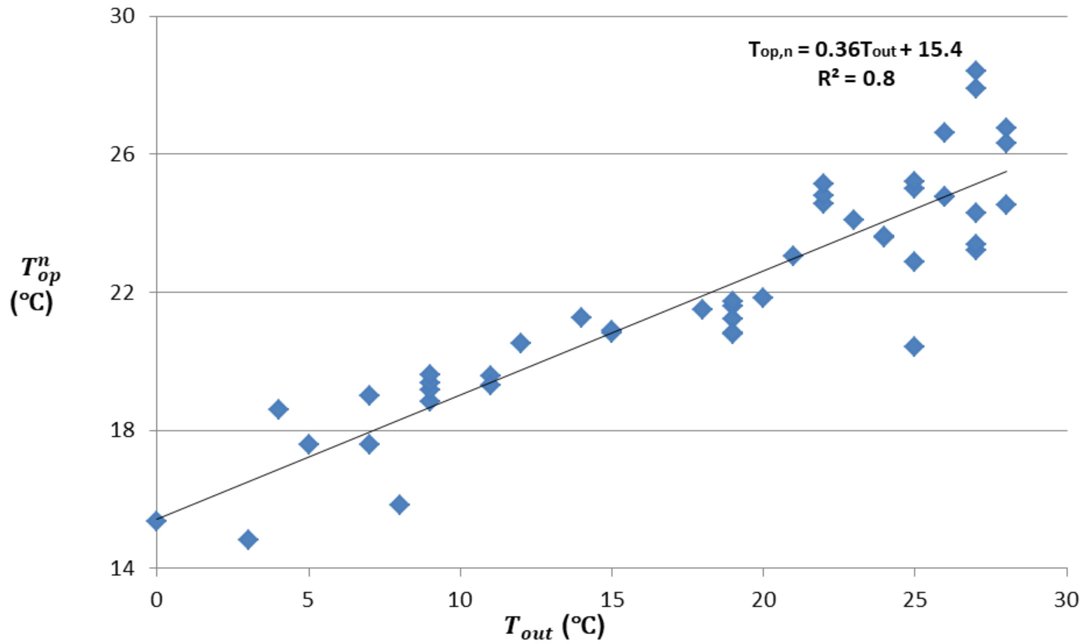

Figure 34: Correlation of neutral temperatures $\boldsymbol{T_{op}^{n}}$ and outdoor air temperature $\boldsymbol{T_{out}}$

3.1.5 Characterization of psychological coefficient and thermal conditions parameters

The objective of this research is also to investigate the influence of thermal conditions on occupants' psychological perception. Hence the method to quantify subjects psychological coefficient has been generated, thus the relationship between the parameters of thermal conditions and weight of psychological coefficient can be examined by computing their correlations. The thermal condition parameter considered in this research is the mean radiant temperature and the operative temperature. Mean radiant temperature considers radiant temperature of all the surfaces surrounding the subjects including their respective view factors and radiant heat exchange. While operative temperature considers the average of mean radiant temperature and air temperature, being weighed by their respective heat transfer coefficient. This is relevant due to the significance of the radiant and convective heat transfer processes as explained earlier in section 3.1.2.

The graphical representation in Figure 35 and Figure 36 below shows a correlation between psychological coefficient, mean radiant temperature and operative temperature in cool experiment and cold experiment respectively.

The magnitude of the correlation coefficient of the regression equations indicates the level of influence that these thermal radiation parameters have on psychological factors and thermal perception of subjects. It can be observed that subjects' thermal perception is directly influenced by the radiant load in their thermal environment. These correlations provide a means to determine psychological coefficient when either the operative temperature or mean radiant temperature is known. These regressions and their corresponding correlations are as follows:

For cool experiments:

$$K_\delta = -0.65 \times T_{op} + 13.8 \qquad R^2 = 0.7 \qquad (25)$$

$$K_\delta = -0.62 \times T_{mrt} + 12.9 \qquad R^2 = 0.6 \qquad (26)$$

For cold experiments;

$$K_\delta = -1.6 \times T_{op} + 29 \qquad R^2 = 0.6 \qquad (27)$$

$$K_\delta = -1.6 \times T_{mrt} + 29.6 \qquad R^2 = 0.6 \qquad (28)$$

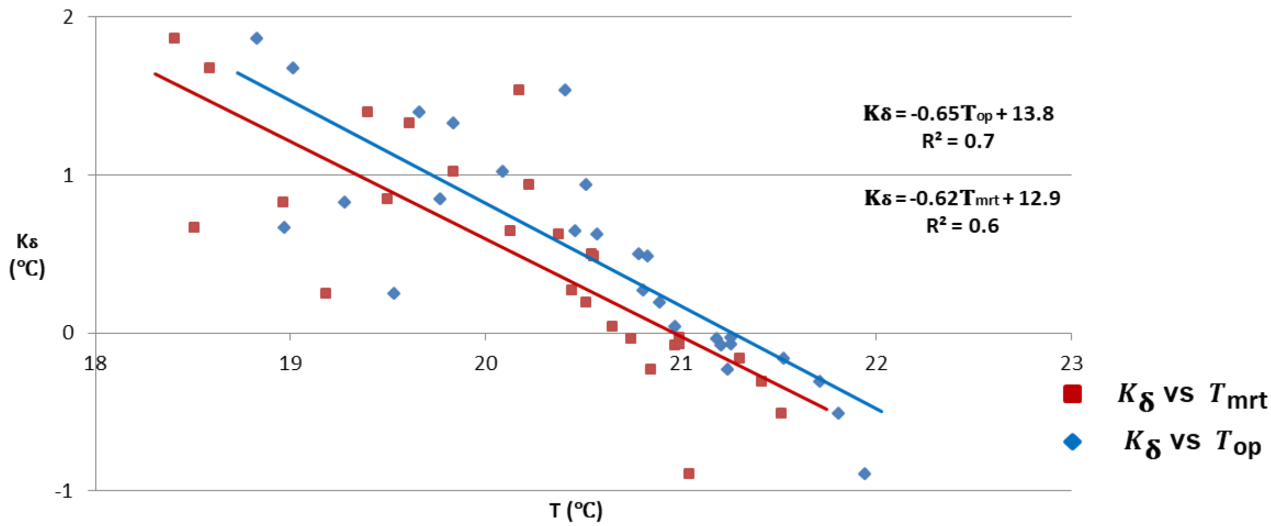

Figure 35: Correlation of psychological coefficient, mean radiant temperature and operative temperature (cool experiments)

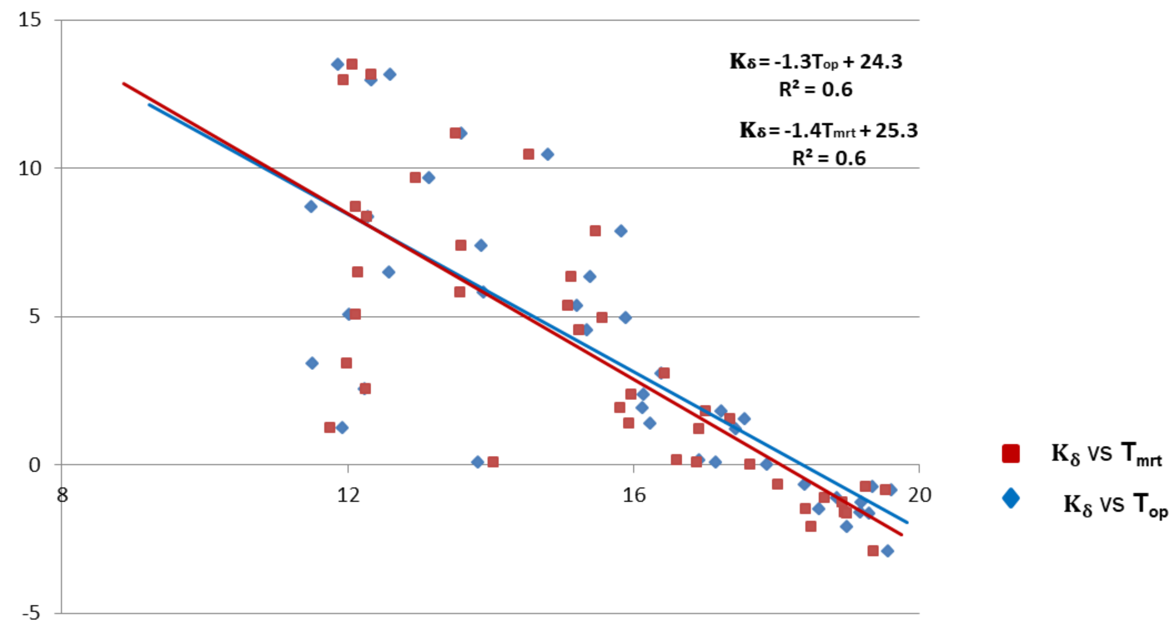

Figure 36: Correlation of psychological coefficient, mean radiant temperature and operative temperature (cold experiments)

Based on the relationship between the parameters of the physical thermal factors (such as the operative temperature) and the psychological coefficient. The evaluation of the thermal perception of the subjects can be further simplified by substituting equation (25) and (27) into equation (24) as represented in equation (29) and (30) for cool and cold thermal conditions respectively:

$$\text{aPMV} = \text{PMV} - \left(\frac{-0.65 \cdot T_{op} + 13.8}{T_{op} - 0.36T_{out} - 15}\right) \tag{29}$$

$$\text{aPMV} = \text{PMV} - \left(\frac{-1.6 \cdot T_{op} + 29}{T_{op} - 0.36T_{out} - 15}\right) \tag{30}$$

In summary, operative temperature and mean radiant temperature has high correlation coefficient with subjects' psychological coefficient in cool and cold thermal conditions. Therefore, these temperatures can be used to determine the weight of psychological coefficient in specific locations. The values of adaptive factor for cool and cold thermal condition were -0.7 and -1.4 respectively via the proposed model. Also, this proposed model is able to account for the subjects thermal perception when PMV=0 or aPMV=0, unlike the Yao's model that has some discrepancy. Thus, the proposed model has enabled us to consider the adaptive and psychological parameters of thermal comfort, to evaluate and integrate them into thermal comfort evaluation.

3.2 Hot experiment conditions

The "hot experiments" was carried out in summer period when outdoor temperatures was high, ranging from 20°C to 38°C. These experiments were held on the 5th-8th July 2022. The method of analyzing the parameters in this section is the same as the cool and cold experiments. However there are some peculiar characteristics of the hot experiments, considering the subjects adaptation evaluation. Thus, the analysis of data evaluated for these experiments will be expounded hence.

Sample size and characteristics of subjects

The heating and cooling of the cell was generated externally and then conducted into the internal surface, which radiates inside the cell. Hence, this experimental setup was intended to produce an outcome of thermal sensational votes (TSV), ranging from -2 to +3.

The participants include the ENSAM Bordeaux staffs and students, ENSAP Bordeaux staff and students as well as I2M Bordeaux staff and students. A total number of 29 subjects participated in the summer experiments consisting 15 males and 14 females. The age range from 21-62 years old, the age range of highest population was 21-31 years. Most of participants were from French origin, although participant from other countries includes Spain, Morocco, Vietnam, Algeria, and China. Therefore, all participants were adults of height ranging from 1.5m to 1.8m. The total number of sessions executed was 59 sessions and each session lasted for about 20 minutes for each participant.

Data taken during experiment from each subjects were their metabolic rate and clothing insulation. Metabolic rate was the same for all participants because it was based on subjects' activity level. This corresponds to the activity level of a seated, quiet and reading occupant in ASHRAE standard 55-2017. Thus, it was assumed to be uniform for all subjects. The clothing insulation varied slightly among subjects, their clothing insulation ranged from 0.3 to 1.0 clo.

3.2.1 Characterization of the physical thermal factors

The magnitude of some of the physical thermal factors changed due to the modification of internal surface temperature of the cell walls, ceiling and floor. Thus, some evolutions were observed in mean radiant temperature, air temperature and relative humidity. Figure 37 depicts the trends in these physical thermal factors and it shows that an increase in mean radiant temperature resulted into a proportionate increase in air temperature. Relative humidity was high at low temperature and vice versa. The change in air temperature can be accounted for by considering radiant heat absorbed by air particles as well as reflected radiation within air particles and water vapor in the air. Another factor that could be responsible for this change in air temperature is natural convection between the air and heated or cooled surfaces of the cell. Thus, we observed that the radiant heat influenced the weight of air temperature, and relative humidity when thermal condition is hot.

Figure 38 depicts a regression with high correlation coefficient between mean radiant temperature and air temperature of the experimental cell. Figure 39 shows that correlation coefficient between mean radiant temperature and relative humidity was high too. This is unlike cold thermal condition where the correlation coefficient was relatively low. Thus, it infers that mean radiant temperature actively influenced the magnitude of relative humidity when thermal conditions of the indoor space are hot.

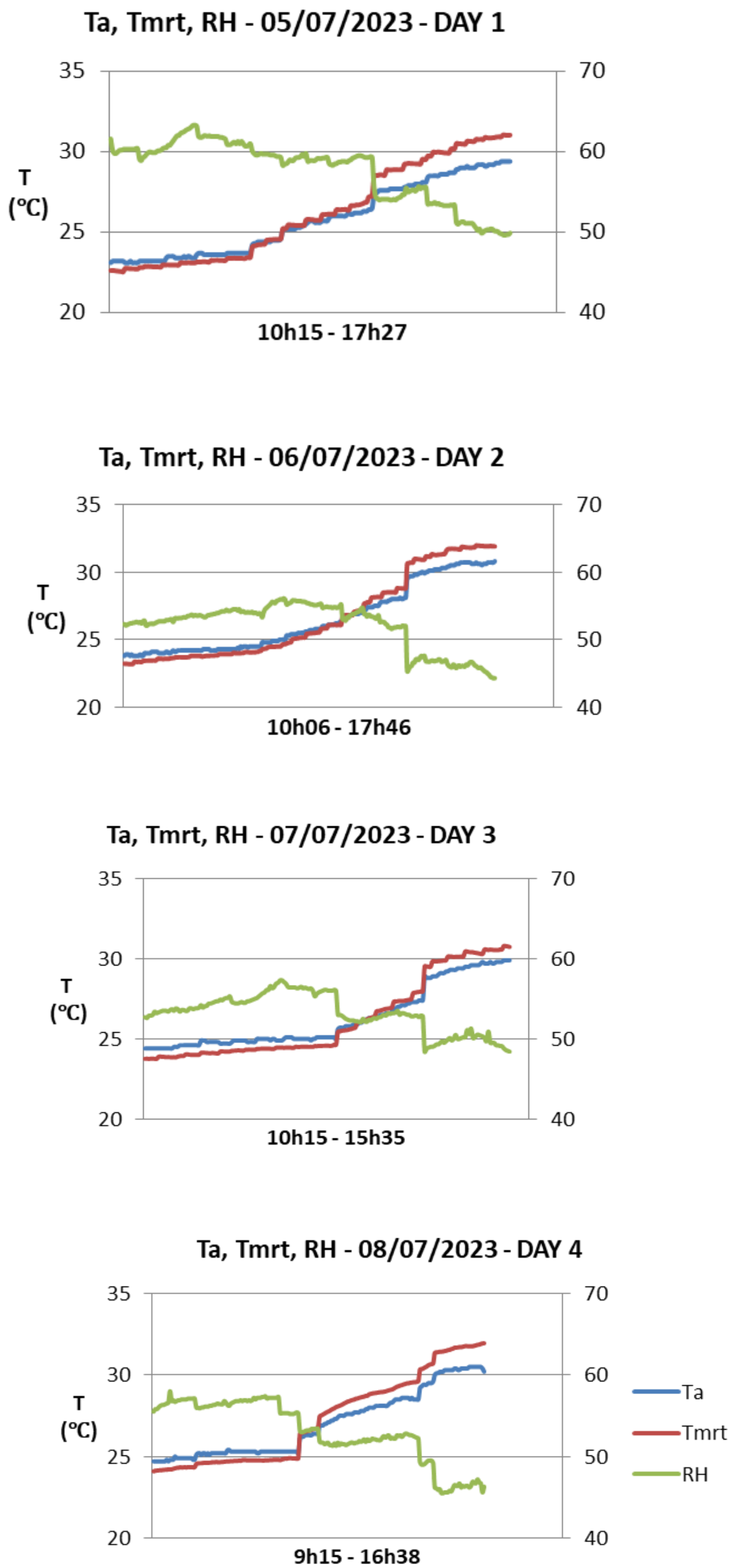

Figure 37: Evolution of physical thermal factors in experimental cell (hot experiment)

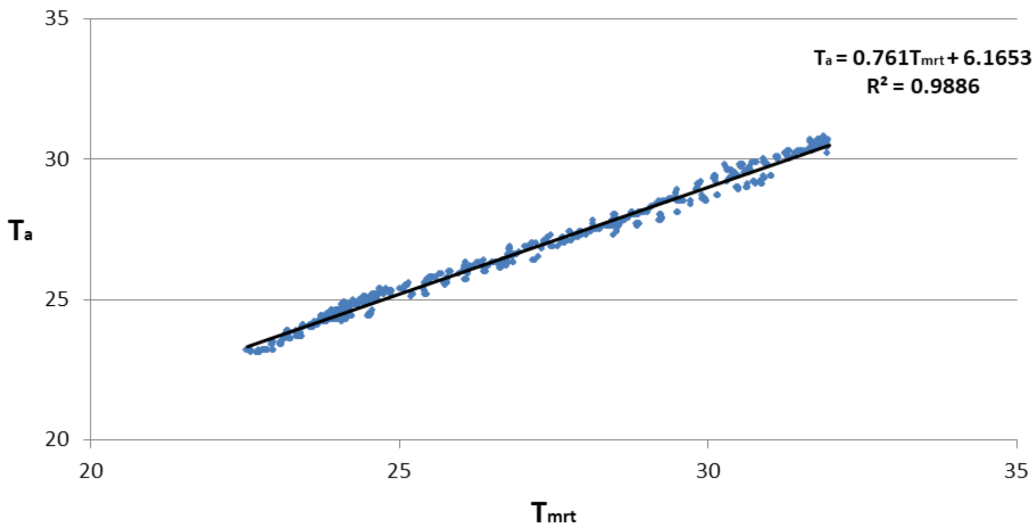

Figure 38: Correlation of air temperature and mean radiant temperature (hot experiment)

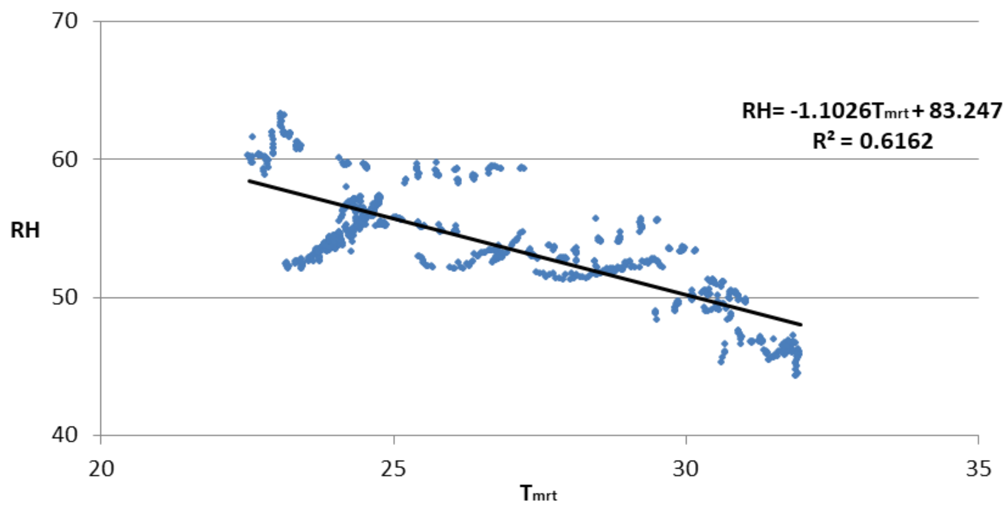

Figure 39: Correlation of relative humidity and mean radiant temperature (hot experiment)

3.2.2 Characterization of physiological factors

Figure 40 below depicts the trends in heat loss from subjects' body in experimental cell. This analysis expressed in graphical form, the average heat losses from all the subjects' body as well as the different processes at which this heat is being exchanged with their environment. From the graph below, average heat losses (via various processes of heat loss from subject's body) were plotted on vertical axis while duration of experimentation was plotted on horizontal axis. The analysis can be mathematically represented by the equation below:

$$\overline{\varphi^*} = \frac{\sum_{i=1}^{N_{exp}} \varphi_i^*(t)}{N_{exp}(t)} \quad (14)$$

Where φ^* mean φ_{cl}^{Conv}, φ_{cl}^{rad}, φ_{sk}^{Sw}, φ_{sk}^{Diff}, φ_{resp}^{Conv}, φ_{resp}^{Lant} and exp mean experiments

Hence, it can be observed that convectional and radiant heat losses from the body surface were the prominent heat loss indicated on the graph. The average radiant heat loss ranged from 20 to 30W/m^2 while the average convective heat loss ranged from 12 to 18 W/m^2.The heat losses by body surface via radiation and convection followed relatively the same evolution in accordance to temperature change within the cell. This indicates that as air temperature and radiant temperature increases, convectional and radiant heat loss decreased respectively and vice versa. The heat loss by sweating was uniform and low throughout experiment because the activity level of each subject was uniformly sedentary. Also, heat loss by diffusion from skin surface was relatively uniform and respiratory latent heat loss was also negligible.

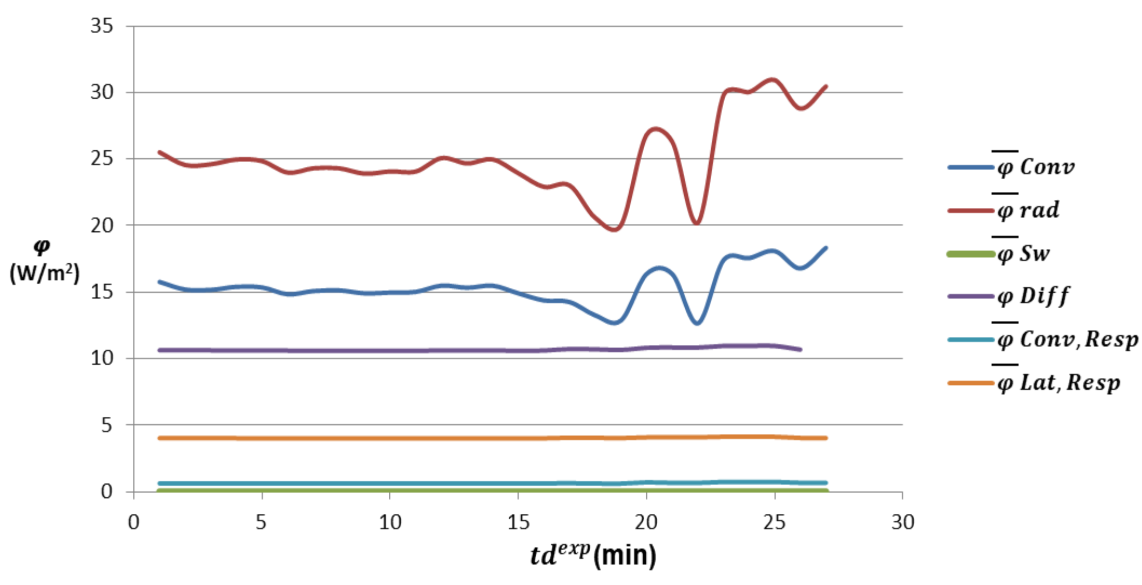

Figure 40: Trends of heat losses from the subject’s bodies (hot conditions)

The heat loss by body surface through convectional and radiant process played a major role in subjects' thermal sensation. Consequently, the results from these investigations inform us on the significance of the operative temperature a relevance parameter in evaluating thermal sensation of subjects as explained in the cold experiments section.

A further analysis shown in Figure 41 below was explored to determine the percentage weight of heat loss from human body due to their respective thermal conditions as enumerated for the cold experiments. It can be expressed with the equation below:

$$\varphi_{\%}^{*} = \frac{\int_{0}^{td^{exp}} \overline{\varphi^{*}}(t)dt}{\int_{0}^{td^{exp}} \overline{L}(t)dt} (\%) \qquad (15)$$

Where φ^{*} is φ_{cl}^{Conv}, φ_{cl}^{rad}, φ_{sk}^{Sw}, φ_{sk}^{Diff}, φ_{resp}^{Conv}, φ_{resp}^{Lant} and exp mean experiments

Figure 41 shows that 45% of the total heat loss from human body in indoor space during hot experiments is radiant heat loss. Therefore radiant heat loss defines 45% of the weight of thermal sensation experienced by subject. It can therefore be concluded that in physiological realm, radiant heat loss is the most significant physical thermal factor influencing the subject's thermal sensation in hot conditions.

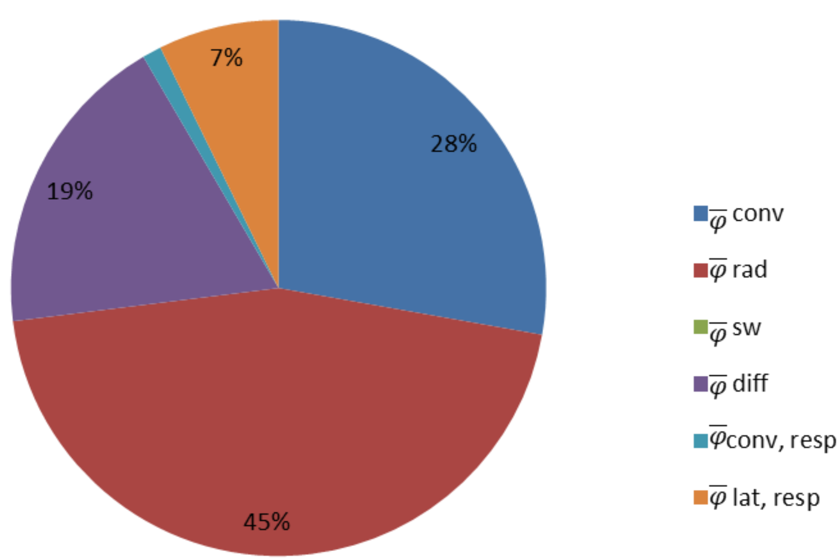

Figure 41: Percentage of average heat loss by various process of heat loss (hot)

To further investigate the influence of radiant heat loss, PMV graph against subject radiant heat loss was plotted as shown in Figure 42. Subjects hot thermal sensation proportionately increases (as PMV tends to +3) when radiant heat loss decreased. The graph also showed that when PMV=0 radiant heat loss is 28 $W/m^{2.}$ This infers that a consistent radiant heat loss of 28 W/m^2 is required by the body to make it be thermally comfortable when the body is at rest. This result is the same for the cool experiments.

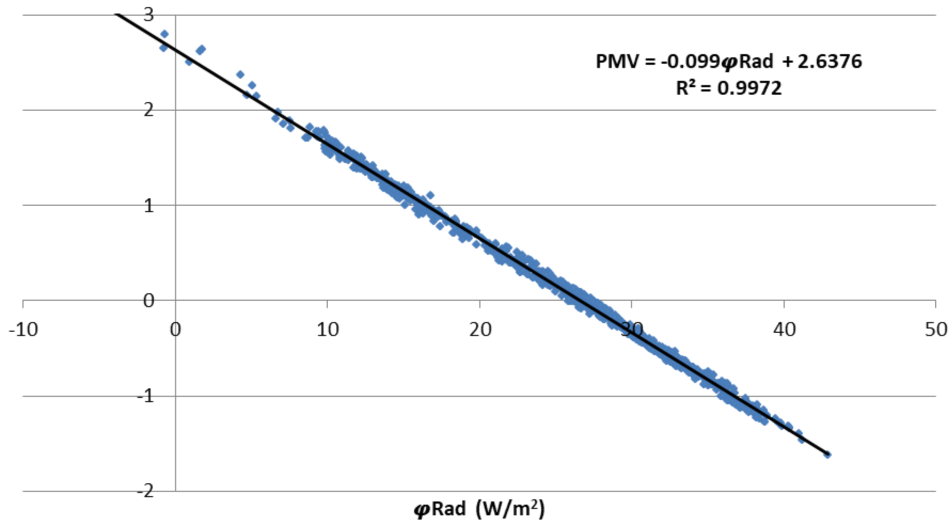

Figure 42: Relationship between thermal sensation and radiant heat loss (hot conditions)

Figure 43 below shows the trends of the total heat loss by subjects and their PMV. We can observe that decrease in heat loss resulted into increase in PMV values. We can also deduce that when the body is at rest, a total heat loss of 58 W/m^2 is required by the body to be thermally comfortable (where PMV=0).

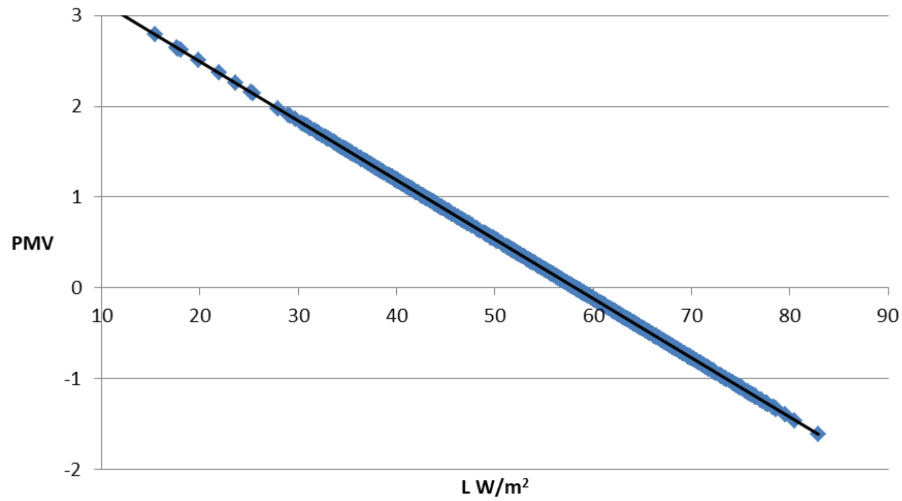

Figure 43: Trends of PMV due to total heat loss by subject's body (hot conditions)

3.2.3 Characterization of the adaptive and psychological factors

The adaptive factor η exist for a hot thermal conditions when;

$$\mathrm{PMV} - \mathrm{aPMV} > 0$$

This concept was expressed in Figure 30. It explicates that a subject can chose to apply his adaptive process or not, depending on his adaptive capacity and the environmental context. Therefore, an individual can be adaptive or contra-adaptive depending on these factors.

Figure 44 shows subjects adaptive behavior during hot experiments. In this hot thermal conditions, adaptive factor η greater than zero ($\eta > 0$) indicate that subject is adaptive while adaptive factor lesser than zero indicate that subject is non-adaptive. Hence, values generated by adaptive subjects will be selected for evaluations in this analysis.

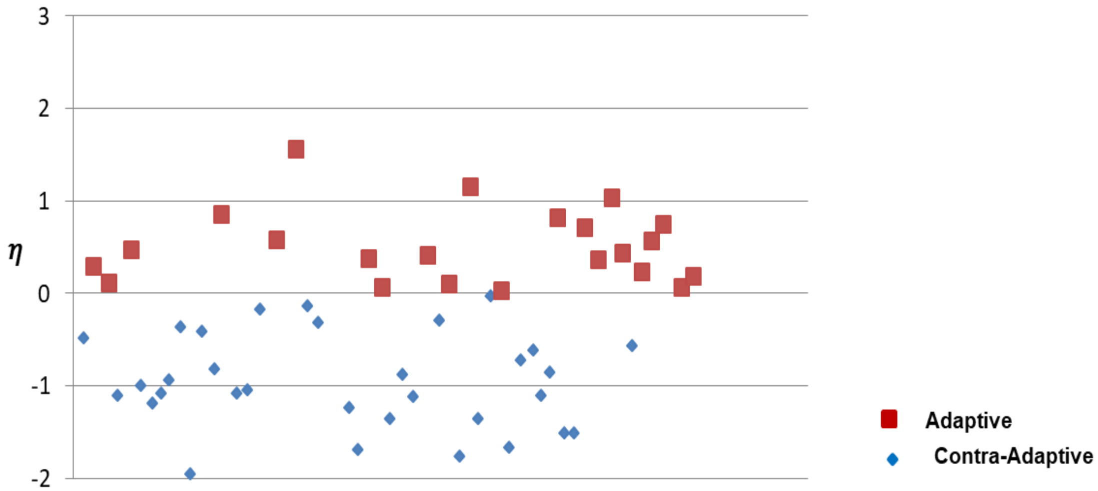

Figure 44: Adaptive and contra-adaptive behavior of subjects during the hot experiments

Characterization of the psychological coefficient

To evaluate the psychological coefficient, we needed to determine the neutral temperature as explained in the cold experiments in the previous section. We estimated this by calculating the average value of operative temperatures when subjects voted aPMV=0. Another method was to plot the graph of aPMV vis-a-vis mean operative temperature and then define the regression line as shown in Figure 45 . The result of both methods for the neutral temperature was approximately 25^0C. Thus, the value of physical input factor δ of each subject was evaluated as the difference between 25^0C and its corresponding operative temperature as enumerated in equation (13).

$$\delta = \mathrm{T_{op}} - T_{op}^{n} \tag{13}$$

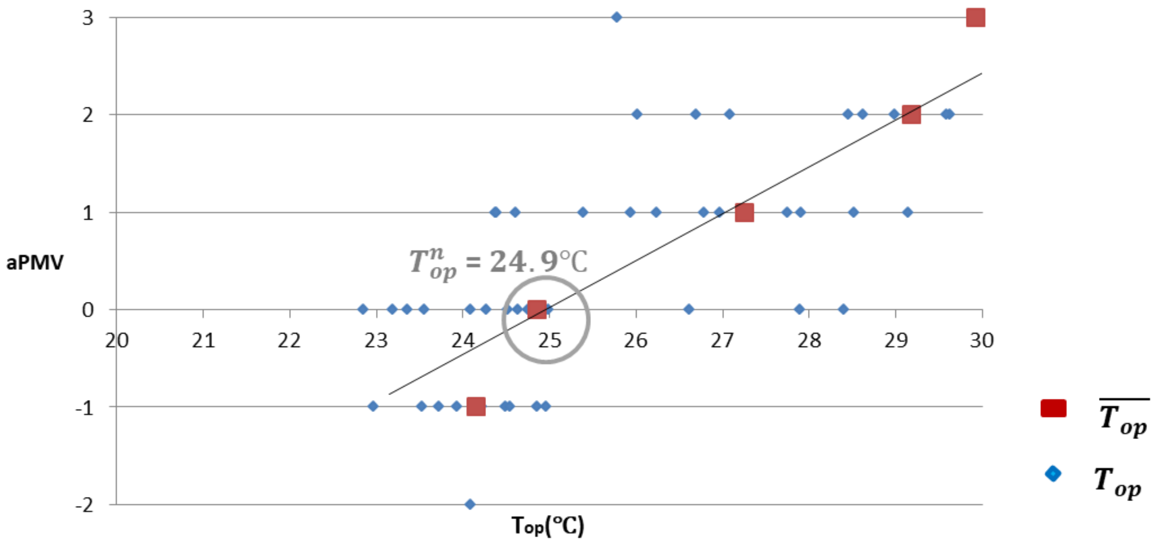

Figure 45: Correlation of aPMV and operative temperature $\boldsymbol{T_{op}}$ for hot thermal conditions

Having obtain the value of two variables (adaptive coefficient η and physical input factor δ) , it is possible to evaluate the values of psychological coefficient as defined in equation (10).

$$\eta = \frac{K_\delta}{\delta} \tag{10}$$

Figure 46 below is the graphical correlation of the values of psychological coefficient K_δ against physical input factor δ. This is aimed at calibrating the behavior of adaptive factor η as represented in equation (10). The regression equation and correlation coefficient is thus:

$$K_\delta = 0.5 \cdot \delta \qquad R^2 = 0.7 \tag{31}$$

Thus:

$$aPMV = PMV - 0.5 \tag{32}$$

The above equation infers that the adaptive factor in hot thermal condition is 0.5 and the closure equation is equation (31).

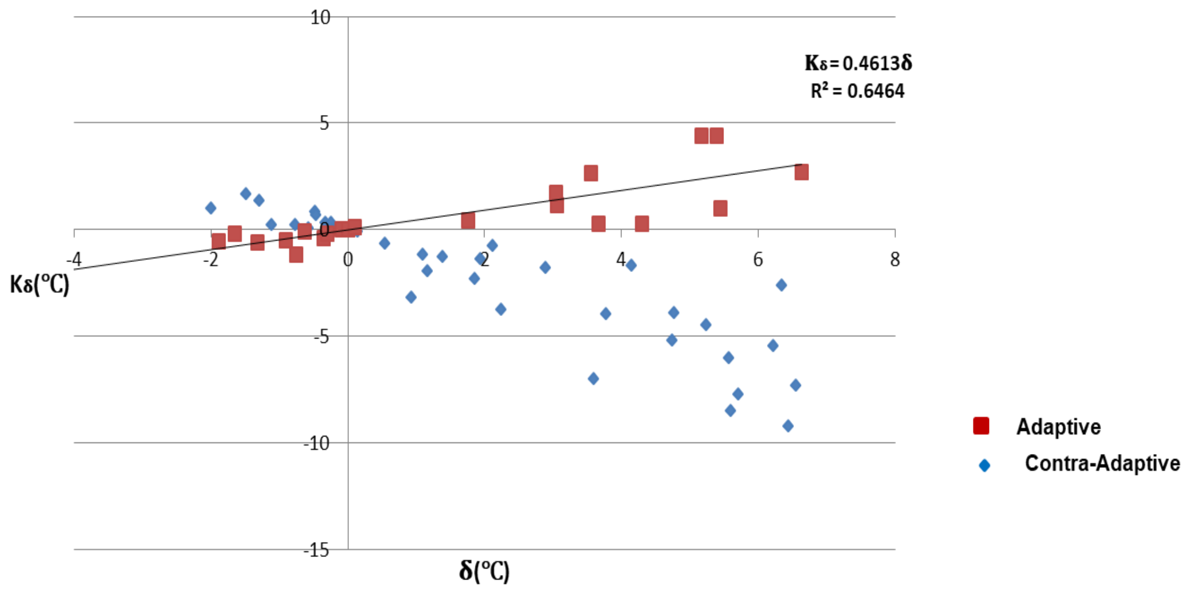

Figure 46: Correlation of psychological coefficient versus physical input factor (hot)

3.2.4 Characterization of psychological coefficient and thermal conditions parameters

The relationship between the parameters of the physical thermal factors and weight of psychological coefficient can be examined by computing their correlations. The graphical representation in Figure 47 below shows the correlation between psychological coefficient, mean radiant temperature and operative temperature.

The magnitude of the correlation coefficient infers a strong relationship between the thermal parameters explored and the subjects' psychological factors. These regressions and corresponding correlations include:

$$K_\delta = 0.5 \cdot T_{op} + 11.6 \qquad R^2 = 0.7 \qquad (33)$$

$$K_\delta = 0.4 \cdot T_{mrt} + 10.7 \qquad R^2 = 0.7 \qquad (34)$$

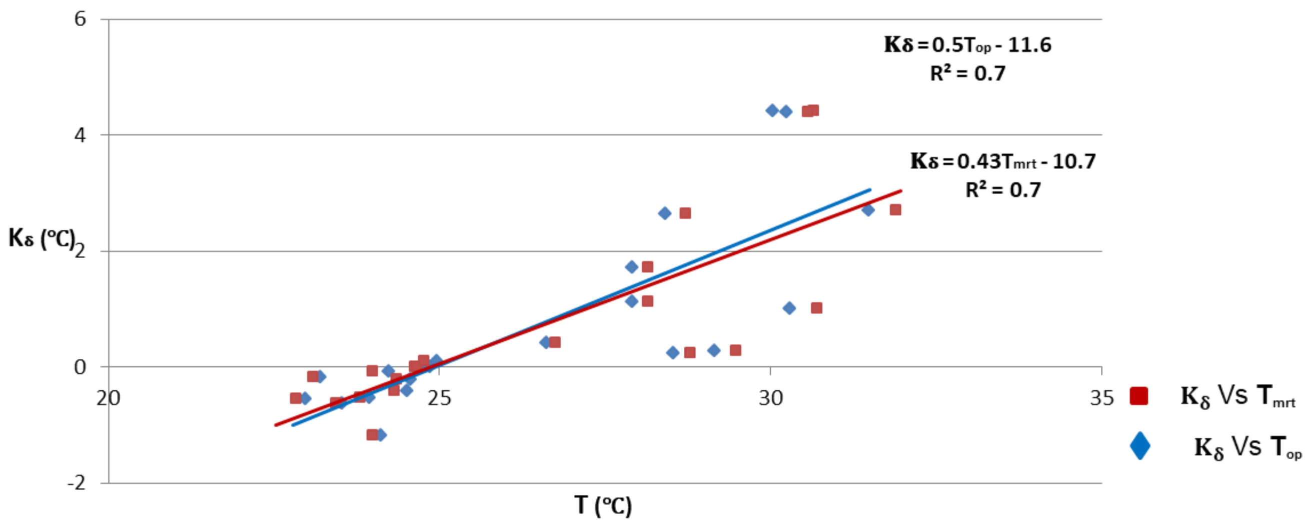

Figure 47: Correlation of psychological coefficient, mean radiant temperature and operative temperature (hot conditions)

Based on the relationship between the parameters of the physical thermal factors (such as the operative temperature) and the psychological coefficient. The evaluation of the thermal perception of the subjects can be further simplified by substituting equation (33) into equation (24) as represented in equation (57) for hot thermal conditions:

$$\text{aPMV} = \text{PMV} - \left(\frac{0.5 \cdot T_{op} - 11.6}{T_{op} - 0.36T_{out} - 15}\right) \tag{35}$$

The relationship between psychological coefficient vis-à-vis operative temperature and the mean radiant temperature is characterized by a high correlation coefficient in hot thermal conditions. These thermal parameters can be used to determine the weight of psychological coefficient in specific hot and warm locations. Thus, the value of adaptive factor for hot thermal condition is 0.5

3.3 Chapter conclusions

In this chapter we were able to process and evaluate the experiment data using the proposed model and creating ways to statistically deploy the data in the course of achieving the research objectives. The data was analyzed based on the prevailing thermal condition during the experiments. This includes the “cold experiments” and the “hot experiments”. These experiments was group based on the outdoor thermal conditions namely, the winter and summer climate respectively. Each type of experiments was analyzed based on the characteristics of the physical thermal factors, the component and processes of the physiological factors, the adaptive and psychological factor. Based on the physical thermal factor we can infer that there is a strong relationship between the mean radiant temperature and the air temperature such that they influence each other directly. We could also observe that the radiant heat influence the magnitude of the relative humidity during the hot experiments but its effect was relative low during the cold experiments. Thus the mean radiant temperature and the air temperature are significant factors when considering the indoor thermal conditions.

The physiological factors and processes where analyzed considering the various heat loss processes of the human body as relating to the thermal sensational vote calculated namely, PMV. The analyses showed that the radiant heat loss was predominant than other heat loss process, which is about 50% of the total heat loss, then followed by the convectional heat loss which is approximately 30% of the total heat loss for both hot and cold thermal conditions. Thus we were able to deduce that a combined influence of the radiant and convective process is significant in inducing the stimuli experienced by the subjects. Therefore we proposed that the operative temperature is a significant parameter in evaluating the perceived comfort of the subjects. Since the magnitude of the radiant heat exchange was more predominant, we correlated it to the PMV values and observed that the average radiant heat loss of $28W/m^2$ and the total heat loss of $58W/m^2$ (1met) is required at thermal comfort (physiologically), when the body is at uniformly at rest.

In evaluating the adaptive and psychological factors influencing thermal comfort, the proposed model postulates that the deviation between the physiological evaluation and the actual thermal perception of the subjects represents the magnitude of the adaptive factor. Consequently, the psychological factor is a function of the adaptive factor. Hence the values of the adaptive factor were the difference between the calculated PMV and the actual sensational vote of the subjects. Furthermore, to evaluate the psychological coefficient of the subjects, the neutral temperature was determined so that the deviation of the operative temperature from the neutral temperature, evaluates the stimuli or physical input factor experienced by the subjects. Hence we observed that the neutral temperature varies proportionately with the outdoor temperature, so a regression equation was generated. However based on the values of the psychological coefficient and physical input factor calculated, the adaptive factor was determined. The adaptive factor for the cool, cold and hot thermal conditions was -0.7, -1.4, and 0.5 respectively. These values represent the magnitude of adaptation of the subject when weighed on the thermal sensation scale TSS. Applying this adaptive factor into thermal comfort evaluation will greatly increase the precision of perceived comfort evaluation and the changes in human adaptation will be accounted for. Hence, thermal design will be planned to suit occupants' physical and mental satisfaction. Furthermore, we were able deduce the relationship between the psychological coefficient of thermal perception and some physical thermal factors. Thus, evaluating with the derivatives of these relationships can simplify the evaluation of thermal comfort.

CHAPTER 4

4 CONCLUSIONS AND DISCUSSIONS

Thermal comfort has been defined as the mind condition that expresses satisfaction with the thermal environment and can be assessed by subjective evaluation. The evaluation of thermal comfort has been an important subject in the building research domain due to its impact on human health, energy consumption and efficiency, architectural and engineering design considerations, choice of building materials, and human comfort. It is also important in determining occupants' satisfaction in public, private and semi-private spaces. Precision in thermal comfort evaluation is necessary for passive systems, smart systems, and intelligence systems in buildings. Thus the overall well-being of human is dependent on thermal conditions of their immediate environment and these conditions must be properly evaluated, designed and regulated. The aim of this research was to resolve the complex synchronization that existed between physical thermal conditions, physiological reaction and psychological perception of occupants. It is important that these entities be quantified by mathematical or statistical methods to enable a precise evaluation of factors affecting thermal perception, and then to examine the influence of physical thermal factors on thermal perceptions of occupants.

4.1 Conclusion

The heat balance approach and models were the initial and prominent method developed and used by researchers for the evaluation of thermal comfort. It is dependent on thermal equilibrium between core segments of human body and its outer layers. It is also depends on physiological heat exchange between human body and its immediate environment. These heat balance approach is evaluated by the thermal equilibrium that exists between heat produced and heat loss by occupant's body. Therefore, several models were developed with PMV model being the most popular. However, this model, being a laboratory acquired model, could not predict and evaluate thermal comfort efficiently for naturally ventilated buildings and semi-naturally ventilated buildings especially in hot and warms climate regions.

Hence, the research about occupants' adaptation started. Adaptation is a diminution of occupant's responses to the thermal conditions that they are repeatedly exposed to. Therefore, further researches resulted into the development of some adaptive comfort model of which adaptive predictive mean vote (aPMV) of Yao et al is one of them. This model distinctly evaluates physiological and adaptive component of thermal comfort and strategically combined these components into a quantifiable weight of human thermal perception. Hence, evaluating the adaptive component of occupant's perceived comfort was significant to this research of which the aPMV model was suitable. Also it had the capacity to estimate the psychological components of thermal perception when adapted and ameliorated.

To evaluate the adaptive component of thermal comfort, occupants' physiological sensation had to be evaluated via the PMV model. Then the results were applied to the proposed modeling-experimentation methodology that adapted Yao's model:

$$\mathrm{aPMV} = \frac{\mathrm{PMV}}{1 + \eta \times \mathrm{PMV}}$$

Where:

$$\eta = \frac{K_\delta}{\delta}$$

The model was useful for evaluating the psychological coefficient, however the aPMV equation above depicts that when PMV = 0 then aPMV = 0, and this concept was not efficient based on the outcome of the experiments executed. Consequently, an improved model was proposed by modifying Yao's model so as to resolve these anomalies. The experiments were basically done by participant in an experimental cell where thermal conditions were being altered radiantly. Simultaneously, the subjects were required to complete a questionnaire to express their thermal perception. The equation of proposed model is thus:

$$\mathrm{aPMV} = \mathrm{PMV} - \eta$$

Where:

$$\eta = \frac{K_\delta}{\delta}$$

Using the equation above to evaluate experiment's data, the correlation between psychological coefficient and physical input factor had a high correlation coefficient for the two thermal conditions: “the cool and cold” and “the hot” thermal conditions. Therefore closure equations for these conditions were derived respectively to be:

$$K_\delta = -0.7 \times \delta$$

$$K_\delta = -1.4 \times \delta$$

$$K_\delta = 0.5 \times \delta$$

Consequently, the aPMV equations for these conditions were derived respectively to be:

$$aPMV = PMV + 0.7$$

$$aPMV = PMV + 1.4$$

$$aPMV = PMV - 0.5$$

In the above equation, the adaptive and psychological factors were represented in thermal comfort evaluations. Also, the statistical relationship between parameters of the physical thermal factors and subject’s psychological coefficient were derived. This includes the relationship between psychological coefficient vis-à-vis operative temperature and mean radiant temperature. These statistical relationships were generated for cold and hot thermal conditions. The derived regression equation for cool conditions includes:

$$K_\delta = -0.65 \times T_{op} + 13.8$$

$$K_\delta = -0.62 \times T_{mrt} + 13$$

The regression equation for cold thermal conditions includes:

$$K_\delta = -1.6 \times T_{op} + 29$$

$$K_\delta = -1.6 \times T_{mrt} + 29.6$$

The regression equation for hot thermal conditions includes:

$$K_\delta = 0.47 \times T_{op} - 11.6$$

$$K_\delta = 0.43 \times T_{mrt} - 10.7$$

Thus, it can be established from the above statistical relationships and equations that thermal conditions influences the weight and the choice of psychological adaptive factors deployed by the human cognitive system. The weight of these adaptive factors is a function of the magnitude of the stimuli received and the cognitive "information" in the person. Therefore, via the above equations, psychological coefficient of these subjects can be determined. Hence, Psychological coefficient can be referred to as the magnitude of the thermal adaptive "information" in the subject's cognitive system.

Furthermore the regression equations derived via the modeling-experimentation methodology in this research can be applied into occupants' perceived comfort evaluations, since it considered significant adaptive factors that influence the thermal perception of the occupants. In accordance to the proposed model, the perceived comfort of occupant can be evaluated as the function of PMV, psychological coefficient K_{δ}, indoor operative temperature T_{op} and the outdoor temperature T_{out} as expressed below:

$$\text{aPMV} = \text{PMV} - \left(\frac{K_{\delta}}{T_{op} - 0.36T_{out} - 15} \right)$$

Based on this model equation above we can conclude that the adaptive factor is a function of the duration of exposition to a specific outdoor climate, the climate period of the year, the magnitude of the stimuli initiated due to thermal conditions in the indoor space and some other emotions and believes. Thus, occupant's perceived comfort can be measured, evaluated and predicted.

To further simplify this evaluation, the regression equations of the relationship between the psychological coefficient and the operative temperature were applied into the above equation. Thus, the perceived comfort evaluation of occupants for the cool, cold and hot thermal condition respectively, can be expressed as follows:

Cool thermal condition;

$$\text{aPMV} = \text{PMV} - \left(\frac{-0.65 \cdot T_{op} + 13.8}{T_{op} - 0.36T_{out} - 15} \right)$$

Cold thermal condition;

$$\text{aPMV} = \text{PMV} - \left(\frac{-1.6 \cdot T_{op} + 29}{T_{op} - 0.36T_{out} - 15}\right)$$

Hot thermal conditions;

$$\text{aPMV} = \text{PMV} - \left(\frac{0.47 \cdot T_{op} - 11.6}{T_{op} - 0.36T_{out} - 15}\right)$$

In this case the perceived comfort evaluation is a function of the PMV, indoor operative temperature T_{op} and outdoor temperature T_{out}.

4.2 Discussions

Advantages of the proposed model

The advantage of this model is the fact that it endeavored to consider adaptive and psychological factors unlike the heat balance models and evaluations. This model considered the climate season of the year by generating evaluation for cold condition and hot condition separately. This is because the occupants perceive their environment differently at different climate season even if the thermal conditions are of the same temperatures or magnitude. Therefore the relationship between the outdoor temperature and the neutral temperature was deployed to resolve this concept. However, most thermal comfort evaluation do not consider this climate seasons separately.

It is also imperative to deduce that the evolution of the thermal perception and response of the occupants for the cold and hot thermal condition was different from each other. With respect to this model we can observe that the subjects had lower adaptive factor of 0.5 in the hot thermal conditions than the cold conditions where they had an adaptive factor of -1.4. This depict that in this location or region where these experiments was conducted, the subjects have more adaptive capacity to the cold conditions than the hot condition. Therefore the evolution of response based on the different thermal conditions is slower in the cold condition than the hot condition. However, most other thermal comfort models consider the same evolutions for both the hot conditions and the cold conditions. This evolution of perception and response by subjects may vary from place to place.

Nevertheless, to further this research, this methodology can be carried out in other geographical locations or regions to affirm its variations and universality. The inclusion of adaptive and psychological parameters in thermal comfort evaluation will strengthen the precision in thermal energy design of buildings.

Prospective Benefit of Research Results

The result of this research is vital for occupant's well-being, health and satisfaction especially in this period where the world climate is changing fast. The global warming is creating a lot of change by activating some adjustments and adaptations in the occupant thermal perception. These adjustments must be considered by evaluating thermal comfort subjectively. The changes in the occupant thermal perception have consequently affected the manner in which energy is being required in buildings. Hence, considering and evaluating the factors affecting the occupant adaptations in energy design of buildings, will aid to reduce energy wastage and maximize energy efficiency.

Furthermore, energy efficiency is important in our building design, construction and occupancy. The management of energy in building influences the accommodation cost of occupants and this consequently determine if the building is cost effective or not. Therefore, to evaluate the thermal energy requirements of buildings, the adaptive and psychological factor should be included. This will aid to increase the thresholds in occupant thermal perception and the corresponding thermal conditions. Therefore, consumption of thermal energy in building will be efficiently conserved and managed. Consequently, the energy design of buildings will aid to minimize the cost of occupancy.

The strategic influence and significance of some physical thermal factors was also established in this research. The radiant heat was observed to be the most significant physical thermal factor, influencing both physiological and psychological realm of thermal comfort in this research. Therefore, the intrinsic characteristics of thermal radiation should be fully considered in our building design considerations. The radiant characteristic such as emissivity, reflectivity, absorptivity and transmisivity of building materials should be considered in material designs and productions. It should be adapted into building design to redirect, convert, conserve, store, and control energy consumption in building. The conversion and control of thermal radiation can be useful for passive buildings, smart buildings and intelligent designs. For example the electromagnetic characteristics of the infrared radiation can be used to detect the occupant's radiant temperature. It can automatically regulate or control building energy system to suite occupant satisfaction based on the program of the building energy devices. This will minimize thermal energy wastage and maximize energy utility. Thus, the comprehension of the relationship between parameters of thermal conditions and occupant thermal perception can result into a massive reduction in thermal energy wastage in our building. Thus, energy supply in buildings will be efficiently maximized.

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List of figures

Figure 1: Factors influencing the thermal comfort of occupants 7
Figure 2 : Two main approaches to thermal comfort evaluation and their corresponding models 13
Figure 3 : Thermal Sensational scale (TSS) (source: www.simscale.com) 18
Figure 4: PMV-PPD thermal sensational scale (source: www.simscale.com)..............................19
Figure 5: The adaptive component (Y) in the "black box" acts adaptively contrary to the value of the physiological sensation (X) when weighed on a thermal sensational scale 29
Figure 6: Components and reactions of the adaptive predicted mean vote model (aPMV)...........29
Figure 7: The Phy-Psy model to describe thermal perception. (Lenzholzer et al., 2020).............35
Figure 8: The psychological evolution of the Phy-Psy model 37
Figure 9: Input and output factors of the proposed model 43
Figure 10: Adaptive and psychological transition in the proposed model....................................45
Figure 11: Diagram showing the demarcation of space at the experiment station 48
Figure 12: Pictures showing the stages of constructing the experimental-cell 49
Figure 13: Delta Ohm HD32.3TC captured indoor micro-climate 51
Figure 14: Graphtec GL840 captured the surface temperatures 51
Figure 15: Types of data evaluated during the data analysis 56
Figure 16: Evolution of the physical thermal factors in experimental-cell (cool conditions)........63
Figure 17: Evolution of the physical thermal factors in experimental-cell (cold conditions)........64
Figure 18: Correlation of air temperature and mean radiant temperature (cool conditions)..........65
Figure 19: Correlation of air temperature and mean radiant temperature (cold conditions)..........65
Figure 20: Trends of heat losses by subject's body (cool conditions) 66
Figure 21: Trends of heat losses by subject's body (cold conditions) 66
Figure 22: Percentage of total heat loss by various heat loss process (cool conditions)................68
Figure 23: Percentage of total heat loss by various heat loss processes (cold conditions) 69
Figure 24: Relationship between thermal sensation and radiant heat loss (cool conditions).........69
Figure 25: relationship between PMV and total heat loss (cold conditions).................................70
Figure 26: Correlation of aPMV and operative temperature for cool thermal conditions 72
Figure 27: Correlation of aPMV and operative temperature for cold thermal conditions 73
Figure 28: Correlation of psychological coefficient and physical input factor (cool) 74
Figure 29: Evolution of PMV and adaptive feedbacks in human thermal perception 75

Figure 30: Evolution of PMV and adaptive feedbacks on human thermal perception 76
Figure 31: Adaptive and contra-adaptive behavior of subjects during cold experiments 77
Figure 32: Correlation of psychological coefficient and physical input factor (cool) 78
Figure 33: Correlation of psychological coefficient and physical input factor (cold) 79
Figure 34: Correlation of neutral temperatures and outdoor air temperature 80
Figure 35: Correlation of psychological coefficient, mean radiant temperature and operative temperature (cool experiments) 82
Figure 36: Correlation of psychological coefficient, mean radiant temperature and operative temperature (cold experiments) 82
Figure 37: Evolution of physical thermal factors in experimental cell (hot experiment) 85
Figure 38: Correlation of air temperature and mean radiant temperature (hot experiment) 86
Figure 39: Correlation of relative humidity and mean radiant temperature (hot experiment) 86
Figure 40: Trends of heat losses from the subject's bodies (hot conditions) 87
Figure 41: Percentage of average heat loss by various process of heat loss (hot) 88
Figure 42: Relationship between thermal sensation and radiant heat loss (hot conditions) 89
Figure 43: Trends of PMV due to total heat loss by subject's body (hot conditions)....................90
Figure 44: Adaptive and contra-adaptive behavior of subjects during the hot experiments..........91
Figure 45: Correlation of aPMV and operative temperature for hot thermal conditions 92
Figure 46: Correlation of psychological coefficient versus physical input factor (hot)................93
Figure 47: Correlation of psychological coefficient, mean radiant temperature and operative temperature (hot conditions) 94
Figure 48: Components of pierce 2-node model 145
Figure 49: Adaptive thermal comfort in HVAC and naturally ventilated (NV) buildings 153
Figure 50: Comfort zone in naturally ventilated building for ASHREA 55 standard.................154
Figure 51: Comfort zone in NV building based on outdoor temperature and indoor operative temperature..155
Figure 52: Lines of influence between the different parameters of psychological adaptation (Nikolopoulou et al., 2003) 158
Figure 53: Network of interrelationships between the parameters of psychological adaptation. (Nikolopoulou et al. 2003) 159
Figure 54: Proposed direct and indirect (via moderator/ mediator) influences of a place on a person's human response (Knez et al., 2009)...162

Figure 55: The evolution of schema in psychological adaptive comfort 169

List of tables

Table 1: linear regression of clothing and thermal conditions parameters....................................23
Table 2: linear regression of air velocity and thermal conditions parameters 24
Table 3: Climate Adaptation Model in China 26
Table 4: Climate Adaptation Model in China 26
Table 5: Expectancy Factors for the PMV Index (Fanger and Toftum, 2002) 28
Table 6: Characteristics of HD32.3TC probes used for the experiments......................................50
Table 7 : Occupants subjective reactions to various velocities (Auliciems et al., 2007)...........125
Table 8 : The value of the clothing insulation for various clothing style (ASHRAE 2017)........137
Table 9: Convective heat transfer coefficient for various thermal conditions (de Dear et al. 1997, ASHREA 55:2017) 138
Table 10 : The value of based on the activity level of the subjects (ASHRAE 55-2017)...........140
Table 11: New standard effective temperature (SET*) scale..147
Table 12: Heat stress index (HSI) scale 149
Table 13: Physiological Equivalent temperature (PET) scale...151
Table 14: Categories of thermal comfort in buildings (ISO 7730) 157

APPENDICES

A. Details of physical thermal factors

(i) Air temperature (T_a)

The air temperature is the ambient temperature (T_a) in $^{\circ}$C of the air surrounding the occupants, with respect to location and time (ASHRAE, 2013). It aids to perceive the temperature differences between the human body and its surroundings, which in turn affects the rate of heat loss or gain through convection.

(ii) Mean Radiant Temperature (T_{mrt})

ASHRAE defines mean radiant temperature (T_{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, 2013). It can also be said to be the solid-angle-weighted average temperature of surrounding surfaces. Mean radiant temperature is a means of expressing the influence of surface temperatures in the room, on occupant's comfort. CIBSE also describes 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 2006).

(iii) Air velocity (v)

This is the rate of air movement at a point, without regard to direction. According to ANSI/ASHRAE Standard 55, it is "*the average speed of the air surrounding a representative occupant, over a time interval with respect to location and time*". It results from (1) the free buoyant motion caused by a warm body in cool air medium, (2) forced ventilation of the environment, and (3) bodily motion caused by activity of the object itself. An increased airflow across a space or body can alter the sensation of comfort, causing the skin or body to feel cooler in warm spaces (ISO, 2005; Nasrollahi, 2007). Different research studies have also shown that, in hot and humid climate zones, an increase in air velocity can positively influence the thermal perception and adaptation of occupants in naturally ventilated spaces (Cândido, de Dear, & Lamberts, 2011; Cândido et al., 2010; Manu et al., 2014). In addition, increased air movement leads to increased evaporation, which results in a cooling effect (Aronoff & Kaplan, 1995).

It is common experience that air movement, be it a natural wind, or generated by a fan, has a cooling effect. This largely depends on the velocity of that air movement. Under everyday conditions, the average subjective reactions to various velocities are (Auliciems et al., 2007):

Table 7 : Occupants average subjective reactions to various velocities (Auliciems et al., 2007)

Air velocity	Occupants subjective reaction
< 0.25 m/s	unnoticed
0.25-0.50	pleasant
0.50-1.00	awareness of air movement
1.00-1.50	draughty
> 1.50	annoyingly draughty

(i) Vapor pressure (P_a)

When water vapor is confined over its liquid so that the vapor comes into equilibrium with the liquid, and the ambient temperature T_a of the medium is held constant, the vapor pressure (P_a) approaches a maximum value called the saturated vapor pressure (P_s). The saturated vapor pressure in an enclosure is equal to the vapor pressure at its dew-point temperature (T_{dp}). The dew point is the temperature at which condensation first occurs when an air-water vapor mixture is cooled at constant pressure. The water vapor pressure of an enclosure may be calculated from the observed wet bulb and dry bulb temperatures and the atmospheric pressure, by using standard steam or meteorological tables and equations.

(ii) Humidity

Humidity is the water vapor or moisture content of the air. It can either be stated as relative humidity (RH) or absolute humidity (ISO, 2005). Relative humidity (RH) 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, 2013). 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). The recommended level of indoor relative humidity is in the range of 30-60% in air conditioned buildings.

(iii) 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 $0.155 m^2 C/W$. Clothing insulation relates to heat transfer from the whole body, and the uncovered parts of the body, such as the hands and the head (ASHRAE, 2013). According to ASHRAE Standard 55 and ISO 7730, users of the ASHRAE clothing table are required to determine the insulation values of clothing by matching garments similar to the ones given in tables and assume that the evaporative resistance of every day clothing is low (McCullough, 2001). The amount of thermal insulation worn by a person has a significant impact on heat loss and, consequently, their thermal balance.

B. Physiological factors of thermal comfort

These factors are related with the functioning of body's system which regulate, manage and adapt the body's thermal balance. They are influenced by various situations and body's specific needs at a given moment. These factors include, but are not limited to, heat transfer through the human metabolism, evaporation, convection, radiation and conduction. The following provides explanations of these physiological factors.

(i) 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, it is usually expressed in terms of unit area of the total body surface*" (ASHRAE, 2013). It is likewise defined in the standard ISO 13731:2001 as the "*rate of transformation of chemical energy into heat and mechanical work by aerobic and anaerobic metabolic activities within an organism*". According to the standard ISO 8996:2004, the metabolic rate "*measures the energetic cost of muscular load and gives a numerical index of activity*". Therefore, it is largely dependent on the level of activity (CIBSE, 2006). 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 stated as 1.8 m^2 in both the ASHRAE and ISO standards (ASHRAE, 2013; ISO, 2005).

(ii) Evaporation

Evaporation is the process through which a liquid turns into gas. When a portion of a liquid evaporates, it cools the remaining liquid by extracting the required heat of vaporization from it, causing the phase change to the gaseous state. The human body utilizes evaporative cooling by perspiration and diffusion from the skin and respiratory track to release energy to their surroundings, even in conditions when the surrounding temperature is higher than the body temperature.

(iii) Convection

Convection is the process of heat transfer through the movement of gas or liquid, where the amount of heat transferred depends on the temperature difference between the two mediums and the velocity of the fluid. Three different processes exist: free, mixed and forced convection. In free convection, fluid motion occurs due to buoyancy, driven solely by a temperature gradient. It generally occurs at low air speeds (below 0.2 $m.s^{-1}$) in the surrounding environment. Buoyancy refers to the upward force exerted by a fluid that counteracts the weight of an immersed object in it. Mixed convection is a combination of forced and free convection, normally observed at air speeds ranging from 0.2 and 1.5 $m.s^{-1}$. Forced convection is characterized by fluid motion generated by an external source, and the velocity of the fluid is usually higher than 1.5 $m.s^{-1}$.

In the evaluation of thermal comfort, convection is considered in the heat exchange between the body or clothing surface and the surrounding ambient air.

(iv) Radiation

Thermal radiation refers to the emission of electromagnetic waves from any matter with a temperature above absolute zero (José, 2012). It involves the conversion of thermal energy into electromagnetic energy, and unlike other heat transfer mechanisms, it does not require a medium to propagate. The characteristics of thermal radiation depend on various properties of the surface, such as temperature, emissivity, absorptivity, reflectivity, and the view factor or geometric factor of the surfaces involved.

In thermal comfort evaluation, radiation typically occurs between the human body or clothing surface and the surrounding surfaces. It plays a role in the exchange of heat energy in this context.

(iv) Conduction

Heat conduction occurs between two objects in contact, and heat energy transfers from one object to another. It follows the principle that heat travels from a hotter point to a colder point. In the context of the human body, heat conduction commonly occurs between the clothing and skin surfaces. The amount of heat transfer is determined by factors such as the conductivity or resistance of the closing material.

C. Psychological factors of thermal comfort

The detailed explanations of the psychological factors of thermal comfort are as follows:

Sensation

It is the initial detection of a stimulus resulting from the stimulation of a receptor in a sense organ, as each sense organ responds to a specific type of physical stimulation and possesses specific receptor cells. Sensation is also the sensory unconscious detection of environmental stimulation and information (Knez et al. 2009). During sensation, our sense organs are engaging in transduction, that is the conversion of one form of energy into another. Physical energy such as light or sound waves is converted into electro-chemical stimulations. Sensation is possible if the stimulus is strong enough to excite sensory receptors and send nerve impulses to the brain.

Perception

Perception is the organizing and understanding of the incoming sensational information. In order for sensations to be useful, we must add meaning to those sensations, which create our perceptions. Knez et al. 2009 defined perception as the conscious interpretation and elaboration of sensory data. Perception of the same senses may vary from one person to another because each person’s brain interprets stimuli differently based on that individual’s learning, memory, emotions, and expectations. Perception can be bottom-up or top-down processing. Bottom-up processing refers to the fact that perceptions are built from sensory input while top-down processing interpret those sensations by the influenced of our available knowledge, our experiences, and our thoughts.

Environmental cognition

Environmental Cognition refers to the mental process of acquiring knowledge and understanding our surroundings through thought, experience, and the senses. It includes intellectual functions and processes such as: thought, intelligence, the formation of knowledge, memory, evaluation, reasoning and computation, problem solving and decision making, as well as comprehension. Cognitive processes use existing knowledge and discover new knowledge. It is how we learn, remember, and think about information (Knez et al., 2009).

Emotion

Emotions are mental states brought on by neurophysiological changes, variously associated with feelings, behavioral responses, and a degree of pleasure or displeasure (Cabanac, 2002; Damasio, 1998). They are reactions that human beings experience in response to events or situations. The type of emotion a person experiences is determined by the circumstance that triggers the emotion. They are therefore states, processes, and expressions that convey qualities of affect, feeling, and mood (Knez et al. 2009). Emotional experiences have three components: a subjective experience, a physiological response and a behavioral or expressive response. Most emotions begin with a subjective experience, also referred to as a stimulus. The physiological response is the result of the autonomic nervous system's reaction to the emotion we are experiencing. The autonomic nervous system controls our involuntary bodily responses and regulates our fight-or-flight response. A behavioral response includes smiles, grimace, laugh or a sigh, along with many other reactions depending on societal norms and personality.

Coping

Coping refers to a complex set of behaviors and cognitions that individuals uses to deal with stress and adversity. Coping is constantly changing, involving both cognitions and behavior, effortful, concerned with the management of specific demands, and its availability when demanded from within or outside of a person. Coping can be evaluated as taxing when it exceeds the person's resources. In thermal comfort, coping is psychological regulation and strategic ways for dealing with some place-related stimulation and surpassing environmental situations (Knez et al., 2009). Richard Lazarus et al. 1984, describe the coping process as consisting of appraisal, behavior, and reappraisal. This is because coping involves the evaluations or appraisals of a situation as exceeding a person’s resources to manage the situation. It also refers to the effortful responses people make to manage a situation including their emotional responses to it.

Behavior

This refers to physical action and activities, doings, reactions, movements based on the information and interpretation of the mind (Knez et al., 2009).This is simply the activity of an organism that is interacting with its environment (Doron and Parot, 1999). It also implies the assembly of responses that a body equipped with the nervous system performs as a response to the stimuli of his environment, which are objectively observable (Neveanu, 1978). Gabriela Popescu 2014, describe behavior as a total response of an organism, in reply to living circumstances, depending on the environmental stimulation and the internal tension of successive movements, which are oriented in a significant way. It is putting into play the psychological sensory motors and physiological components of an organism to designate the way to be and to act through observable manifestations.

Experience

Experience refers to conscious events in general, more specifically to perceptions, or to the practical knowledge and familiarity that is produced by these conscious processes. This is associated both with recurrent past acquaintance and the abilities learned through them. It includes an event that is actually lived through, the present contents of consciousness, and the stimulus that has resulted from learning. However, Mittelstraß 2005, explained that experience refers not to conscious events themselves but to the knowledge and practical familiarity they bring with them. Therefore, it may include only real items, only unreal items, or a mix between the two. This includes various types of experiences, such as perception, bodily awareness, memory, imagination, emotion, desire, action and thought (Smith, 2018). Nevertheless, "experience" in everyday language usually sees the knowledge in question not merely as theoretical knowledge or descriptive knowledge; instead, it includes some form of practical know-how, i.e. familiarity with a certain practical matter. This familiarity rests on recurrent past acquaintance or performances (Borchert, 2006)

Expectation

Expectation is a perceptual state of anticipation of an event or occurrence. They are personal beliefs about occurrences that may take place in the future, which are usually developed from a combination of individuals' experiences and knowledge. Therefore, they serve a basic function to prepare humans for future action. Expectations affect the thought processes that involve attention, interpretation, explanations, and memory, such that people pay more attention to information that is consistent with their expectations. In the same way, people also pay attention to information that are noticeably inconsistent to their expectation. Expectations are subjective because it depends on the person's judgment of how the world works based on his past experience or education.

Attitude

It can be defined as the readiness of the psyche to act or react in a certain way (Main, 2004). They are set of emotions, beliefs or philosophies towards a person, place or event that creates the feelings individuals have about themselves and the world such that they evaluate things in a certain way. Attitude is therefore a psychological construct, a mental and emotional entity that is inherent in or characterizes a person (Richard, 2016). It can also refer to a mental and neurophysiological state determined by experience that exerts a dynamic influence on the individual by preparing him or her to act in a particular way towards a number of objects or events. In other words, attitude is seen as an intermediate variable that prepares the individual to act in a certain way towards a given object. It is a more or a less favorable evaluation of a given object. Hence, these predispositions are said to be stable, because they are based on personality, identity (innate part) and learned, because of experiences.

Attitude is a hypothetical construct, it is not observed as we can with behavior, and we deduce it from the statements or responses of individuals. It is an integrative conceptual tool and it is composed of three fundamental components:

- Cognitive: knowledge, beliefs, values, opinions, convictions about an attitude object

- Affective or emotional: feelings, emotions, moods about the attitude object

- Conative or behavioral: intentions or anticipatory function, especially to act.

Also attitude is formed from; Intrinsic elements (personality and education), Extrinsic elements (social position, belonging and/or reference group, learning by conditioning or by beneficial imitation).

Habituation

Habituation is the reduction of psychological or behavioral response occurring when a specific stimulus occurs repeatedly. It is a decrement in behavioral response that results from repeated stimulation but does not involve sensory adaptation, sensory fatigue or motor fatigue because it involves accessible conscious control in the brain, and not in the sensory organs. It is not influenced by the intensity of the stimulus, but is influenced by the length and recency of prior exposures. Habituation is a form of non-associative learning in which an innate (non-reinforced) response to a stimulus decreases after repeated or prolonged presentations of that stimulus (Bouton, 2007). It is non-associative learning because by diminishing the response to an inconsequential stimulus, it free-up cognitive resources to other stimuli that are associated with biological importance. In that way people can tune out non-essential stimuli and focus on the things that really demand attention. The factors affecting habituation includes (1) the frequency of the stimulus; the more frequently a stimulus is presented, the faster habituation will occur; (2) the duration of the stimuli; a habituated response to a stimulus increases when a significant amount of time (hours, days, weeks) passes between stimulus presentations; (3) Changing the intensity, duration or frequency of the stimulation. Therefore habituation will occur to other stimuli that are similar to the original stimulus (stimulus generalization).

There are some theories of habituation that were proposed by some researchers, this includes the Sokolov Comparator theory of habituation which suggests that our brain creates a model of the expected stimulus. With continued presentations, the stimulus is compared to the model and, if it matches, the response is inhibited (Sokolov, 1963). The second one is the Groves and Thompson dual-factor theory of habituation which suggests that, there are underlying neural processes that regulate responsiveness to different stimuli. Therefore our brains choses the most pressing stimuli we need to focus our attention on.

Representation

Representation is simply a hypothetical internal cognitive code that represents external reality (Morgan, 2014). They are mental imagery of things that are not actually present to the senses

(Mckellar, 1957). These mental images are used to help solve certain types of problems, by visualizing the objects (problem) in question and then mentally representing the images to solve it (solution) (Robert, 2009). It can be referred to as the internal image (not only visual) of a place that constitutes a functional means of organizing information, particularly for orientation. Therefore, representation is processed by a series of psychological transformations in which people codes and stores information relating to the positions and qualities of phenomena taking place in his or her environment.

They are the contents of thoughts that are represented in symbolic structures. Representation possesses both syntax and semantics very much like those of codes. The syntax of thought is the set of rules, operations and processes, of the symbol structures while the semantics of thought is the concepts and propositions of the structured symbols. The symbolic system contains three distinct aspects; the symbols, the rules that govern the manipulation of those symbols, and the measuring processes.

Evaluation

Evaluation is the process of making value judgements about our environment. It can be said that the perceptual and evaluative processes are dependent on each other. On the one hand, it is difficult to imagine that we can evaluate the qualities of an environment without first perceiving them; while on the other hand, our judgements can lead to changes in our perception. Any perception of space is also a way of evaluating it according to more or less normative codes or criteria: for example, if a space 'must' be clean, we will perceive it according to its degree of adequacy to this quality. Perception is a judgement: we weigh the relevance of environmental elements against our system of reference (our representations). This shows once again the importance of culture, of values, as determining factors in the interaction between human and environment

D. Socio-cultural factors of thermal comfort

Cultural behavior

They are ways that cultural traditions and social practices regulate, express, and transform the human psyche. It depicts how culture reflects and shapes the mind and behavior of its members (Heine, 2015). The culture cycle consists of four layers (Individuals, Interactions, Institutions, Ideas) of cultural influence that help to explain the interaction between self, behavior and culture (Markus & Conner, 2013). The Individuals layer is concerns with how an individual thinks about and expresses itself. For example the United States, individuals are more likely to think of themselves as "independent", "equal", and "individualistic" while in Japan, the individuals are more likely to think of themselves as "obligated to society", "interdependent", and "considerate" Heine (2011). The interaction layer refers to interactions through stories, songs, architecture, and advertisements that guide individuals in a culture to promote certain values and teach them how to behave (Kitayama et al., 2002). The Institution layer determines and enforces the rules for a society that include legal, government, economic, scientific, philosophical, and religious bodies. While the ideas layer focuses on the big ideas that each culture has which answers the big questions of life, such as why are we here, where did we come from, and where are we going. These cultural factors and behaviors definitely influence how we perceive our environment and space.

Standard of living

In simple words, the standard of living implies the level of welfare provided to the residents of a country, i.e. it may refer to all those goods and services that people are able to consume and the resources they can access. Practically, the Standard of Living of people of a country is reflected in the way in which people live, such as how much money they have to spend, how their houses are constructed, how educated they are, what facilities are available to them, etc. The Factors that determine a standard of living include income, physical health, quality of the environment, housing availability, life expectancy, personal safety, and access to education, medical facilities, and social services. These factors determine the behavior and the comfort choices made by individuals when affected by thermal and environmental conditions.

Technological advancement

The word technology refers to the making, modification, usage, and knowledge of tools, machines, techniques, crafts, systems. It also includes the methods of organization, in order to solve a problem, improve a preexisting solution to a problem, and achieve a goal. Technologies consist of what is known as systems; Systems operate by obtaining an input, altering this input through what is known as a process, and then producing an outcome that achieves the intended purpose of the system. Technologies significantly affect human ability to control and adapt to their environment conditions. Technological advancement equips individual with advanced devices and systems that enable him to live a more comfortable life.

E. Parameters and equations of heat balance approach

(i) Metabolic heat loss by convection (φ_{cl}^{Conv})

The convectional heat transfer of the ambient air and the human body surface is a function of their temperature difference, the surface area and the speed with which they are moving relative to each other. Therefore, the heat loss/gain is proportional to the area and temperature difference between the fields in the heat flux. The convective heat exchange can occur between the skin and the body core as well as between the skin and its ambient air. The convective heat transfer between the skin and the ambient air for an unclothed body can be given by the equation (36);

$$\varphi_{sk}^{Conv} = h_c \times (T_{sk} - T_a) \qquad [W.m^{-2}] \tag{36}$$

To take into account the effect of clothing:

$$\varphi_{cl}^{Conv} = f_{cl} \times h_c \times (T_{cl} - T_a) \qquad [W.m^{-2}] \tag{37}$$

(McPherson, 1993)

Consider the fact that convectional heat loss from the skin surface to the clothing surface is in equilibrium with the heat loss from the clothing surface to the surrounding. If the clothing resistance (***clo***) is known then the convectional heat loss can be given as:

$$\varphi_{cl}^{Conv} = \frac{T_{sk} - T_a}{clo + {}^{1}/_{f_{cl} h_c}} \qquad [W.m^{-2}] \tag{38}$$

This is also an alternative way to determine the clothing temperature T_{cl} when the skin temperature T_{sk} is known or vice versa; by equating equation (36) to equation (37)

The clothing factor (F_{cl}) can be expressed as:

$$f_{cl} = \frac{\text{Surface area of clothed body}}{\text{Surface area of unclothed body}} \tag{39}$$

Also according to Auliciems et al., 2007 clothing factor f_{cl} is a function of the clothing resistance clo. It can be calculated as:

$$f_{cl} = \frac{1}{1 + 0.155 \times clo \times h} \qquad [°C/W] \tag{40}$$

1 clo = 0.155 m^2 °C/W

1 clo maintains the temperature comfort of a sedentary man indefinitely at 21°C, 50% RH, and a wind speed of 0.01 m/sec.

Table 8 : The value of the clothing insulation *clo* for various components of clothing style (ASHRAE 2017)

Garment Description[a]	$I_{clu,i}$, clo[b]	Garment Description[a]	$I_{clu,i}$, clo[b]	Garment Description[a]	$I_{clu,i}$, clo[b]
Underwear		Long-sleeved, flannel shirt	0.34	Long-sleeved (thin)	0.25
Men's briefs	0.04	Short-sleeved, knit sport shirt	0.17	Long-sleeved (thick)	0.36
Panties	0.03	Long-sleeved, sweat shirt	0.34	**Dresses and Skirts**[c]	
Bra	0.01	**Trousers and Coveralls**		Skirt (thin)	0.14
T-shirt	0.08	Short shorts	0.06	Skirt (thick)	0.23
Full slip	0.16	Walking shorts	0.08	Long-sleeved shirtdress (thin)	0.33
Half slip	0.14	Straight trousers (thin)	0.15	Long-sleeved shirtdress (thick)	0.47
Long underwear top	0.20	Straight trousers (thick)	0.24	Short-sleeved shirtdress (thin)	0.29
Long underwear bottoms	0.15	Sweatpants	0.28	Sleeveless, scoop neck (thin)	0.23
Footwear		Overalls	0.30	Sleeveless, scoop neck (thick)	0.27
Ankle-length athletic socks	0.02	Coveralls	0.49	**Sleepwear and Robes**	
Calf-length socks	0.03	**Suit Jackets and Vests (Lined)**		Sleeveless, short gown (thin)	0.18
Knee socks (thick)	0.06	Single-breasted (thin)	0.36	Sleeveless, long gown (thin)	0.20
Panty hose	0.02	Single-breasted (thick)	0.44	Short-sleeved hospital gown	0.31
Sandals/thongs	0.02	Double-breasted (thin)	0.42	Long-sleeved, long gown (thick)	0.46
Slippers (quilted, pile-lined)	0.03	Double-breasted (thick)	0.48	Long-sleeved pajamas (thick)	0.57
Boots	0.10	Sleeveless vest (thin)	0.10	Short-sleeved pajamas (thin)	0.42
Shirts and Blouses		Sleeveless vest (thick)	0.17	Long-sleeved, long wrap robe (thick)	0.69
Sleeveless, scoop-neck blouse	0.12	**Sweaters**		Long-sleeved, short wrap robe (thick)	0.48
Short-sleeved, dress shirt	0.19	Sleeveless vest (thin)	0.13	Short-sleeved, short robe (thin)	0.34
Long-sleeved, dress shirt	0.25	Sleeveless vest (thick)	0.22		

[a]"Thin" garments are summerweight; "thick" garments are winterweight. [b]1 clo = 0.155 ($m^2 \cdot K$)/W [c]Knee-length

The coefficient of convectional heat transfer (h_c) is a function of the air velocity, the relative air velocity, temperature difference between the body and environment, and the activity of the subjects. The equations in Table 9 below can be used to determine the coefficient of convectional heat transfer based on the subject's conditions.

Table 9: Convective heat transfer coefficient for various thermal conditions (de Dear et al. 1997, ASHREA 55:2017)

EQUATION ($\boldsymbol{W/m^2K}$)	**CONDITION** (*m/s*)	**LIMIT**
$\boldsymbol{h_c = 3.1}$	$0 < v < 0.2$	Seated with moving air
$\boldsymbol{h_c = 8.3v^{0.6}}$	$0.2 < v < 4.0$	Seated with moving air
$\boldsymbol{h_c = 5.1}$	$0 < v < 0.15$	Reclining with moving air
$\boldsymbol{h_c = 2.7 + 8.7v^{0.67}}$	$0.15 < v < 1.5$	Reclining with moving air
$\boldsymbol{h_c = 8.5v^{0.53}}$	$0.5 < v < 2.0$	Walking in still air
$\boldsymbol{h_c = 5.7(M - 0.8)^{0.39}}$	$0.5 < v < 2.0$	Active in still air
$\boldsymbol{h_c = 6.5v^{0.39}}$	$0.5 < v < 2.0$	Walking on treadmill in still air
$\boldsymbol{h_c = 4.0}$	$0 < v < 0.15$	Standing in moving air
$\boldsymbol{h_c = 14.8v^{0.69}}$	$0.15 < v < 1.5$	Standing in moving air

(ii) **Radiant heat loss from the human body ($\boldsymbol{\varphi_{net}^{rad}}$)**

Radiant heat exchange takes place between the human body and its surroundings, from the outer surface of the clothed body. The heat loss by radiation can be expressed in Equation (41) below.

$$\varphi_{net}^{rad} = h_r \times f_{cl} \times (T_{cl} - T_{mrt}) \qquad [W.m^{-2}] \tag{41}$$

where, h_r is the radiative heat transfer coefficient (W/m^{2}K). h_r is nearly constant for typical indoor temperatures (10 - 30 °C) (Olsen, 1982) (ASHRAE, 2013) with the value of 4.7 W/m^{2}K and this suffices for most calculations (ASHRAE, 2013).

The radiative heat transfer coefficient can therefore be calculated by the equation (42) below:

$$h_r = 4\varepsilon\sigma f_{eff}\left(273.2 + \frac{T_{cl}+T_{mrt}}{2}\right)^3 \qquad [W.m^{-2}K^{-1}] \tag{42}$$

Where $\boldsymbol{f_{eff}}$ represent the effective area factor.

The mean radiant temperature can be evaluated by considering the sum of each of the surface temperature of the enclosure surfaces being multiplied by their respective view factor with respect to the enclosed person or subject. This is estimated with the assumption that the walls are black bodies therefore their emissivity of the enclosed surfaces is approximately unity.

The equation below depicts the mean radiant temperature of an enclosed space.

$$T_{mrt}^4 = T_1^4 F_{1-i} + T_2^4 F_{2-i} + \ldots\ldots T_n^4 F_{n-i} \qquad [°C] \tag{43}$$

Where n is the number of the surfaces in the enclosure and *i* is the subjects in the enclosure.

Using the principle above for a cuboid enclosure with six surfaces, the mean radiant temperature may also be calculated from the plane radiant temperature T_{pr} in six directions (up, down, right, left, front, back) via the projected area factors of a person in the same six directions. Note that the plane radiant temperature describes thermal radiation in one direction and its value thus depends on the direction. Therefore, the mean radiant temperature for a person in a cuboid enclosure can be estimated thus (ASHREA 55:2017):

For a seated person:

$$T_{mrt} = \frac{\{0.18[T_u + T_d] + 0.22[T_r + T_l] + 0.30[T_f + T_b]\}}{[2(0.18 + 0.22 + 0.30)]} \qquad [°C] \tag{44}$$

For a standing person:

$$T_{mrt} = \frac{\{0.08[T_u + T_d] + 0.23[T_r + T_l] + 0.35[T_f + T_b]\}}{[2(0.08 + 0.23 + 0.35)]} \qquad [°C] \tag{45}$$

An “approximated” expression of the mean radiant temperature T_{mrt} exists for conditions in which the surrounding surface geometry is complex or in an outdoor situation:

Auliciems et al. (2007) expressed the relation between the mean radiant temperature and the globe Temperature (T_g) in his review. He explained that in still air, $T_{mrt} = T_g$, but if natural or forced convection occurs then air is not still, therefore a correction due to air movement of *v* velocity (in m/s) was proposed as follows**:**

$$T_{mrt} = \left[\left(T_g + 253\right)^4 + \frac{1.1\times10^8(v^{0.6})}{\varepsilon d^{0.4}}\left(T_g - T_a\right)\right]^{0.25} \qquad [°C] \tag{46}$$

(iii)**Evaporative heat loss by sweating (φ_{sk}^{Sw})**

Removal of heat from the body by evaporation of water from the skin is a major means of heat depletion. The transfer of heat between the body and the environment by convection and radiation may be either toward the body or away from it, depending upon the ambient conditions and temperatures. However evaporation always constitutes a rejection of heat from the body. In hot environments, sweating provides the dominant method of heat removal from the body by the thermoregulatory system (Stoecker et al., 1982). Based on the linear regression obtained from the work of Rohles et al. 1971, the heat loss by sweating is the function of the difference between the metabolic heat produced by the body due to its activity φ and the metabolic heat produced when the body is at rest φ_O. It is given as:

$$\varphi_{sk}^{Sw} = 0.42[(\varphi - w) - 58.15] \qquad [W.m^{-2}] \tag{47}$$

(Enescu 2019, Oğulata, 2006)

Table 10 : The value of φ based on the activity level of the subjects (ASHRAE 55-2017).

ACTIVITY	**METABOLIC HEAT PRODUCTION**	
	W/m²	*met*
Resting		
Sleeping	40	0.7
Reclining	45	0.8
Seated, quiet	60	1.0
Standing, relax	70	1.2
Walking (on level surface)		
0.9 m/s	115	2.0
1.2 m/s	150	2.6
1.8 m/s	220	3.8
Office activities		
Reading, seated	55	1.0
Writing	60	1.0
Typing	65	1.1
Filing, seated	70	1.2
Filing, standing	80	1.4
Walking about	100	1.7
Lifting/packing	120	2.1

(iv) **Heat loss by water diffusion on the skin surface (φ_{sk}^{Diff})**

This is the rate of heat transfer by insensible evaporation which is controlled by the resistance of the deep layers of the epidermis and then to the diffusion of water from beneath the skin surface to the ambient air (Stoecker et al., 1982). It can be referred to as the heat loss due to the difference between the saturated vapor pressure of the skin at the skin temperature P_{sk} and the vapor pressure of ambient air at air temperature P_a.

$$\varphi_{sk}^{Diff} = 3.05 \times 10^{-3}[5733 - 6.99(\varphi - W) - P_a] \qquad [W.m^{-2}] \tag{48}$$

(ISO 7730:2005, Enescu 2019)

$$\varphi_{sk}^{Diff} = 3.05 \times 10^{-3}(\mathrm{P_{sk}} - \mathrm{P_a}) \qquad [W.m^{-2}] \tag{49}$$

(Krittiya, 2017)

$$\varphi_{sk}^{Diff} = 0.68 \times 0.61(\mathrm{P_{sk}} - \mathrm{P_a}) = 0.4148(\mathrm{P_{sk}} - \mathrm{P_a}) \qquad [W.m^{-2}] \tag{50}$$

(Oğulata, 2006)

In equation (50) the saturated vapor pressure at skin temperature P_{sk} and vapour pressure at air temperature P_a are in torr;

0.68 is the passive water vapor diffusion rate, (g/h·m^2·Torr)

0.61 is the latent heat of water, (W·h/g)

Based on the equation above it's necessary to evaluate the saturated vapor pressure and the vapor pressure at skin temperature.

$$\mathrm{P_{sk}} = 133.3224\ (1.92\mathrm{T_{skr}} - 25.3) \qquad [Pa] \tag{51}$$

Note that 1torr = 133.3224 Pa

P_{sk} can be expressed in kilopascal kPa

Skin Mean Temperature of the body based on the activity level and energy produced by the body:

$$\mathrm{T_{skr}} = 35.7 - 0.028\ \varphi \qquad [°C] \tag{52}$$

Vapor pressure (P_a) or the partial pressure of water vapor in the atmosphere is linearly related to absolute humidity (AH), in units of kilopascal kPa. Similarly, the saturation humidity (SH) can be expressed as saturation vapor pressure (P_{sa}). Therefore:

$$RH = \frac{AH}{SH} \times 100\% = \frac{P_a}{P_{sa}} \times 100\% \quad (53)$$

Relative humidity (RH) is referred to as 'percentage saturation' in some text.

According to Antonine equation saturated vapor pressure can be valued as:

$$P_{sa} = 0.133322 \exp[18.6686 - 4030.183/(T_a+235)] \quad [kPa] \quad (54)$$

(Auliciems et al., 2007)

(v) **Respiratory heat loss by convection (φ_{res}^{Conv})**

Heat is lost from the body when breathing because the exhaled air is warmer than the inhaled air. This heat exchange is a function of the difference between the exhaled air temperature and the inhaled air Temperature. The exhale air temperature is usually 34^oC

Therefore the Respiratory dry heat loss by convection can be represented by:

$$\varphi_{res}^{Conv} = 0.0014\varphi(34 - T_a) \quad [W.m^{-2}] \quad (55)$$

(Gagge et al., 2011)

(vi) **Respiratory latent heat loss (φ_{res}^{vap})**

This heat loss is a function of the difference between the vapor pressure of the human body at mean body temperature and the atmospheric vapor pressure at air temperature $\boldsymbol{P_a}$.

The Respiratory Latent Heat loss is given by:

$$\varphi_{res}^{vap} = 1.72 \times 10^{-5}\varphi\,(5867 - P_a) \quad [W.m^{-2}] \quad (56)$$

(Krittiya, 2017, Olsen 1982, ISO 7730:2005)

$$\varphi_{res}^{Conv} = 0.0023\varphi(44 - P_a) \quad [W.m^{-2}] \quad (57)$$

(Gagge et al., 2011)

In equation (57) above 44 torr is the vapor pressure of water at the mean body or skin temperature

F. Other heat balance models

Other heat balance model suitable for indoor space includes; (1) The pierce two-node model (2) the new standard effective temperature SET*, (3) heat stress index HSI, (4) Munich energy balance for individual MEMI, (5) the physiological equivalent temperature PET and much more.

Pierce two-node model

The Pierce Two-Node model was developed at the John B. Pierce Foundation at Yale University. The model has been continually expanding since its first publication in 1970 (Gagge et.al., 1970). The model was also written in the 1986 ASHRAE Transactions (Gagge et.al., 1986). The Pierce model thermally lumps the human body as two isothermal, concentric compartments. The first compartment is the internal section or core where all the metabolic heat is generated while the second compartment is the skin being the outer membrane of the body in contact with the external physical environment. In this case the respiratory heat loss is accounted for directly from the core section where metabolic heat is generated while the evaporative and sensible heat loss by convection and radiation are accounted for from the heat that is conducted to the body surface or skin through the conductance of the body tissue and the convective blood flow. Thus the passive heat conducted from the core compartment to the skin surface is accounted for, and the boundary line between the two compartments changes with respect to the skin blood flow rate per unit skin surface area (SKBF in L/hrm^2). This can be derived through the fraction of total body mass attributed to the skin compartment (Doherty and Arens 1988).The body mass to skin ratio (α) is given by:

$$M_{sb} = 0.0417737 + \frac{0.7451832}{SKBF + 0.585417} \tag{58}$$

Where SKBF is the skin blood flow and M_{sb} is the Body mass to skin ratio

Furthermore, the model takes into account the deviations of the core, skin, and mean body temperature from their respective neutral points so that the thermoregulatory effectors (Regulating sweating, skin blood flow, and shivering) are defined based on the thermal signals received from the core, skin and body. This signals is proportional to the degree of deviation from their average neutral point.

$$SIG_c = T_{cr} - 36.8°C$$

$$SIG_{sk} = T_{sk} - 33.7°C$$

$$SIG_b = T_b - 36.49°C$$

Where SIG_c=Thermal Signal of the Core, SIG_{sk}=Thermal Signal of the Skin, SIG_b = Thermal Signal of the Body.

$$SKBF = \frac{6.3 + C_{dil} \times SIG_c}{1 + S_{ctr} \times -SIG_{sk}} \quad \text{L/hr•m}^2 \tag{59}$$

Where C_{dil} is the dilation constant of skin blood flow and S_{ctr} is the Constriction constant of skin blood flow.

The Total Metabolic Rate of the body is given by:

$$\varphi = \varphi_{act} + \varphi_{shiv} \quad W.m^{-2} \tag{60}$$

$$\varphi_{shiv} = 19.4 \times (-SIG_c) \times (-SIG_{sk}) \quad W.m^{-2} \tag{61}$$

Where φs_{hiv} is the metabolic heat produced due to shivering and φ_{act} is the metabolic heat produced by the body activity.

The model has a heat flow term describing the heat transfer between the internal core compartment and the outer skin shell (Doherty and Arens 1988). Given by:

$$\varphi_{cr,sk} = (5.28 + 1.163SKBF)(T_c - T_{sk}) \quad W.m^{-2} \tag{62}$$

Thus, the model uses empirical expressions to predict thermal sensation (TSENS) and thermal discomfort. These indices are based on 11-point numerical scales, where positive values represent the warm side of neutral sensation or comfort, and negative values represent the cool side. TSENS is based on the same scale as PMV, but with extra terms for ±4 (very hot/cold) and ±5 (intolerably hot/cold). Recognizing the same positive/negative convention for warm/cold discomfort TSENS is defined in terms of deviations of mean body temperature tb from cold and hot set points representing the lower and upper limits for the zone of evaporative regulation.

The values of these set points depend on the net rate of internal heat production and are calculated by

$$T_{b,c} = \frac{0.185}{58.2}(\varphi - W) + 36.313 \tag{63}$$

$$\varphi T_{b,h} = \frac{0.359}{58.2}(\varphi - W) + 36.664 \tag{64}$$

$$TSENS_c = 0.68175(T_b - T_{b,c}) \qquad T_b \leq T_{b,c} \tag{65}$$

$$TSENS_h = \frac{4.7(T_b - T_{b,c})}{(T_{b,h} - T_{b,c})} \qquad T_b > T_{b,c} \tag{66}$$

Nevertheless, Gagge model had more physiological parameters such as blood flow rate, tissue conductance etc. instead of engineering parameters. Hence the fanger's model was more acceptable for engineering evaluations than the pierce two-node model. Figure 48 below shows the analysis of the pierce two-node model.

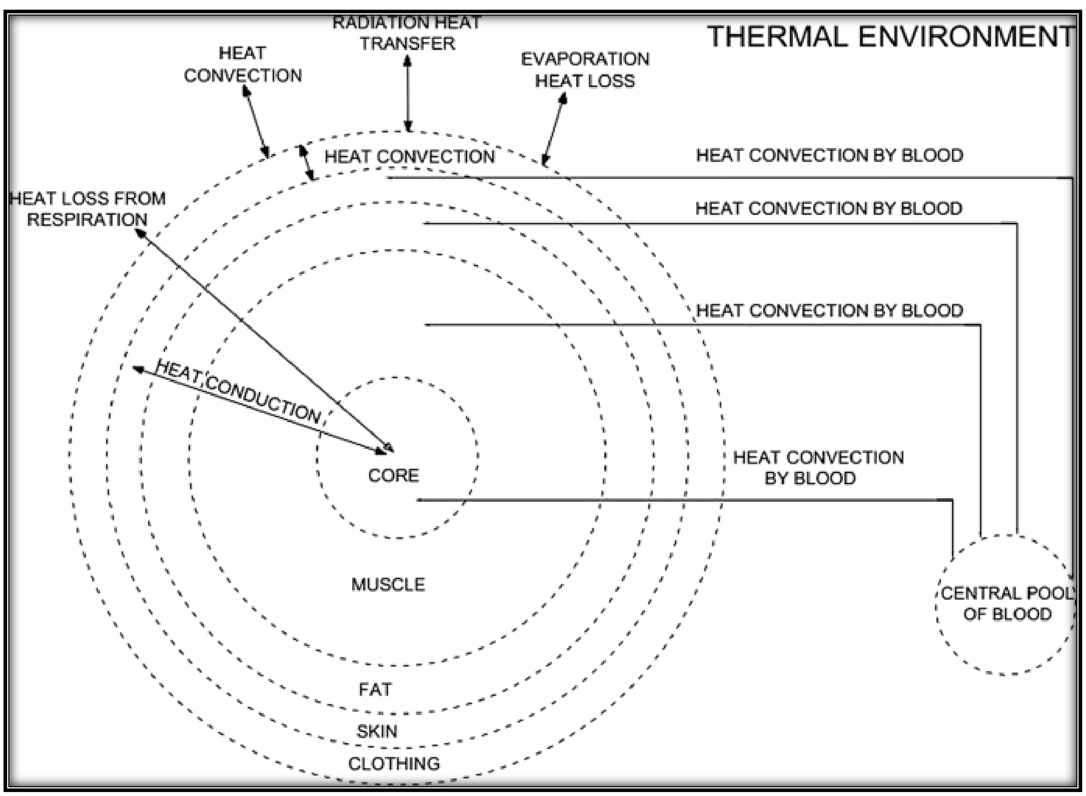


Figure 48: Components of pierce 2-node model

New standard effective temperature (SET*)

Gagge (1967) presents the New Standard Effective Temperature (SET*), defining it as the air temperature in which, in a given reference environment, the person have the same skin temperature (T_{sk}) and wettedness (w) equal to that in the real environment. Therefore the reference and the real environments are equivalent in physiological strain and thermal comfort. Thus, the SET* is "the temperature of an imaginary environment at 50% relative humidity, <0.1 m/s average air speed, and mean radiant temperature equal to average air temperature, in which total heat loss from the skin of an imaginary occupant with an activity level of 1.2 met and a clothing level of 0.6 clo is the same as that from a person in the actual environment, with actual clothing and activity level" (ASHRAE, 2013). This is based on the work of Gagge et al., 1986. The reference environment is defined as: mean radiant temperature (T_{mrt}) = air temperature (T_a); air speed (v_a) = 0.1 m/s; relative humidity (Rh) = 50%; metabolism (M) = 1.2 met; clothes resistance (I_{clo}) = 0.6 clo. The SET* is determined by a two-node-model of human body thermal regulation, as proposed by Gagge et al. (1986), following the steps: (1) determination of T_{sk} and w for a given environment; (2) input of T_{sk} and w (heat loss by sweating) found, solving the equations to find a new air temperature (T_a), considering T_{mrt}=t_a; v=0.15 m/s; Rh=0.5; M=1.2 met; I_{clo} = 0.6 clo; (3) the new T_a found is the SET*.

The SET* is applicable to dynamic conditions (Du et al., 2020), and predicts the thermal quantities of the body, e.g., the skin temperature and skin wettedness. It has been widely used for indoor thermal comfort evaluation in air-conditioned buildings (Nguyenet et al., 2012) and naturally-ventilated buildings, for the sleeping scenario (Omrani et al., 2017), sedentary scenario (Li et al., 2018) and transient scenario (Yu et al., 2016). Besides the indoor environment, the SET* has also been applied to the semi-enclosed space (He et al., 2010) and the outdoor environment (Fang et al., 2019). SET* have the capability to predict the skin temperature and skin wettedness, therefore it is recommended because it includes the effects of the relative humidity (Li et al., 2017) and air velocity in thermal comfort evaluation (Takasu et al., 2017). SET* is linearly related to average body temperature in the thermal equilibrium. Thus:

Between 23°C and 41°C:

$$SET = 34.95\ T_b - 1247.6 \tag{67}$$

Below 23°C:

$$SET = 23 - 6.13\,(36.4 - T_b)^{0.7} \quad (68)$$

Above 41°C:

$$SET = 41 + 5.58\,(T_b - 36.9)^{0.87} \quad (69)$$

T_b is the Body average temperature at thermal equilibrium. Table 11 below is the scale of SET*. It explains the thermal comfort sensation and the physiology of occupant (Auliciems and Szokolay, 2007).

Table 11: New standard effective temperature (SET*) scale

SET (°C)	**T_b (°C)**	**Sensation**	**Physiology**
37.5–44	36.77–37.4	Very hot, great discomfort	evaporative regulation disrupted
34.5–37.5	36.68–36.77	Hot, very unacceptable	Profuse sweating
30–34.5	36.55–36.68	warm, uncomfortable, unacceptable	sweating
25.6–30	36.44–36.55	slightly warm, slightly unacceptable	Slight sweat, vasodilation
22.2–25.6	36.27–36.44	Comfortable, acceptable	thermal neutrality
17.5–22.2	34.63–36.27	slightly cool, slightly unacceptable	Initial vasoconstriction

The heat balance equations are valid for the SET* but at a uniform predefined thermal conditions as stated above therefore, the results are equivalent temperatures and not the thermal sensation of occupants.

Heat stress index (HSI)

Belding & Hatch 1955 propose the Heat Stress Index. Considering the thermal balance model, they make four physiological suppositions: (1) the heat load in the body is equal to required evaporative sweat: $E_{rsw} = \varphi + R + C$; (2) the physiological strain is determined by the relation E_{rsw} / E_{max}; (3) the skin temperature is constant during the thermal stress: $t_{sk} = 35°C$; (4) the maximum sweat rate during an eight hour period is 1L/h, that is equivalent to 390 W/m^2 for a male, 75 kg, 1.70m. They propose the following equations for estimating the heat storage:

$$E_{rsw} = \varphi + 22 \cdot (T_{mrt} - T_{sk}) + 2 \cdot v^{0.5} \cdot (T_a - T_{sk}) \quad (70)$$

$$E_{max} = 10 \cdot v^{0.4} \cdot (p_{sk} - p_a) \quad (71)$$

Where: $[22 \cdot (t_{rm} - t_{sk})]$ = radiation loads, in Btu/h; t_{rm} = mean radiant temperature, in ºF; t_{sk} = superficial skin temperature, in ºF; $[2 \cdot v^{0.5} \cdot (t_a - t_{sk})]$ = convection loads, in Btu/h; t_a = air temperature, in ºF; v = air speed, in ft/min; E_{rsw} = required evaporative sweat, in Btu/h; E_{max} = maximum evaporative capacity, in Btu/h; P_{sk} = skin vapor pressure, in mmHg; P_a = air vapor pressure, in mmHg

$$HSI = (E_{rsw}/E_{max}) \cdot 100 \text{ or } HSI = (E_{rsw}/632.27) \cdot 100 \quad (72)$$

This index is valid when: T_a = 21-49 ºC; P_a: (22.5-315.0 kP_a); v: 0.25-10.0 m/s and φ: 86-430 W.

Table 12 shows the Heat Stress Index (HSI), (Belding & Hatch, 1955; Givoni, 1969 and Parsons, 1993)

Table 12: Heat stress index (HSI) scale

HSI	INTERPRETATION
0 – 10	no thermal stress (thermal comfort)
10 – 30	light response, intellectual work decrease as well as heavy mechanical work efficiency
40 – 60	several response, danger to non-acclimatized people, mechanical work efficiency decrease
70 – 90	very several response, just little percentage of people support to work under such conditions
90 – 100	maximum response tolerated daily by acclimatized and adapted young man
100 – 200	heat storage (thermal stress)

The heat stress index is mainly effective in warm temperature and at high activity level where sweating, diffusion and evaporation occur on the skin surface. It assumes that the total heat loss or gain by the body is proportional to the evaporative heat losses. Therefore at cold temperature the HSI may not be effective.

Munich energy-balance model for individuals (MEMI)

Höppe (1999) proposes the Munich Energy-Balance Model for Individuals, based in some parameters of Gagge (1967) two node model. The MEMI differs from Gagge model in the way it calculates the regulatory sweat and heat fluxes. It considers separately the temperature of clothed parts of the body and unclothed ones. The equations below shows the thermal balance, the heat flux from the core of the body to skin surface ($F_{c\text{-}sk}$), the heat flux from skin surface to external cloth surface ($F_{sk\text{-}cl}$) respectively. By solving these three equations, the clothing surface temperature (t_{cl}), the skin temperature (t_{sk}) and the core body temperature (t_c) can be evaluated:

$$M - W + R + C + Q_{res} - E_{dif} - E_{rsw} = 0$$

$$F_{c\text{-}sk} = v_b \cdot \rho_b \cdot c_b \cdot (t_c - t_{sk}) \qquad (73)$$

$$F_{sk\text{-}cl} = (t_{sk} - t_{cl}) / I_{cl} \quad (74)$$

Where: v_b = blood flux from core to skin, in l/s·m^2; ρ_b = blood density, in kg/l; c_b = blood specific heat, I_{cl} = Clothing resistance, in W·s/K·kg; all heat fluxes in W/m^2

Physiological equivalent temperature (PET)

Höppe (1999) defines the Physiological Equivalent Temperature of a given environment as the equivalent air temperature, in a reference environment, where the thermal balance between the skin and core temperatures are the same as that found in the given or non-uniform environment. The reference environment is defined as: mean radiant temperature (T_{mrt}) = air temperature (T_a); air speed (v_a) = 0.1 m/s; vapor pressure (p_v) = 12 hPa (relative humidity (Rh) = 50% at t_a=20 °C); metabolism (M) = 114W; clothes resistance (I_{clo}) = 0.9 clo. The PET is found as follows: (1) determination of T_{sk} and T_c for a given environment, using MEMI; (2) input T_{sk} and T_c found from the (MEMI) equations into the heat balance equations to find a new air temperature (t_a). The reference parameters includes; t_{mrt} = t_a; v = 0.1 m/s; P_a=12 hPa; M=114W; I_{clo} = 0.9 clo; (3) the new t_a calculated is the PET.

The strength of this index is that it uses the common climate parameters as air temperature, humidity, wind speed, and long and short wave fluxes.). Therefore, it is suitable for both indoor and outdoor environment evaluations. Also PET is suitable for assessing thermal stress in different climatic conditions, because it depends on the human energy equilibrium (Höppe, 1999). Table 13 below is the list of the equivalent temperatures and their corresponding thermal perception based on the PET index.

Table 13: Physiological Equivalent temperature (PET) scale

PET	Thermal perception	Grade of physiological stress
4°C - 8°C	Very cold	Extreme cold stress
8°C - 13°C	Cold Strong	cold stress
13°C -18°C	Cool Moderate	cold stress
18°C - 23°C	Slightly cool	Slight cold stress
23°C-29°C	Comfortable	No thermal stress
29°C - 35°C	Slightly warm	Slight heat stress
35°C - 41°C	Hot Strong	heat stress
41°C above	Very hot	Extreme heat stress

G. Evolution of adaptive comfort standards by international organizations

The details of the evolution of adaptive thermal comfort standards and evaluation by the international organizations are comprehensively explained below.

ASHRAE Standard 55: ASHRAE RP-884 project

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. In 1995, ASHRAE RP-884 began by collecting raw field data from various projects around the world that had followed standardized protocol where the data met strict requirements regarding measurement techniques, type of data collected, and database structure. The RP- 884 database contains approximately 21,000 sets of raw data from 160 different office buildings located on four continents, and covering a broad spectrum of climate zones. The locations selected for the database include Bangkok, Indonesia, Singapore, Athens, Michigan, several locations in California, England, and Wales, six cities in Australia (Darwin, Townsville, Brisbane, Sydney, Melbourne, Kalgoorlie) and five cities in Pakistan (Karachi, Quettar, Multan, Peshawa, Saidu). The data includes a full range of thermal questionnaire responses, clothing and metabolic estimates, concurrent indoor climate measurements, a variety of calculated thermal indices, and concurrent outdoor meteorological observations. The buildings in the database were separated into those that had centrally-controlled heating, ventilating, and air-conditioning systems (HVAC), and naturally ventilated buildings (NV). (de Dear & Brager, 2002).

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 then the subsequent revision of the Standard thereafter (ASHRAE, 2004, 2010, 2013, 2017).

The purpose of the adaptive component of ASHRAE, is ‘‘to specify the combinations of indoor thermal environment and personal factors that will produce thermal environmental conditions acceptable to 80% or more of the occupants within a space’’ (ASHRAE Standard 55, 1992). While ‘‘acceptability’’ was not really defined by the standard, it is commonly agreed within the thermal comfort research community that ‘‘acceptable’’ is synonymous with ‘‘satisfaction’’. Also ‘‘satisfaction’’ is associated with the thermal sensations of ‘‘slightly warm’’, ‘‘neutral’’, and ‘‘slightly cool’’. In adaptive comfort, the theory of thermal perception states that factors beyond fundamental physics and physiology plays an important role in occupants’ expectations and thermal preferences. Thermal sensations, satisfaction, and acceptability are all influenced by the match between one’s expectations about the indoor climate in a particular context, and what actually exists (Fountain et. al., 1996).

Figure 49 below shows some of the findings of the separate analysis of HVAC and NV buildings, respectively. The graphs represent a regression of indoor comfort temperature against mean outdoor air temperature recorded for the duration of study of the building. Two strong patterns emerge from these graphs. First, the steeper gradient of observed (OBS) responses in NV buildings (Figure 49b) compared to HVAC buildings (Figure 49a) suggests that occupants of HVAC buildings become more finely adapted to the narrow, constant conditions typically provided by mechanical conditioning. While occupants of NV buildings prefer a wider range of conditions that closely reflects changes in the outdoor climate patterns. Therefore in the HVAC buildings, PMV was remarkably successful at predicting comfort temperatures.

The difference between the PMV-based predictions and the adaptive model (fitted OBS) shows that, the behavioral adjustments accounted for only half of the difference. This suggests that psychological adaptation is likely the explanation for the other half of this difference. Therefore it was hypothesize that indoor comfort temperatures in NV buildings are strongly influenced by the adjustment due to thermal expectations. However these thermal expectations are the result of the combination of the perceived control and thermal experiences of the occupants.

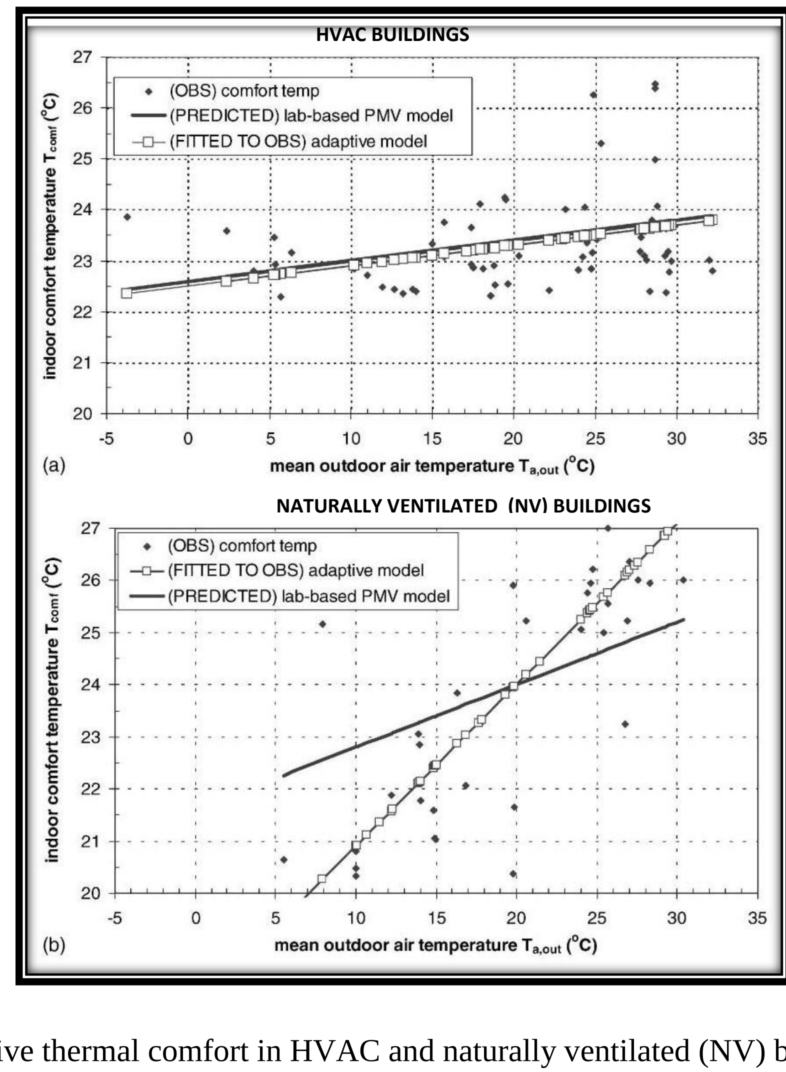
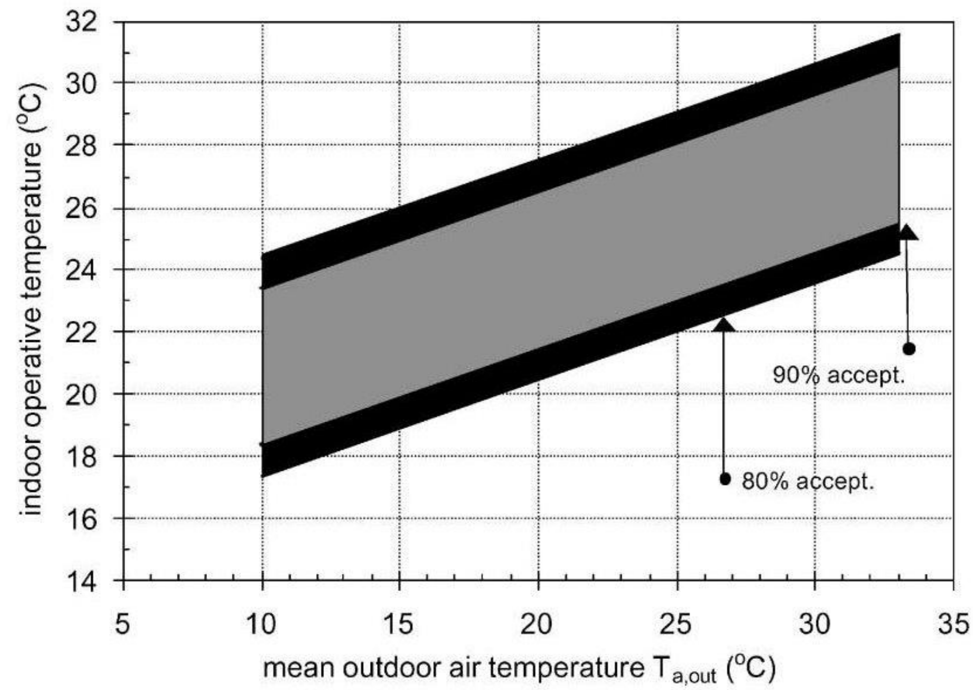


Figure 49: Adaptive thermal comfort in HVAC and naturally ventilated (NV) buildings

The adaptive model findings depicted in Figure 49b led to the Adaptive Comfort Standard ACS in ASHRAE Standard 55 for naturally ventilated buildings. The ACS predicts the Optimum comfort temperature, T_{comf}, based on the regression shown in Figure 49b:

$$T_{comf} = 0.31T_{a,out} + 17.8 \quad (75)$$

However, the range of temperatures around T_{comf} corresponding with 90% and 80% thermal acceptability was derived to be ±0.5 and ±0.85 of the thermal sensational votes respectively. It was derived via a regression model of thermal sensation votes and indoor operative temperature. Also, arithmetically averaging the comfort zone widths across all the NV buildings, a mean comfort zone band of 5 ^{0}C for 90% acceptability, and 7 ^{0}C for 80% acceptability, both centered on the optimum comfort temperatures was generated. The resulting 90 and 80% acceptability limits are shown in Figure 50.



Proposed adaptive comfort standard (ACS) for ASHRAE Standard 55, applicable for naturally ventilated buildings.

Figure 50: Comfort zone in naturally ventilated building for ASHREA 55 standard

Figure 51 a and b shows the operative temperatures and thermal sensations from each of the NV buildings in the RP-884 database, as a function of the mean outdoor air temperature. The patterns shows that below mean outdoor temperatures of 23^{0}C, the NV buildings were primarily operating within the limits of the ACS, with the mean thermal sensations primarily within ±0.5. However above mean outdoor temperatures of 33°C, the interior temperatures raised above the ACS limits. Therefore it was decided that the temperature threshold of applicability of this adaptive Model is within the outdoor temperature range of 10-33°C based on measured available data. Hence outdoor Temperature above 33°C is not applicable.

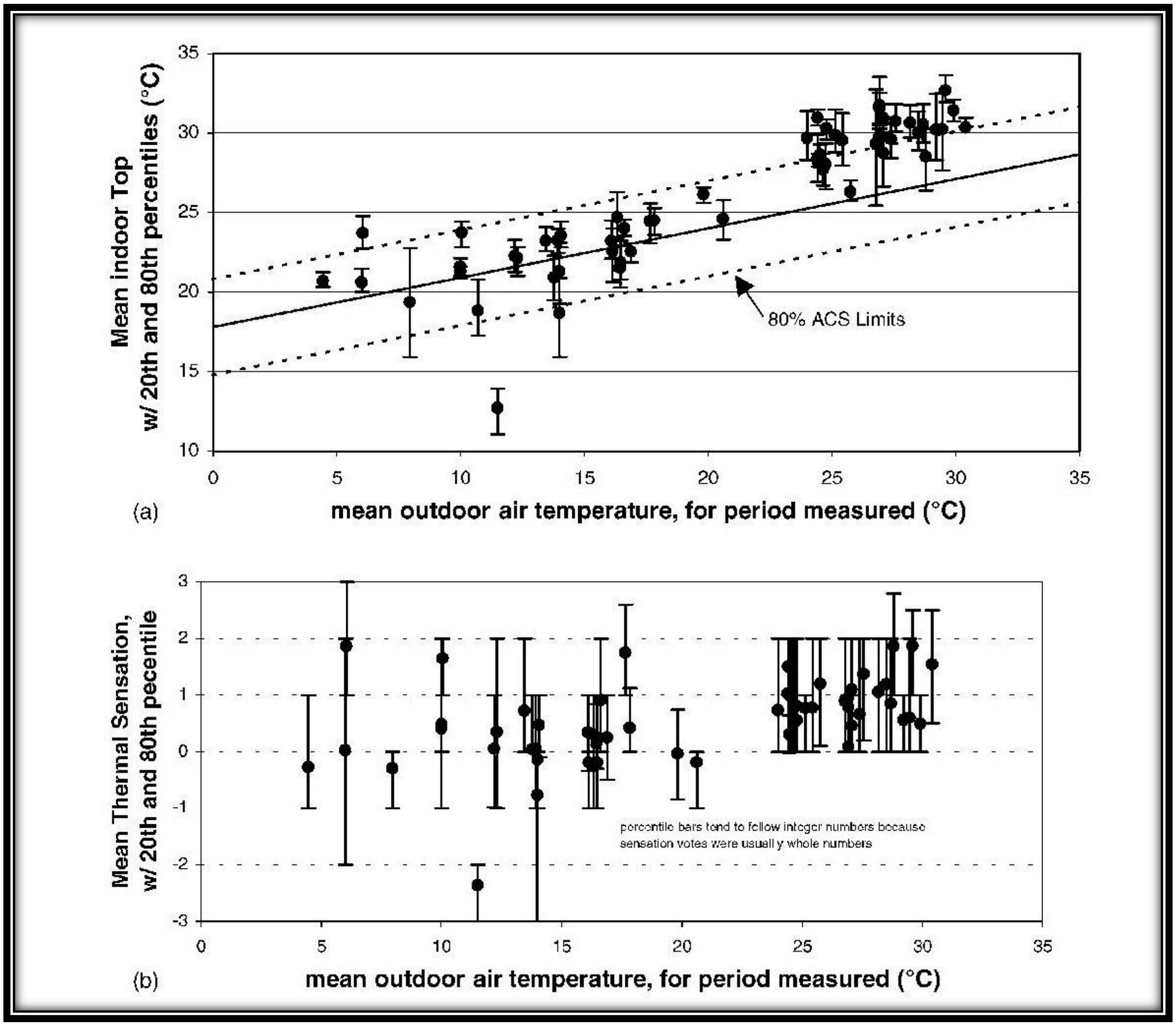


Figure 51: Comfort zone in NV building based on outdoor temperature and indoor operative temperature

CEN/EN 15251: Smart controls and thermal comfort (SCATs) project

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. This is to address the 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 (Humphreys et al., 2016; Nicol et al., 2012). CEN/EN 15251 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 the criteria for indoor air quality, thermal environment, lighting and acoustics, which may have significant influence on the energy demand of a building (CEN, 2007). The values of the acceptable indoor operative temperature are defined according to the comfort equation below.

$$T_{comf} = 0.33T_{out,m} + 18.8 \tag{76}$$

Where T_{comf} is the comfort temperature, $T_{out,m}$ is the exponentially weighted running mean of the outdoor temperature.

ISO 7730

ISO 7730 (Ergonomics of the thermal environment) enables the analytical determination and interpretation of thermal comfort using calculation of PMV (predicted mean vote), PPD (predicted percentage of dissatisfied) and local thermal comfort criteria. It considers the environmental conditions deemed 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 developed in parallel with ASHRAE standard 55. The standard has a list of measured values of the thermal insulation of various clothing items and ensembles; and the list of typical values for the metabolic rates of different activities. The standard categorizes buildings according to the range of PMV that should occur within them. As shown in the Table below.

Table 14: Categories of thermal comfort in buildings (ISO 7730)

Category	Explanation	PPD%	Limitation for PMV
I	High level of expectation, recommended for spaces occupied by very sensitive and fragile person with special requirements such as Handicaps, sick, elderly, babies	< 6	$-0.2 < \text{PMV} < +0.2$
II	Normal level of expectation, should be used for new buildings and renovations	< 10	$-0.5 < \text{PMV} < 0.5$
III	An acceptable moderate level of expectation and may be used for existing building	< 15	$-0.7 < \text{PMV} < +0.7$

H. Other psychological adaptive models

The concept of relative influence of the psychological parameters

According to Nikolopoulou et al., 2003, the evaluation of psychological adaptation can be done by assessing the relative impact of the different parameters involved in thermal perception. This includes past experience and expectation, perceived control and environmental stimulation etc. Hence, understanding the interrelationship between the different parameters of psychological adaptation would enable us to compare their relative significance and influence on each other. It may also aid in evaluating the resultant effect of psychological adaptation on the perception of the occupants.

Figure 52 below depicts the network of the different parameters affecting psychological adaptation with lines of influence between them by indicating how one parameter affects the other. Some parameters have a two-way relationship, such as between perceived control and expectations. These lines are not weight related and there is no magnitude associated with the strength of relationship. Hence it only denotes that a relationship exists between them. These lines of inter-relationship have developed the insights into other thermal psychological researches.

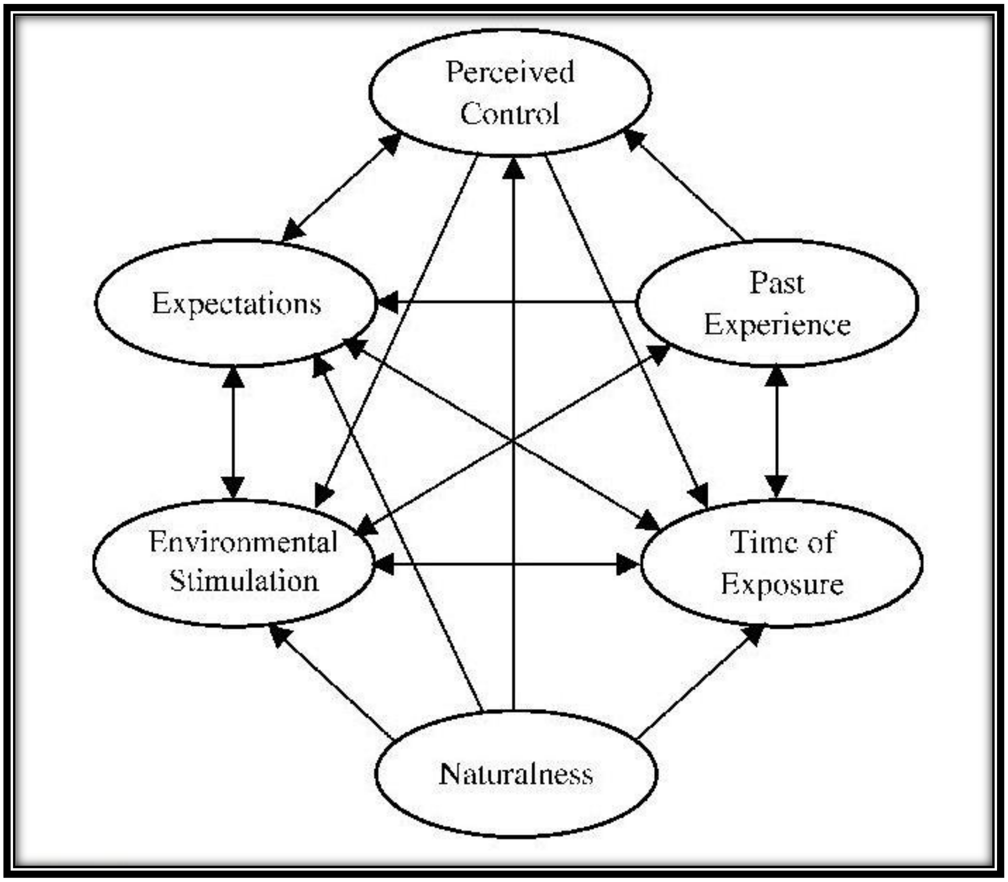


Figure 52: Lines of influence between the different parameters of psychological adaptation (Nikolopoulou et al., 2003)

Furthermore, the speculative relationships among these parameters are summarized in Figure 53 below. It indicates the degree at which one variable influences, and is being influenced by another. It is interesting to notice that expectations, environmental stimulation and time of exposure can be seen to be affected by every variable in the group. These three variables that are influenced by all other parameters of psychological adaptation were grouped together so that we can denote the interrelations between each group of psychological factors.

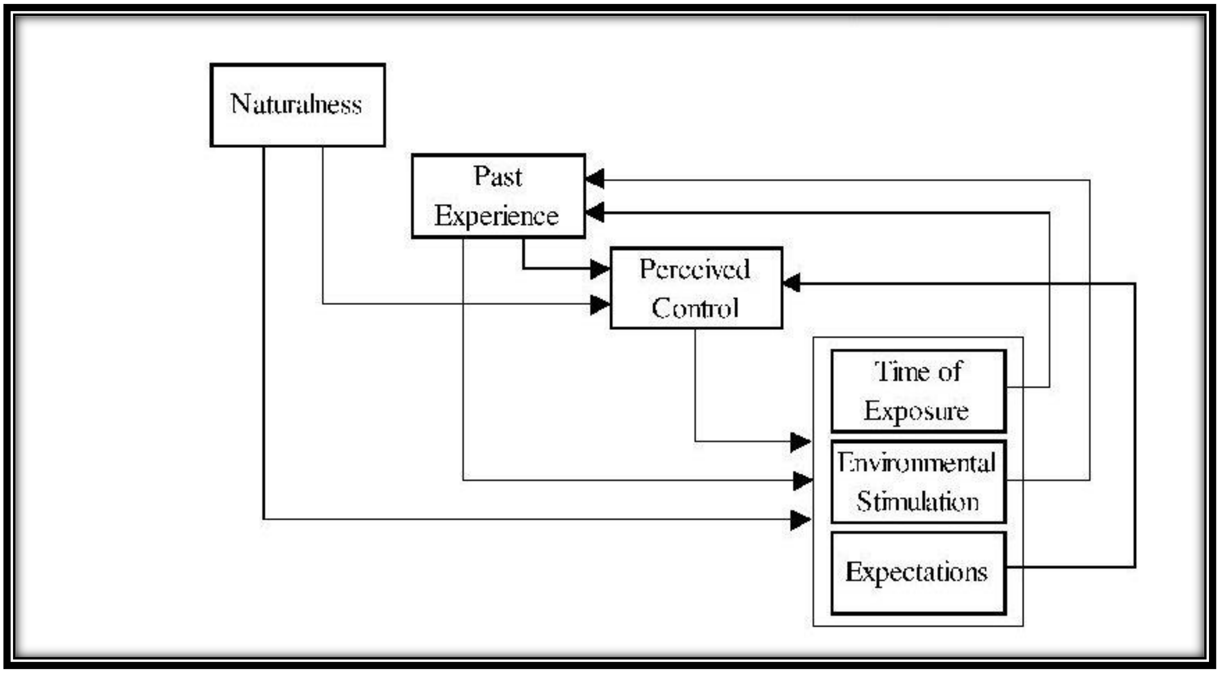


Figure 53: Network of interrelationships between the parameters of psychological adaptation. (Nikolopoulou et al. 2003)

Concept of place, moderator and human response

According to Knez et al., 2009 the human memory comprises of two basic stores, a short-term memory and a long-term memory. The Short-term have a very limited capacity where the sensory data is cognitively identified, named and held for about 12 s. The short-term memory is the psychological "now" where any distraction of coding, storing, and recalling of the ongoing information and incoming sensory information happens, as well as causing the forgetting. The long-term memory is virtually unlimited, holding information for over extremely long periods of time. This is referred to as the psychological "past" that gives us the meaning of the world, because this is the store where all our experiences and knowledge (from facts to personal related events) are stored. The long-term memory is organized into several different memory systems and storing. These include the declarative information (factual knowledge and experiences) and procedural information (know-how skills such as how to ride bicycle). The declarative parts of the long-term memory contain different organizing structures such as schemata or schema. These are packets of information and mental representations about different events, such as how to behave when playing football, attending a conference, or eating at a restaurant etc. Schema may affect our processes of perception and comprehension (Bartlett 1932; Piaget and Inhelder 1973; Minsky 1975) because it serves both as a guide for action and as a framework for interpreting the world. Brewer and Treyens (1981) suggested that schemata might affect encoding, storing, and retrieving information in the memory of places. Knez and Thorsson (2006, 2008) showed that both collectivistic attitudes of the Japanese culture can impose different environmental attitudes upon their citizens, and the individualistic environmental attitude such as finding pleasure in nature, can affect the perceptual and emotional estimations of a space.

Figure 54 below shows a model of direct and indirect influence of place-related parameters on human responses. This conceptualization involves three main organizing entities, namely: (1) place, (2) moderator/mediator and (3) human response.

Place

Place is used instead of space (Eliasson et al. 2007) because the concept of space implies only physical and spatial connotations while the notion of place includes the psychological and social aspects of the space experiences (Canter 1997; Graumann 2002). The experience of place evolves out of transactions between the personal and cognitive-emotional system that a person brings to any settings. It is also the socially structured patterns of actions that occur within the settings, depending on the culture in which the transactions occur. (Canter 1997).

Place entails: (1) physical base, (2) weather and (3) function. Physical base comprises form (structure, openness), material, naturalness, and location (space dimension). Weather includes meteorological parameters such as temperature, radiation (long-wave and short-wave radiation), air speed, and humidity. Function is divided into physical activity (standing, sitting, lying, walking, running, etc.) and social activity (talking, playing, associating, etc.).

Moderators and mediators

Moderators and mediators are variables including personal factors that interact with place parameters, to influence human thermal sensational responses (Evans and Lepore 1997). Moderators are independent variables which interact with a place variable and some personal factors to affect human response. While mediators on the other hand, are factors that intervene between independent (Moderators) and dependent variable (other mediators). (Evans & Lepore 1997; Baron & Kenny 1986). In Figure 54 below there are three types of moderators/mediators:

(1) Culture (rules, norms, values); (2) Person (knowledge/ experience, attitude/expectation, belief/preference, perceived control), demographic variables (age, gender, education, etc), biological base (e.g., metabolic rate), physical and social activity (function of the Place and Personal related activities); (3) Situation (length of exposure, momentary clothing).

Culture is "The system of information that codes the manner in which people in an organized group, society or nation interact with their social and physical environment." (Reber, 1985). It eventually becomes the standards for perceiving, believing, evaluating, communicating, and acting among those who share a language, a historic period, and/or a geographic location." (Eisler et al., 2003).

Person refers to the declarative parts of an individual's long-term memory where all kinds of knowledge, experiences and skills are stored and organized, and the person's demographic variables, such as age, gender, education, etc.

Human response consist of sensation (sensory unconscious detection of environmental stimulation/information); Perception (conscious interpretation and elaboration of sensory data), Cognition (how we learn, remember, and think about information); Emotion (states, processes, and expressions that convey qualities of affect, feeling, and mood); Adaptation (a reduction in the responsiveness of a receptor as a result of repeated stimulation); Coping (strategic ways for dealing with, for example, place-related stimulation); and Behaviors (activities, doings, action, reactions, movements).

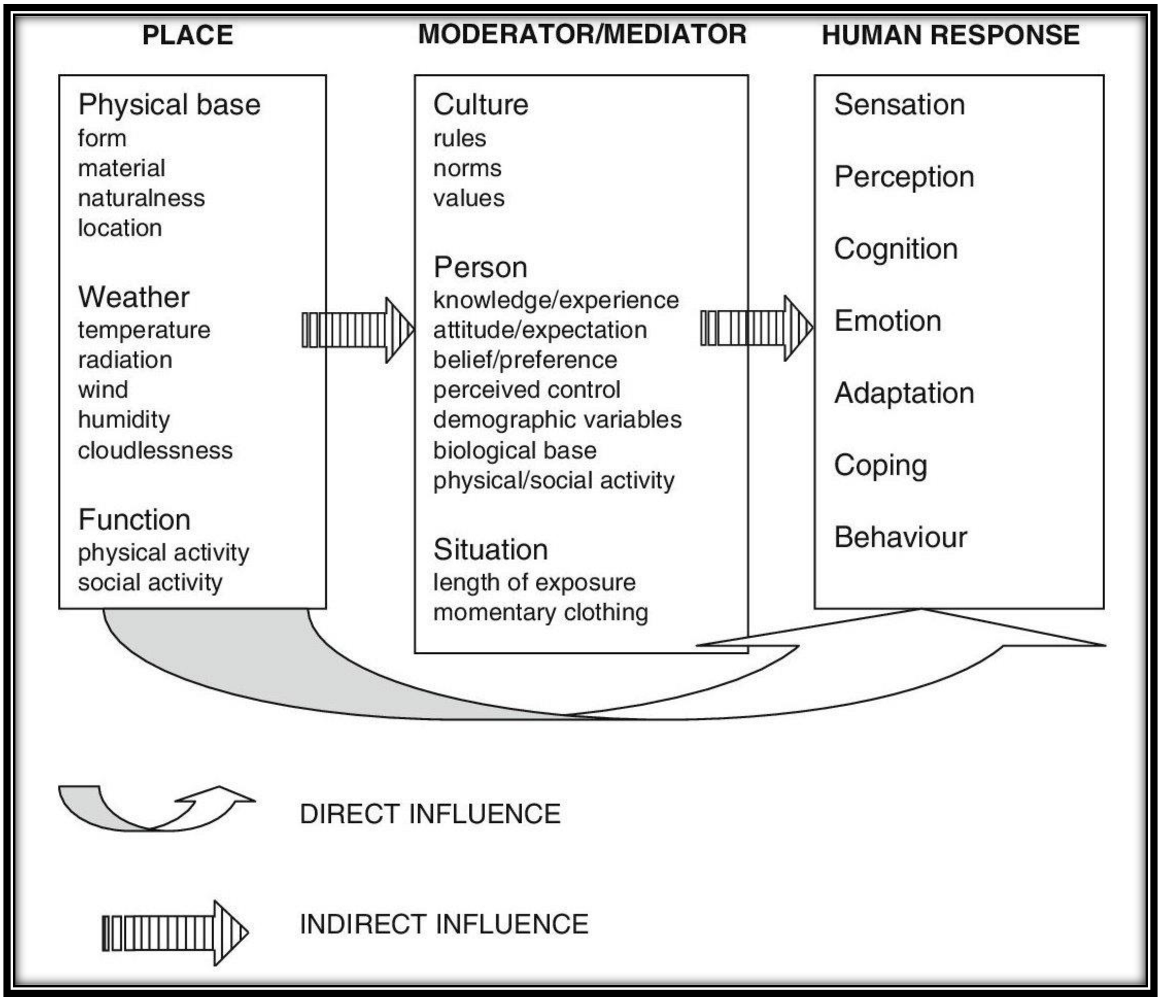


Figure 54: Proposed direct and indirect (via moderator/ mediator) influences of a place on a person's human response (Knez et al., 2009)

I. The concept of schema

An important ingredient in the evaluation of thermal perception is the schema, because people perceive the environment in different ways, and the human response to a physical stimulus is not in direct relationship to its magnitude, but depends on the “information” that people have for a particular situation (Nikolopolou et al., 2003). Schema serves as the tools that people use to extract the maximal useful “information” from an environment using the least amount of effort (Rosch, 1978). Therefore a proper calibration of the “information” in a person’s memory, his physical thermal conditions and his physiological thermal processes will give a more accurate evaluation of thermal perception and comfort. Hence the study and evaluation of schema will be a major route in quantifying psychological “information” and comportment.

Schema refers to the cognitive structures used by individuals to encode and represent incoming information efficiently (Markus, 1977). They are mental maps (Weick, 1979) that enable individuals to orient themselves within their experiential terrain such that they make individual sense-making possible. Weick (1979) defined schema is an abridged, generalized, corrigible organization of experience that serves as an initial frame of reference for action and perception. It is the cognitive structure that represents the organized knowledge about a given stimulus—that is, a person or situation—as well as rules that directs information processing. It therefore provides observers with a knowledge base that serves as a guide for the interpretation of information, actions, and expectations. Schemas help people simplify and effectively manage information in complex task and social characteristic settings (Lord et al., 1986). They are stable organizations of knowledge that integrate and summarize an array of information and experience (Markus & Sentis 1982); because they integrate and summarize a person’s thoughts, feelings, and experiences in a specific behavioral domain (Karen, 1995).

The quantity and variety of stimulation available at any time is vastly greater than a person can process or even attend to. Therefore, individuals are necessarily selective in what they notice, learn, remember, or infer in any situation. Schema functions as selective mechanisms which determine whether information is attended to, how it is structured, how much importance is attached to it, and what happens to it subsequently.

Some Studies have shown that people are more likely to direct their attention to information that is consistent with an established schema, so that they can process information more quickly, and have greater recall for schema-consistent versus schema-irrelevant information (Bargh, 1982; Kuiper & Rogers 1979; Markus, 1977; Rogers, Kuiper, & Kirker 1977). As individuals accumulate repeated experiences of a certain type, their schema becomes increasingly resistant to inconsistent or contradictory information. They represent patterns of behavior that have been observed repeatedly, to the point where a framework is generated that allows one to make inferences from limited information or to quickly streamline and interpret complex sequences of events. Schema is an organization of the representations of past behavior, it is more than a "depository" entity; It serves an important processing function and allows an individual to go beyond the information currently available. The concept of schema implies that information about oneself in some area has been categorized or organized and the result of this organization is a discernible pattern which may be used as a basis for future judgments, decisions, inferences, or predictions about oneself (Markus, 1977).

Consistency in patterns of response to a particular stimulus should provide evidence for the existence of an organization of knowledge on a particular dimension of behavior, or schema; therefore individuals that do not possess an articulated schema on a particular dimension of behavior, will not exhibit consistency in response. Hence, the role of schema in processing information can be examined by linking schema to a number of specific stimulus and references that facilitates the processing of information about the behavior and decisions of people. This will provides easily retrievable behavioral evidence and basis for the prediction of behavior on schema-related dimensions. Therefore schema can be analyzed through the functions of cognitive structures, by making use of a variety of measures including recognition, recall, response latency, etc. Techniques such as signal detection, chronometric descriptions of information flow may also be useful. If a person has a developed schema, he should be readily able to;

a. Process information in the given domain with relative ease

b. Retrieve behavioral evidence from the domain

c. Predict his own future behavior in the domain

d. Resist counter-schematic information about himself

The above requirements are necessary for determining the characteristics of some specific element of schema in an individual. It is also applicable in determining the intensity or weight of the schema that are being examined. Therefore it is essential to understand some intrinsic characteristic or nature of schema so that they can be easily identified and possibly evaluated.

Nature and characteristics of schema

The context-specific nature of schemas

Schemas are context-specific. We have different cognitive structures for different domains of experience. Context is embedded in events, or "scripts"; this refers to knowledge concerning expected event sequences and appropriate behavior in specific situations (Gioia & Manz 1985; Gioia & Poole 1984; Lord & Foti 1986; Lord & Kernan 1987; Martin, 1982).

Schemas and semantic networks

Schemas are generic knowledge structures that help people interpret the world around them (Fiske & Taylor 1991; Piaget 1976; Rumelhart 1980; Rumelhart 1998; Rumelhart et al., 1986). The more elements of a schema that we observe, the more likely that schema will be activated (Rumelhart et al., 1986). The fewer the elements relevant to a schema that is observed, or the less prototypical the elements are, the less likely the schema will be activated. A prototype is the standard conceptualization of a particular phenomenon (Rosch, 1973; Rosch, 1978). The closer an element, event or stimulus is to its corresponding prototype, the more will be the input variables that would be present to the affiliated schema. Hence the schema is more likely to be activated (Rosch et al., 1976).

Often times, objects, people, and events can be viewed through multiple schematic lenses, and which lens one opts for will shift one‘s interpretation of future stimuli (Crocker et al., 1984). according to the connectionist underpinnings of schema theory (McClelland et al. 1986; Rumelhart et al., 1986), individual scripts and schema structures do not exist in isolation. They are inherently linked to each other to varying degrees, and the activation of one influences the activation of another. The entirety of one‘s interconnected schemata is termed a semantic or associative network (Collins & Loftus 1975; Collins & Quillian 1969; Woods 1975). A semantic network is a model of conceptual interconnectivity, with each individual schema serving as a node, and the relationships between the schemas, produces a link of varying strengths. The interconnected nature of schema structures and the semantic networks in which they are embedded influences both perception and behavior. Hence, when one schema is activated, other schemata with which it is associated to are simultaneously primed for activation (Lerner et al., 2012). This process is known as spreading activation (Collins & Loftus 1975).

Schema sharedness and scripts

The phenomenon of "sharedness," is emphasized in most definitions of organizational culture, which allows us to move from the individual level of sense-making to the group-level dynamics of culture, in which individuals come to similar understandings of similar circumstances. Meaning that social interaction and shared experiences drive people within a culture to construct certain schemata in similar and converging manners (Casson, 1983; D'Andrade, 1981; Strauss & Quinn, 1997). This is because when people identify with a group, they behave in accordance with the demands of that group because they don't want to risk losing their association with the group. Therefore schema structures that are shared within a culture are more resistant to change, as they are continually reinforced through social interaction (Strauss & Quinn, 1997). Hence it is necessary to know if a schema is shared or not, because it determines the strength and weight of the schema and its corresponding comportments.

A script can be seen as a sequence of actions in which a person could, and typically does engage in. Therefore it is the schema for an event with varying levels of specificity (Abelson 1981; Schank & Abelson, 1977). Most social norms are also grounded in scripts (Bicchieri, 2006). A script can be some empirical expectations, which inform us of what people usually do and expect us to do. Also it can be some the normative expectations, which inform us of what people think that we should do. When the empirical and normative expectations are present in the same script and the same situation, then a sequence of typical actions could occur. These kind of behaviors can be explained in the comportment of people in different part of the world wearing different clothing ensembles irrespective of their environmental and physical conditions.

Script and schema change

Researches on schema has emphasized schemata's ability to assimilate schema-discrepant information and resist change (Brown, 2011; Crocker et al. 1984; Hilton & von Hippel 1996). However Piaget (1976) believed that people strive to maintain equilibrium between the outside world and the internal mental systems, through which they process the world. When the perceived stimuli and the existing schemata do not match perfectly, there are two ways to resolve the conflict; (1) assimilation, (2) accommodation. As we accumulate new experiences, some of which defy our schematic interpretations, we either assimilate the new information and cast aside the discrepancies or accommodate it by refining the existing schema and change its boundaries.

Models of schema change

There are several theoretical models of schema change, and there are certain circumstances under which this schema change is more likely to occur than others (Brown 2011; Crocker et al. 1984; Hilton & von Hippel 1996; Hewstone et al. 1992; Poole et al. 1989; Queller & Smith 2002; Rothbart 1981; Weber & Crocker 1983). The most prominent models of schema change are the:

(1) Book-keeping model

(2) The conversion model

(3) The subtyping model (Crocker et al., 1984).

The most intuitive model (based on basic understanding of schemata) is the book-keeping model. It asserts that people continuously update their schemata whenever they encounter discrepant information (Rothbart 1981, Rumelhart & Norman 1976). A few instances of discrepant information will not change one‘s schemata much, but in aggregate, many instances will.

The conversion model of schema change provides a more dramatic alternative to the bookkeeping model. This model asserts that a few highly salient instances of discrepant information will catalyze the process of schema revision (Rothbart, 1981). This means the observation of a few salient schema discrepant instances will trigger a single, sudden revision, instead of many instances of mildly schema-discrepant information.

The subtyping model asserts that the observation of schema-discrepant information will not cause an overall revision of schema but rather induce a new sub-schema that is capable of “explaining” the discrepancy (Hewstone et al., 1992). This new schema will be a specific subcategory of the original schema.

Schema and psychological adaptation

The schema is normally situated in the long-term memory of an individual and it’s an organized system for the storage and processing of vital information. It aids the interpretations of the world around a person so that he can make suitable decision based on the circumstances he perceives.

They can also be referred to as the stored files and archives of cognitive generalizations derived from past experience, that organize and guide the processing of the information contained in an individual (Markus, 1977). Hence, they serve more like a 'tool-box' that people use to extract the maximal useful information from an environment using the least amount of effort (Rosch, 1978). This 'tool box' contained various psychological representations that become activated depending on the stimuli or conditions it finds itself. So that it functions as a selective mechanism which determines whether information is attended to, how it is structured, how much importance is attached to it, and what happens to it subsequently.

Therefore in the psychological adaptive mechanism of a person, the schema being like a 'tool-box' become selective on the tool of schema mechanism that will be active based on the weight of the incoming stimuli and the information deposited in the 'schema box'. In this study, the schema tools are grouped into the (1) perceptive schema (2) behavioral schema and (3) habituation (see Figure 55). The perceptive schemas are psychological generalizations and interpretation of the world around a person experiencing some environmental and physical conditions such that the interpretation and information from his representations depicts that the situation can be mentally organized and adapted to, without any physical behavioral feedback. These schemas can express itself through perceived control, attitudes, philosophies and beliefs. The behavioral schemas interpret the stimuli in its environment with the representations that depicts some behavioral feedbacks due to magnitude of the stimuli and the depository information in his schema. This schema is usually activated when the magnitude of the stimuli is beyond the capacity of the perceptive schema. The behavioral feedbacks are in the form of actions, reactions and in-actions that aim to improve the comfort for the person. This includes mental reasoning leading to clothing or unclothing, cultural and normative ensembles and behaviors, etc. While habituation schemas are psychological adaptive mechanism that engage in the mental 'shut-down' or deadening of the perception from some environmental stimuli that are beyond the person's perceptive and behavioral schema capacity. This includes coping, tolerance, endurance etc.

In the psychological behavior of a person, each type of schema is activated depending on how the schema interprets the magnitude of the incoming stimuli. This interpretation is based on the information the schema has for such stimuli within his mental code and cognitive structure. The schemas can be solely or simultaneously active depending on the thermal conditions and the perceived interpretation by the subjects. However the behavioral schema being centrally functional between the two ends of the perceptive schema and habituation schema, (Figure 55) is adaptively active to regulate the comfort perception of the subjects towards the perceptive schema zone. The perceptive schema zone can be referred to as the most comfortable zone for the subjects when compared with the behavioral and habituation schema zone. It is characterized with perceived control without any behavioral action, reaction or coping. However if the perceived stimuli goes beyond the terrain of the behavioral schema then the habituation schema will be activated to adaptively diminish the perception of the subjects. Thus, the behavioral schema acts more like a regulating schema that keep the subject within the comfort zone.

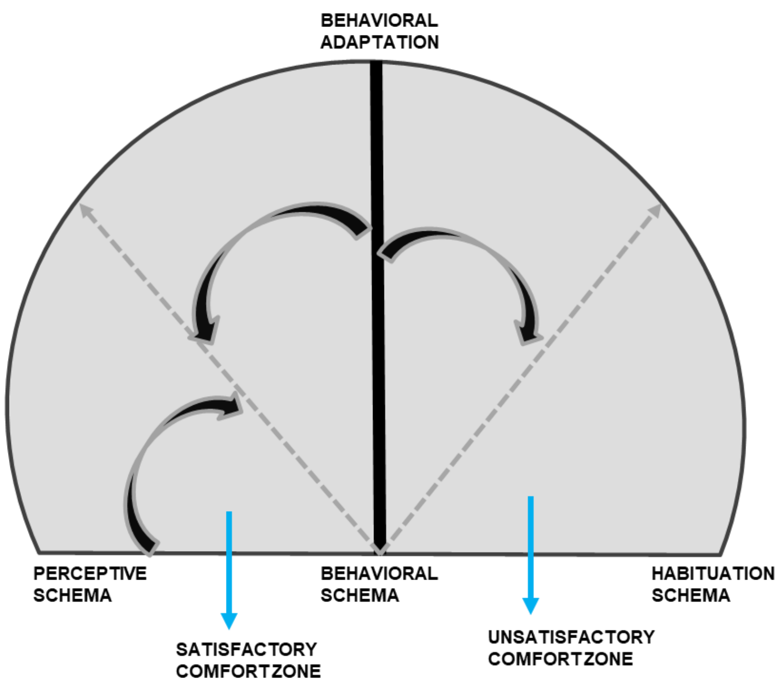


Figure 55: The evolution of schema in psychological adaptive comfort

J. Content of the questionnaire administered

Below are the list of questions and the reasons why the question were considered useful for the research goals.

1. *How do you feel currently?* (Cold, cool, slightly cool, neutral, slightly warm, warm, hot). This Question is based on the thermal perception of the subjects using the ASHRAE seven point scale to obtain the thermal sensational vote of the subjects during the experiments. Thus Nikolopoulou 2011 stated that thermal satisfaction may only be

achieved through sensation and not thermal neutrality. Therefore examining thermal sensation is fundamental in determining the thermal satisfaction of the subjects.

2. *How would you like the room temperature to be?* (Cold, much cooler, slightly cooler, as it is now, slightly warmer, much warmer, hot). This question is based on the preferred perception of the subjects. This is because people may prefer sensation that deviates from thermal neutrality for their satisfaction. Also others may prefer to have some form of environmental stimulation usually due to the outdoor climatic condition at the moment. For example, subjects may want warmer sensation in winter and cooler sensation in summer. This agrees with the conclusion of Brager et al. 2003 that the occupant's satisfaction is not just an outcome of the physical environment but a complex perception built out of the intersection between objective stimuli with cognitive and emotional processes of the person.

3. *According to you, what is the factor that most influences your comfort in the room where you are currently?* (The air temperature, the air velocity, the relative humidity, the temperature of the wall, I don't know specifically). This question was posed to examine the level of satisfaction derived from each environmental factor which the subjects can sense. It's with the aim to determine the physical factor that is perceived to be more important to the subject than the others.

4. *If the room temperature is not totally comfortable, what would you like to do to be more comfortable?* This is an open ended question due to the fact that people's adaptive behavior and response to environmental discomfort could be different from each other. The adaptive principle states that "if a change occurs that produces discomfort, people will tend to act to restore their comfort" (Nicol et al., 2002). The adaptive behaviors by the people to restore their comfort, actually originates from the cognitive long-term and short term memory based on the information available within their cognitive system. It is therefore essential to precisely group these behaviors and consequently weigh the psychological and behavioral information of the subjects.

5. *Based on the temperature you feel now, what does it remind you of?* (It can be the past, a place, an event, something you read, any information). This is also an open ended question aimed at obtaining the information in the subject's long-term memory based on

his past experience or his cognitive learning. It’s therefore necessary to know the prominent information in people for each level of thermal discomfort. This will enable us to extract the schema information of the subjects during the experiment. It can also be useful to weigh the information in the subject’s cognition during the analysis, by relating it to the value of his psychological coefficient and factors. However some level of consistency in the behaviors and perceptions of the subjects is necessary to verify this type of investigation. Hence, this relates to Nikolopolou et al. (2003) conclusions that people perceive the environment in different ways, and the human response to a physical stimulus is not in direct relationship to its magnitude, but depends on the ’information’ that people have for a particular situation. Thus thermal perception is influence by the information that people have in there cognitive long-term memory known as schema.

6. *If the current temperature was the temperature of your room, how long could you stay there?* (I can’t stay there, 1 hour, 2 hours, 3 hours, more than 3 hours). This question was given to firstly examine the behavior of people at different place. The place factor is a physical-psychological factor that influences the thermal perception of occupant. Oseland 1994 stated that subject in his experiment accepted a lower temperature of comfort of 3K in their houses than in the climatic room. Hence the perception of the subjects where different in different places. Therefore we wish to extract the cognitive information of the subjects in some of these places that makes their thermal perception somewhat different. As a result, we posed the questions for the case of the bedroom and the office environment because we assumed that most adults spend most of their active time in these places. Secondly, this question intended to investigate the level of the thermal tolerance of the subjects as relating to his psychological information of place factor. Tolerance of subjects may also vary based on their past experience or based on the reason why they are in such places. This is evident in the psychological perceived control behavior of occupants.

7. *If this room was your bedroom, what would you like the temperature to be like, compared to your current thermal sensation?* (Cold, much cooler, slightly cooler, as it is now, slightly warmer, much warmer, hot). This is to extract the information in the person mind for different place and difference environmental conditions he finds himself. The same question was asked about his perception for the office environment below.

8. *If this room was your bedroom and the room temperature was not totally comfortable, what would you like to do to be more comfortable?* This is an open ended question intended to know the schema information of the subject's comportment in his bedroom and other relevant places.

9. *In general, what temperature level do you prefer to have in your room most of the time?* (Cold, cool, slightly cool, neutral, slightly warm, warm, hot). Due to past experiences, accommodation and habituation some people have developed preference for thermal condition that are not neutral or significantly deviates from neutral point as their typical condition for thermal satisfaction. This will enable us examine the difference between thermal neutrality and thermal satisfaction of the subjects.

10. *If the current temperature was the temperature of your office, how long could you stay there?* (I can't stay there, 1 hour, 2 hours, 3 hours, more than 3 hours). This question is intended for the same purpose as question 6 above with reference to the bedroom.

11. *If this room was your office, what would you like the temperature to be like, compared to your current thermal sensation?* (Cold, much cooler, slightly cooler, as it is now, slightly warmer, much warmer, hot). This question is intended for the same purpose as question 7 above with reference to the bedroom

12. *If this room was your office and the room temperature was not totally comfortable, what would you like to do to be more comfortable?* This is an open ended question intended to know the schema information of the subject's in his office like in question 8.

13. *In general, what temperature level do you prefer to have in your office most of the time?* (Cold, cool, slightly cool, neutral, slightly warm, warm, hot). This question is intended for the same purpose as question 9 above but with reference to the bedroom.