Understanding Thermal Conditions, Thermal Comfort and Adaptive Behaviours in

Naturally Ventilated Multi-patient Wards in Connaught Hospital, Freetown, Sierra Leone

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Abstract

How can the limited cooling capacity of natural ventilation in multi-patient wards in hot-humid settings with limited resources be extended through a better understanding of the links between thermal conditions, thermal comfort, and occupant adaptive behaviours? Natural ventilation remains the primary environmental mechanism for cooling and airborne infection control in hospitals among the poorest countries with the weakest public health systems across the equatorial zone. In these hospitals, a future rise in energy demand for cooling, made necessary by climate change and increased medical care expectations in inadequate buildings is expected to exacerbate existing infrastructural problems. Their occupants will be exposed more frequently and over prolonged periods to thermally uncomfortable indoor environments. Recommendations about the thermal conditions in naturally ventilated inpatient hospital facilities in hot-humid settings have been overlooked by all existing international standards while overheating criteria for naturally ventilated hospital spaces exist only for those located across the temperate zones. The thermal environmental performance assessment in naturally ventilated inpatient facilities in hot-humid settings becomes more challenging by the lack of any previous overheating assessment of naturally ventilated inpatients facilities in both new and historical buildings where on-site environmental monitoring was applied. Although knowledge about occupant adaptive behaviours, especially among those who are most vulnerable to thermal discomfort, is fundamental for the efficient mitigation of indoor overheating, there is a lack of empirical evidence regarding thermal performance and adaptability in inpatient facilities with hot and humid conditions.

In naturally ventilated hospital wards, where the physiological and behavioural capacity for thermal adaptability is determined by each occupant's type role in a strictly regulated environment while the dispersion of the indoor thermal conditions remains unstable, experienced thermal heat stress might be disproportionate to human thermal vulnerability. In this project, rather than understanding thermal comfort perceptions, practices, and expectations in hospital wards as passive stimuli to transient thermal conditions, the aim is to investigate the dynamic links between the ambient environment and occupants' thermal comfort perceptions and adaptive behaviours while considering the impact of relative humidity, indoor airflows, personal factors, and spatial, temporal, and seasonal conditions. A mixed-methods longitudinal field survey was conducted over nine weeks during the rainy (September 2016) and dry seasons (March-April 2017) in eight naturally ventilated wards at the main tertiary government-run hospital with equatorial-monsoonal climate at one of the epicentres of the 2014-16 Ebola outbreak with the following main research objectives: a) to identify the spatial attributes linked

with hospital design in the tropics before the 1940s; b) to define the associations between thermal conditions and spatial attributes, operational schedules and occupant-controlled window opening behaviours during contemporary hospital operation; c) to determine the ranges of neutral, comfortable and preferred temperatures, relative humidity values and airflows and the thermal adaptive capacity among nurses, patients and visitors; d) to assess the impact of seasonal, temporal, spatial and environmental conditions and personal factors on thermal comfort and adaptive behaviours. The case-study hospital is in Africa's west coastal zone, at a historical site in a central urban location and consists of a complex of buildings built consecutively between the 1920s and the 2000s, including a pavilion-plan building, which is composed of eight Nightingale wards.

Infection control practises were integrated with scientifically standardised protocols and nursing routines following one-week piloting and co-designing processes with doctors and nurses. Context-specific infrastructural challenges and safety concerns hindered the installation of a network of sensors and the monitoring of the existing ceiling fans, which was intermittent due to regular electricity power cuts. A multidisciplinary dataset collected according to the ASHRAE 55: 2013 was composed from environmental and behavioural data. Twenty-one semi-structured interviews with twelve doctors and nine head nurses, 750 Thermal Comfort Interviews (T.C.Is.) (45,000 data), indoor and outdoor environmental monitoring (7,933 hours), window-opening behaviours (1,914 photos) and movement mapping (17 hours) comprised the collected dataset. In total, twenty participants were excluded from the analysis of the T.C.Is. due to their exposure to high airflows coming from personal fans. The final sample consisted of 50.68% (370) nurses, 25.62% (187) patients and 23.70% (173) visitors, who were interviewed across four surgical (43.70%), two medical (14.50%) and two mixed (42.60%) wards. The history and the general model of the hospital complex, which was digitally reconstructed, was informed by archival evidence from Freetown State Library, the National Archives in London, and the British Library, and by a thorough building survey. Empirical and experimental findings were produced through descriptive and non-parametric inferential statistics, predictive correlation (Spearman coefficients, Kendall's W test coefficients and Cramer's V effect size), predictive regression (simple linear, ordinal logistic and probit regression), time-series regression, content analysis and thermodynamic modelling.

In 1864, British colonial officers building on Florence Nightingale's extensive work published a best practice framework for the design of barrack hospitals in British India. Although thermal comfort was not their primary focus, by conceptualising the ward as an instrument for efficient infection control through natural ventilation, they created a system of spatial components to maximise climate sensitivity, airflow rates and nurses' control over the thermal conditions in the ward. Even though the case-study Nightingale wards embodied climate-responsive characteristics influenced by these ideas; during contemporary operation the drivers of their environmental performance were similar to those in the rest of the case-study wards. In all selected wards the windows lacked adequate shading devices and double-glazed windows, while internal window curtains trapped solar radiation and, by convection, induced higher adjacent air temperatures. At the same time, heat gains by conduction through the heavyweight external and internal walls and by convection through the uninsulated ceilings and floors reduced the potential of nocturnal cooling, contributing to higher night-time overheating.

In naturally ventilated multi-patient wards in hot-humid settings with limited resources, the impact of the spatial attributes on ventilative cooling is likely to be different between diverse building typologies and seasons, with cooler indoor temperatures being associated with higher openable window coverage during night-time in the pavilion plan typology during the rainy season (Spearman coefficient=-0.34, p-value<0.001) and in other contemporary typologies during the dry season (Spearman coefficient=-0.32, p-value<0.001), while deeper plan layouts could have a protective impact against indoor overheating especially during night-time over the dry season (Spearman coefficient=-0.63, p-value<0.001) only in the modern building typologies. Despite the statistically insignificant correlation with outdoor temperature and relative humidity levels, occupant-controlled widow operation in the case-study wards displayed weak correlations with rising indoor temperature during the rainy season (0.13<Spearman coefficient<0.19, p-value<0.01) and falling indoor relative humidity values (Spearman coefficient=-0.14, p-value<0.01).

The reported high levels of awareness for adaptive behaviours among all occupant types were not reflected in their realised adaptive actions. Comparisons between reported and observed individual adaptive behaviours showed that nurses drank water, visitors moved to cooler places, and patients asked for help. Nurses' responses revealed that actions for the restoration of patients' thermal comfort were an integral part of nursing care and in line with doctors' advice and patients' needs. Reported thermal discomfort was driven by perceptions of high levels of indoor relative humidity during the rainy season, elevated indoor temperature during the dry season and low levels of indoor airflows during both seasons. Through probit regression of the preference votes, the range of acceptable indoor thermal conditions was defined by operative temperatures varying between 29.00 and 30.00oC during the rainy season and between 28.00 and 29.00 oC during the dry season, relative humidity levels from 66.00 to 69.00% during the rainy season and around 71.00% during the dry season while acceptable airflows stand at 0.9m/s during both seasons. Outdoor environmental conditions were weak predictors of experienced indoor thermal discomfort. Patients expressed the highest levels of sensitivity to thermal discomfort to rising operative temperatures. At the same time, their votes displayed the strongest influence (Cramer's V effect size: 0.50-0.69, p-value<0.001) by diverse building and ward typologies, gender, water and food consumptions and operation of building controls. Furthermore, allocation of patients in buildings with architectural and engineering characteristics like the case-study Nightingale typology can have a strong alleviating impact of thermal comfort during the rainy season (Cramer's V effect size: 0.50-0.66, p-value) while acceptability of the indoor airflows among patients might increase if they can control window operation (Cramer's V effect size: 0.54, p-value<0.001).

Through the integration of critical aspects of thermal adaptability that extend the criteria for ward allocation beyond clinical outcomes, the healing potential of the ward's indoor environment, whose attributes are exploited towards a personalised type of health care, can be strengthened. Seriously ill patients, who will require more intense care and are more sensitive to thermal distress, might be advisable to be allocated in wards built to maximise the potential of natural ventilation for space cooling and airborne infection control similar to the Nightingale ward typology. In hospital wards with facades lacking appropriate shading, bedded areas should be allocated far away from the exterior facades. Priority should be given to the strengthening of indoor airflows around patients and distribution of cool water, and accessibility to cool outdoor places for all occupant types. Installation of environmental monitoring equipment for provision of visual evidence based on real-time monitoring of the outdoor and indoor environmental changes, integration of Informal nursing practices for the amelioration of thermal discomfort among patients with established models of nursing care and infection control protocols, provision of training regarding climate-responsive operation of the windows and guidance through posters and other types of visual aids can transform the high levels of awareness of behavioural thermal adaptability to actions for the restoration of thermal comfort at individual level and in relation to patient care. To avoid overestimation of overheating and the required cooling loads, the low limit of the ASHRAE 55 model is suitable only for night-time overheating. Furthermore, widely accepted assumptions regarding the occupancy schedules and occupants' activities might contradict context-specific aspects of healthcare delivery, resulting in underestimating the impact of nursing and other activities on internal heat gains and, more importantly, on the potential of natural ventilation to protect against airborne infection.

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Part 1/2: Text

Contents

Abstract

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Abbreviations

Fieldwork periods	
September 2016 (rainy)	Sep.2016
March-April 2017 (dry)	Mar.Apr.2017
Buildings accommodating case-study wards	
Pavilion Building	Pav.Buil.
Medical, Sanitary & Administrative Building	Med.San.Adm.Buil.
Accident & Emergency Building (originally named "Outpatient Block")	A & E
Annex of Private Wards (originally named "European Nurses' Quarters")	Annex
Case-study wards	
Ward 2	W2
Ward 3	W3
Ward 6	W6
Ward 7	W7
Ward 9	W9
Room 1 (in Ward 9)	R1
Room 2(in Ward 9)	R2
Physiotherapy	Physio.
Trauma Unit	T.U.
Female Annex	F.A.
Locations of outdoor environmental measurements	
Outdoor location in Freetown's Connaught Hospital Complex	S1
Location of Freetown's meteorological station	Meteo.
Thermal Comfort Interview	T.C.I.
Archival Research	A.R.
Building Survey	B.S.
Indoor Environmental Monitoring	I.E.M.
Outdoor Environmental Monitoring	O.E.M.
Movement Mapping	M.M.
Semi-structured Interview	S.I.
Environmental Measurements	
Indoor air temperature (recorded)	$T.A._{(in)}(^{o}C)$
Historical outdoor (external) air temperature	$T.A._{ext.(His)}(^{o}C)$

Outdoor (external) air temperature recorded at S1 location	$T.A._{ext.(S1)}$(°C)
Running mean of outdoor (external) air temperature recorded at S1 location	$T.A._{rm.ext.(S1)}$(°C)
Outdoor (external) air temperature recorded at the meteorological station	$T.A._{ext.(Meteo)}$(°C)
Running mean outdoor (external) air temperature recorded at the meteorological station	$T.A._{rm.ext.(Meteo)}$(°C)
Indoor relative humidity (recorded)	$R.H._{(in)}$(%)
Historical outdoor (external) relative humidity	$R.H_{.ext.(His)}$(%)
Outdoor (external) relative humidity recorded at S1 location	$R.H_{.ext.(S1)}$(%)
Outdoor (external) relative humidity recorded at the meteorological station	$R.H._{ext.(Meteo)}$(%)
Indoor wind speed (recorded)	$W.S._{(in)}$(m/s)
Historical outdoor (external) wind speed	$W.S._{(His)}$(m/s)
Outdoor (external) wind speed recorded at the meteorological station	$W.S._{ext.(Meteo)}$(m/s)
Air temperature recorded at the location of the participant during the T.C.I.	$T.A_{.(spot)}$(°C)
Operative temperature calculated according to the environmental measurements recorded at the location of the participant during the T.C.I.	$T_{op.(spot)}$(°C)
Operative temperature being recorded at the location of the participant during the T.C.I. that corresponded to comfortable and acceptable thermal conditions.	$T_{op.(spot)(com)}$(°C)
Operative temperatures corresponding to PMV (ASHRAE 55:2013) values from -1 to 1	$T_{op.(spot)(ASHRAE\ 55\ com)}$(°C)
Comfortable operative temperatures estimated by the application of the $T_{op.(spot)}$ values in the Griffins models with the G value of 0.25	$T_{op.(spot)(Grif.0.25)}$ (°C)
Comfortable operative temperatures estimated by the application of the $T_{op.(spot)}$ values in the Griffins models with the G value of 0.33	$T_{op.(spot)(Grif.0.33)}$ (°C)
Comfortable operative temperatures estimated by the application of the $T_{op.(spot)}$ values in the Griffins models with the G value of 0.50	$T_{op.(spot)(Grif.0.50)}$ (°C)
Mean radiant temperature calculated according to the environmental measurements recorded at the location of the participant during the T.C.I.	$T_{mrt(spot)}$(°C)

Globe temperature recorded at the location of the participant during the T.C.I.	T_{globe}(^oC)
Wet bulb globe temperature recorded at the location of the participant during the T.C.I.	W.B.G.T.$_{(spot)}$(^oC)
Relative humidity recorded at the location of the participant during the T.C.I.	R.H.$_{(spot)}$(%)
Relative humidity being recorded at the location of the participant during the T.C.I. that corresponded to comfortable and acceptable thermal conditions.	R.H.$_{(spot)(com)}$(%)
Wind Speed recorded at the location of the participant during the T.C.I.	W.S.$_{(spot)}$(m/s)
Wind Speed being recorded at the location of the participant during the T.C.I. that corresponded to comfortable and acceptable thermal conditions.	W.S.$_{(spot)(com)}$(m/s)
Recorded thermal comfort votes	
Actual Temperature Sensation Vote	A.T.S.V.
Actual Temperature Comfort Vote	A.T.C.V.
Actual Temperature Preference Vote	A.T.P.V.
Actual Relative Humidity Sensation Vote	A.R.H.S.V.
Actual Relative Humidity Comfort Vote	A.R.H.C.V.
Actual Relative Humidity Preference Vote	A.R.H.P.V.
Actual Wind Speed Acceptance Vote	A.W.S.A.V.
Actual Wind Speed Preference Vote	A.W.S.P.V.
Predicted Mean Vote	P.M.V.
Actual Mean Vote	A.M.V.
Predicted Percentage Dissatisfied	P.P.D.
Actual Percentage Dissatisfied	A.P.D.
Design & Delivery of Robust Hospital Environments in a Changing Climate	DeDeRHECC
Singapore General Hospital	S.G.H..
Barrack and Hospital Improvement Commission	B.H.I.C.
American Society of Heating, Refrigerating and Air-Conditioning Engineers	ASHRAE
American Institute of Architects	AIA
Carbon Dioxide	CO2
Total Volatile Organic Compounds	TVOCs
Air Change per Hour	ACH

meter	m.
Dry Bulb Temperature	D.B.T.
Relative Humidity	R.H.
Wind Speed	W.S.

Chapter 1

Introduction

1.1 Need for Research

Natural ventilation remains the primary environmental mechanism for cooling and airborne infection control in hospitals among the poorest countries with the weakest public health systems across the equatorial zone (Figure 1.1). In these hospitals, a future rise in energy demand for cooling, made necessary by climate change and increased medical care expectations in inadequate buildings is expected to exacerbate existing infrastructural problems (WBG, 2017). Hospitals with limited resources across the equatorial zone are expected to find responding to increasing cooling loads challenging (Escombe, et al., 2019). Their occupants will be exposed more frequently and over prolonged periods to thermally uncomfortable indoor environments. A better understanding of existing thermal conditions and adaptive behaviours among hospital occupants can inform efficient strategies for mitigating overheating in hospital buildings, especially among patients who are more vulnerable to thermal discomfort (Carmichael, et al., 2013). However, there is no empirical evidence about the links between indoor thermal conditions, human thermal comfort, and occupant adaptive behaviours in naturally ventilated inpatient facilities s across the equatorial zone. In Sierra Leone, which is the focus of this dissertation, the need for the reinforcement of hospital resilience has become more urgent after the 2014-16 Ebola epidemic, which intensified pre-existing structural and functional deficiencies of health systems in the region (Government of Sierra Leone, 2015) with overheating conditions in clinical spaces for treatment and diagnosis having gained broad media coverage (Fowler, et al., 2014). Patterns of more severe, intense, and unpredictable weather phenomena during the dry and rainy periods have been observed (Government of Sierra Leone, 2007). However, there are no available data regarding existing actual cooling demands (Karliner, et. al., 2019) and future climate change adaptations plans for hospital buildings in Sierra Leone (WBG, 2017).

1.2 The Dissertation's Contribution

Resilient hospitals buildings are core components of resilient health systems[1] (WHO, 2009a). This link is stronger in emerging economies (Watts, et al., 2019). This project examines for the first-time the associations between thermal conditions, thermal comfort, and occupant adaptive behaviours in

[1] Although there is no official definition for "resilient hospitals", the conceptualisation of a resilient hospital as a complex system that needs to maintain the ability to allow for adjustments, recover and self-restore after unexpected disturbances has gained broad acceptance (WHO, 2009a).

operational, naturally ventilated multi-bed wards in a hot-humid setting with limited resources. The optimum contribution of this project is the development of a framework for the integration of the dynamic links between environmental, spatial, and socio-cultural aspects of adaptive thermal comfort in naturally ventilated multi-patient wards, in hot-humid settings with restrained resources. A pavilion-plan colonial hospital building (built between 1921 and 1929) accommodated half of the case-study wards. Therefore, the framework is expected to be useful for the improvement of the thermal conditions not only in new, but also in historical hospitals, which comprise a great part of the existing healthcare infrastructure in many emerging economies of the Global South. The proposed framework will help architects, engineers, and clinicians to tackle key climate and energy-related challenges of healthcare architecture in emerging economies of the Global South across the equatorial zone. In this manner, the framework provided by this dissertation will contribute to the strengthening of the resilient capacity of the existing and new public health infrastructures and their staff to cope with climatic and medical emergencies in the future[2].

1.3 Research Questions and Objectives

My doctoral dissertation aims to explore the interdisciplinary aspects of adaptive thermal comfort in multi-patient wards. Rather than understanding thermal comfort perceptions, practices, and expectations in hospital wards as passive stimuli to transient thermal conditions, I aim to investigate the dynamic links between the ambient environment and occupants' thermal comfort perceptions and adaptive behaviours. This dissertation interrogates the interactions between these dynamic links addressing the following central question: How the limited cooling capacity of natural ventilation in multi-patient wards with hot-humid settings and limited resources can be extended through a better understanding of the links between thermal conditions, thermal comfort, and occupant adaptive behaviours? The following three key questions are further explored in the dissertation:

- How was thermal comfort envisioned and realised in colonial hospital wards in Sierra Leone's capital, Freetown, before the 1940s[3]? How were these ideas applied in the construction of the Connaught Hospital?

[2] Findings of this dissertation were used for the identification of wards for the treatment of COVID19 patients at Freetown's Connaught Hospital.

[3] After WWII, a significant rise in the installation of air-conditioning units, especially in public buildings, has been documented (Bell,1956).

- What is the role of the existing built environment and occupants’ behaviours in modifying thermal conditions?
- How is thermal comfort perceived, practised, and aspired by nurses, doctors, patients, and visitors in hospital wards in a hot-humid setting with limited resources?

Drawing on an interdisciplinary research design comprising of participatory and non-participatory empirical and experimental methodologies for the collection and analysis of both quantitative and qualitative data following random and convenient sampling techniques, the following main research objectives are investigated: a) to identify the spatial attributes linked with hospital design in the tropics before the 1940s b) to define the associations between thermal conditions and spatial attributes, operational schedules and occupant-controlled window opening behaviours during contemporary hospital operation c) to determine the ranges of neutral, comfortable and preferred temperatures, relative humidity values and air movement and the thermal adaptive capacity between nurses, patients and visitors d)to assess the impact of seasonal, temporal, spatial and environmental conditions and personal factors on thermal comfort and adaptive behaviours.

1.4 PhD dissertation Overview

Following the introduction, the dissertation proceeds by exploring the ideas about thermal comfort in colonial hospitals in equatorial climates (Chapter 2). Drawing on extensive archival material, a building survey, and digital architectural reconstructions, the Connaught Hospital's history in Sierra Leone's capital, Freetown, is traced to its colonial history (1817-1960). The inherent potential for climate sensitivity among a sub-sample of the selected wards (built in the 1920s) is explored through a historical study of colonial hospital architecture and environmental engineering (Figure 1.1). In Chapter 3, the synergetic dynamics between the selected wards' thermal performance and occupants' window-opening behaviours on indoor thermal conditions are investigated, while accounting for exceptional operational requirements arising from a contextual limitation of resources (Figure 1.2). In Chapter 4, the associations between the votes of thermal sensation, comfort, preferences, and acceptability and recorded seasonal, temporal, spatial and environmental conditions, participants' characteristics, and adaptive behaviours are explored (Figure 1.2). The acceptable range of indoor temperature, relative humidity and wind speed levels were defined, and the most likely adaptive behaviours for the restoration of thermal comfort were identified (Figure 1.2). In Chapter 5, the recommendations comprising a framework to contribute to improved understandings of the cooling capacity of natural ventilation in multi-patient wards in hot-humid settings with limited resources through the identification of the embodied climate-sensitivity and performed climate responsiveness of the existing building envelopes, the acceptable ranges of thermal conditions and adaptive behaviours and actions among occupants are presented.

1.5 A Case-Study and Mixed-Methods Approach

1.5.1 Project Logistics in Freetown, Sierra Leone

The realisation of a nine-week fieldwork was conducted during two stages, in September 2016 (Sep.2016) and March-April 2017 (Mar.Apr.2017), at Freetown's Connaught Hospital, Sierra Leone, was preceded by a series of preparatory actions (Figure 1.3). In February 2016, the in-situ study of the Connaught Hospital was approved by Chief Medical Officer of the Ministry of Health and Sanitation and the Hospital Care Manager of Connaught Hospital on the provision that research activities involving the participation of human subjects would be approved by the Ethical and Scientific Committee of the Ministry. Due to the nature and the purpose of the project, between November 2015 and June 2016, a set of applications for risk assessment, ethical approval, and financial support of research activities needed to be submitted to different institutions.[4] By February 2017, grants totalling £6,500 were collected from several funding bodies: Wellcome Trust (£3,000), Faculty of Architecture and History of Art (£1,500), Magdalene College (£1,000), and The Smuts Memorial Trust (£1,000).

Between May and July 2016, the relevant committees of the University of Cambridge and the Ministry of Health and Sanitation of Sierra Leone granted the necessary "working away" permission and ethical approvals for the implementation of the study. The risk assessment process involved the detailed description of plans for coping with endemic infectious diseases, general infection risks while conducting research in operational hospital wards, unsafe road networks, and high criminal rates in Freetown. The relevant committees received detailed descriptions of the planned research activities in the hospital, including: a research outline, an information letter, a sample questionnaire, and the relevant consent forms, all provided in English. In the relevant forms, it was clearly stated that participation would be voluntary and only people aged 18 and over, with the capacity to give consent, would be allowed to participate in the survey and interviews. Furthermore, the participants' anonymity would be safeguarded at every stage of the research. All responses would be completely anonymous and regulated by the Data Protection Act 1998. Only the Principal

[4] Copies of the applications and letters of approval are illustrated in Figures 1.1-1.3 in Appendix 1.1.

Investigator (PhD researcher) could have access to the data from the participants' responses, while data would be stored in a secure manner.

1.5.2 A Critical Case-Study: The Connaught Hospital in Freetown, Sierra Leone

1.5.2.1 Overview of the Characteristics of the Critical Case-Study

The critical case-study of Freetown's Connaught Hospital is expected to maximise the acquired knowledge[5] for the following reasons:

1) this project represents the first academic project that has received permission to apply a mixed-method approach for the collection of environmental and subjective data in occupied hospital wards in a hot-humid setting with limited resources.

2) Freetown's Connaught Hospital is the largest tertiary government hospital that provides healthcare indiscriminatory to one of the highest number of patients per year in the country (Lowsby, et al., 2017).

3) Connaught Hospital's staff had a recent experience of extreme operational and thermal stress. During the 2014-16 Ebola outbreak, Connaught Hospital was the only governmental hospital that remained open and operated as an Ebola "holding unit", where suspected cases of Ebola were hospitalised pending clinical diagnosis (Lado, et al., 2015).

Connaught Hospital is located in Sierra Leone's capital, Freetown. Sierra Leone is located on Africa's west coastal zone between the seventh and tenth parallels north of the equator and is bordered by the Atlantic Ocean, to Liberia and Guinea to the west, the south and southeast and the north and northeast, respectively (Figures 1.4-5). Freetown's climate is classified following the Koeppen-Geiger classification system as equatorial-monsoonal (Am) (Koettek, et al., 2006). Freetown is part of the Western Urban Area District. It covers an area of 81.48 million km^2 and, in 2015, it was populated by 1,055,964 inhabitants, constituting 36.35% of the country's urban population (Statistics Sierra Leone, 2015). Connaught Hospital is located in central Freetown and is surrounded by a historical network of streets and mixed-use buildings, and informal settlements (Figures 1.6-8). The College of Medicine and Allied Health Sciences (COMAHS), which is located within the hospital's premises, is the primary and sole educational institution for training in medicine, pharmaceutical science, and core and specialised nursing in Sierra Leone (KSLP, 2017). The current medical staff of the hospital is comprised of forty-four doctors and 400 nurses. The hospital has a capacity of 370 beds in twelve

[5] According to Stake (1995) and Yin (2014), the originality and maximisation of the expected acquired knowledge should be the primary criterion for the selection of a case-study.

medical and surgical wards, with fifteen departments composing the present diagnostic, therapeutic, and research capacity of the hospital (Figure 1.9; Figures 1.10a-c). Connaught Hospital is a historical hospital, built gradually between 1921 and the 2000s (Figures 1.11-12). It remained closed during the Sierra Leone civil war (1991-2002). Although in 2007, the government spent 68% of its budget for hospital reconstruction, the plans for Connaught Hospital's refurbishment produced by the United Nations team were never realised (Kelly and Barrie, 2010)[6].

1.5.2.2 The Social and Public-Health Significance of Connaught Hospital

Historical factors, including colonialism, civil war and continuing structural violence, contribute to the present condition of the economic, social and health systems in Sierra Leone (Government of Sierra Leone, 2015) (Table 1.1). Following the end of the civil war (2002), which had led to 50,000 deaths, foreign investments coming from expatriates (World Bank, 2011) and Chinese investments (Kapuwa, 2010) contributed to Sierra Leone's economy becoming one of the most rapidly advancing sub-Saharan markets (ACET, 2014). Despite the apparent financial progress, Sierra Leone is presently one of the world's five poorest countries (UNDP, 2015a). Since 2003, primary education is free (Commonwealth Foundation, 2013), and yet 55.5% of the population is still illiterate, with 52.2% of children having abandoned primary level education between 2008 and 2014 (UNDP, 2015a). In 2014, the gross annual income for women and men was $1,582 and $1,981, respectively (UNDP, 2015a). As the largest government-run tertiary hospital in Sierra Leone, Connaught Hospital plays a significant role in providing care in a weak health care system and for a population with severe public health problems. According to recent statistics, the outpatient department provides services on average to 12,000 patients per year, with patients with infectious diseases, including TB, typhoid, bacterial pneumonia, HIV, malaria, viral hepatitis, and other infections, accounting for most of the patient admissions (from 60 to 70%) (Lowsby, et al., 2017).

During the first years of independence (1961) in Sierra Leone, there was a lack of medical staff due to the migration of many British doctors and nurses out of the country, while only limited financial aid was provided by the UK (Clapham, 2002). However, in 1961, ambitious public health programmes took place involving measures of infectious disease control, reduction in maternal and

[6] In 2013, an inspection took place at Connaught Hospital that reported a series of problems, including shortages in medical supplies and equipment, unacceptable hygienic conditions, high nosocomial infection rates, low level of maintenance, out of pocket fees, and long waiting time of emergencies (The Patriotic Vanguard, 2017).

child mortalities, and the extension of healthcare infrastructures (Fyle, 1993). Due to a lack of funds, public health programmes' implementation was limited (MoHS, 2009). The governance of the public health sector followed by the independent government was very similar to the model of the colonial authorities' model with the Ministry of Health being directed by the Minister and managed by an administrative team who were the leading actors in the formulation of public health policy (MoHS, 2009). Since the 1960s, the needs for primary, secondary and tertiary care have been covered by a network of healthcare centres, district hospitals and national hospitals managed by the government and various religious and private for profit and non-profit organisations with district hospitals aiming to provide curative, emergency, and diagnostic care, while healthcare centres' services being limited to fundamental aspects of preventive care (MoHS, 2009)[7]. By 1973, Sierra Leone had only 112 trained doctors, all of whom studied medicine abroad (Kaplan, et al., 1976). It was not until 1988 that the first School of Medicine (currently named COMAHS) opened in the country with the implemented medical training consisting of British and American systems (Patton, 1996). Training for nurses was provided by the National School of Nursing, which opened in 1969 (Kaplan, et al., 1976).

During the civil war (1991-2002), public health infrastructural, financial and human resources came under attack and rapidly disintegrated (Oyerinde, et al., 2011). In 2009, following a continuous decline since 1980, Sierra Leone's primary, secondary and tertiary care capacity (including thirty government-run, eleven mission, and two private hospitals) was below population needs and was restricted to 1,028 healthcare facilities (World Bank, 2017). In addition to the shortage of healthcare facilities and beds, the unequal geographical distribution of healthcare providers has been an enduring problem (MoHS, 2009).[8] The problem of asymmetrical spatial distribution has been exacerbated by the acute shortage in specialised health workers. Between 2005 and 2015, the density of specialised physicians, nurses and midwives was only 3.4 per 10,000 inhabitants (WHO, 2016). The scarcity of qualified doctors and nurses was pronounced not only in complex fields, such as neurosurgery, but mostly in typical specialisations, such as gynaecology, paediatrics and orthopaedics with only two paediatricians and sixty-five midwives being available in 2009 (MoHS, 2009).

[7] However, the traditional healers' contribution remained crucial, with 90% of births took place under the supervision of a Traditional Birth Attendant (TBA) (MoHS, 2009).

[8] As of 2009, out of the thirty government hospitals, 46% of the total 6,030 healthcare workers, and fifteen out of the total twenty-four doctors were located in the Western Area (MoHS, 2009).

The dramatic insufficiency of human resources was aggravated after the Ebola epidemic. Out of 295 infected health-workers, 211 succumbed to the virus, including eleven consultant doctors (Government of Sierra Leone, 2015). Until 2015, 65% of healthcare facilities were deprived of diagnostic medical apparatuses, lacking elementary laboratory equipment, while the availability of essential medicinal drugs was restricted to 28% of the healthcare facilities (Government of Sierra Leone, 2015). In 2008, only fifteen hospitals had the capacity of emergency blood transfusion (Maxmen, 2013). In 2011, only 37% of hospitals and 2% of health centres could provide emergency care during childbirth (Oyerinde, et al., 2011). The unavailability of safe water was very common at many government-run hospitals (Amnesty International, 2009). Only 10% of the hospitals and community centres had continuously available electricity (Statistics Sierra Leone and MoHS, 2009).[9] In Sierra Leone's healthcare facilities, solar systems were used for energy generation in 43% of hospitals and 36% of healthcare centres (Adair-Rohani, et al., 2013). The per capita government expenditure on health has been far below the WHO recommended value of US$34, with 19.30% of the country's expenditure on health being covered by government funds, 69.3% by citizens' income, and 0.4% by private sponsors (WHO, 2009b). In 2014, of the total state expenses on health, 6.8% were paid by the government, 61.6% out-of-pocket money, and 46.9% by donors, with the main source of out-of-pocket money being mortgages arranged at the community level (WHO, 2015a).

In 2010, the Free Healthcare Act came into force to provide free healthcare services to pregnant women, lactating women, and children under the age of five (Health Poverty Action, 2010). The rest of the population groups have to pay a government fee for all the diagnostic and medical services (MoHS, 2017). Since the 1980s, patients have been paying for their treatment medicines and have been providing even their own bedsheets during hospitalisation (Fyle, 1993). The design of a health insurance scheme has been under development since 2016 (MoHS, 2017). The high cost and low standards of care have contributed to the low utilisation of medical services (Oyerinde, et al., 2011). In 2009, only 50% of the population visited a medical facility during a year (MoHS, 2009). Another cross-sectional study demonstrated that public hospital medical services were used less by disabled people, a significant fact, given the large number of civil war-related amputees (Trani, et al., 2011). In 2014 only 35% of participating households reported satisfaction with the healthcare's quality (UNDP, 2015a). People's willingness to visit healthcare centres has been further reduced by reported corruption incidents at healthcare facilities (Pieterse and Lodge, 2015).

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[9] A common practice for providing lighting to operation theatres involved the use of mobile phones when the patients could not pay for fuel for the clinic's generator (Amnesty International, 2009).

The indicators for population health in Sierra Leone are among the worst on the global scale. HIV/AIDS & TB are major causes of mortality (CDC, 2017). The AIDS-related mortality rate more than doubled between 2000 and 2012 (WHO, 2015b). Among HIV positive cases, TB prevalence is 11.6%, with an improvement in the treated cases of only 4% between 2004 and 2007 (WHO, 2009b). By February 2015, there were more than 2,000 Ebola survivors in Sierra Leone (WHO, 2015c). A retrospective epidemiological survey of a survivors' sample at the 34th Regimental Military Hospital in Freetown indicated that several "Ebola Syndrome" symptoms remained after recovery (Scott, et al., 2016). During the first post-war years, when maternal mortality was reduced from 1,300 per 100,000 live births in 2005 to 857 per 100,000 live births in 2008, a significant progress was achieved in reducing maternal mortality risk (WHO, 2009b). Nevertheless, in 2015, Sierra Leone had the highest number of maternal deaths globally, having reported a mortality ratio of 1,360 maternal deaths per 100,000 live births (WHO, 2015b). Following the Ebola epidemic, the number of births attended by trained midwives decreased by 23%, resulting in increased maternal mortality and stillbirths (Ribacke, et al., 2016). In 2016, Sierra Leone was ranked at the fifth position for under-five mortality, having recorded 114 per 1,000 live births (WHO, 2015b). Most of the under-five-children morality was caused by malaria, diarrhoea, and pneumonia (WHO, 2009b). Regarding the general population profile, in 2008, malaria, acute respiratory infection and acute diarrhoea accounted for 38%, 16.9% and 9.7% outpatient visits, respectively (Statistics Sierra Leone and MoHS, 2009). Despite improvements in access to clean water for 63% of the population, diarrhoea remained the main cause of mortality (CDC, 2017), with malaria and neglected Tropical Diseases (NTDs) being the second causes of mortality (WHO, 2015c). In 2016, 2,819 excess deaths from malaria, HIV/ AIDS and tuberculosis could be attributed to a 50% limitation of access to healthcare services (Parpia, et al., 2016). In 2015, between 25% and 34% of deaths were attributed to non-communicable diseases, including cardiovascular diseases, cancers, diabetes, and chronic respiratory diseases (Naik and Kaneda, 2015)[10].

The 2014-2016 Ebola epidemic exacerbated the pre-existed financial crisis. Unemployment among people aged 15-35 rose to 60%, with 80% living under the poverty line (UNDP, 2015b). According to the most recent demographic survey, in 2015, whereas only 3.2% of the population living in informal

[10] A study in 2007 revealed that among 256 and 245 adults from a rural and an urban area, respectively, only the urban inhabitants had diabetes with a prevalence of 2.4% (Ceesay, et al. 2007), while a more recent study showed that the prevalence of diabetes might be higher. In a sample of 1,161 adults, 7% were tested positive for type 2 diabetes (Sundufu, et al. 2017).

settlements, 28.0% and 17.6% of the population were deprived of access to clean water and pit or flush latrines, respectively (Statistics Sierra Leone, 2015). In 2015, household energy from electricity consumption was feasible for only 10% of the population at a very high cost. Therefore, 76.4% of the households used batteries as the primary energy source for lighting, while 5.7% of the households used wood, kerosene, generators, solar, gas, and candles for the same purpose (Statistics Sierra Leone, 2015). High electricity consumption is not a problem in Sierra Leone. On the contrary, the neglected and unevenly distributed infrastructure for the generation and allocation of electricity limits electricity use to below 10% of the population (Government of Sierra Leone, 2015).

1.5.3 A Mixed-Methods Approach

1.5.3.1 Overview of the methods for data collection

This project's fieldwork was conducted at Connaught Hospital in Freetown, Sierra Leone, over the 2016-2017 academic year during the rainy season (Sep.2016) and the dry season (Mar.Apr.2017). A mixed-methods data collection protocol was applied in eight operational multi-patient wards. The mixed-methods approach consisted of archival research, a building survey, indoor and outdoor environmental monitoring, photographic recording of the position of window openings, occupant movement mapping, semi-structured interviews, and thermal comfort interviews (T.C.Is.) (Figure 1.13). The cohort of the eight selected wards was a critical sample representing differing capacities in passive microclimate-modification at buildings of diverse ages, layouts, orientations and locations, functions, operational schedules, and occupancies. At the same time, the historical pavilion-plan building accommodated half of the case-study wards. The Pavilion Building (Pav.Buil.) accommodated Ward 2 (W2), Ward 3 (W3), Ward 6 (W6) and Ward 7 (W7), the Medical, Sanitary & Administrative Building (Med.San.Adm.Buil.) contained Ward 9 (W9) and Physiotherapy (Physio.) (Figure 1.14a.1). The Trauma Unit (T.U.) was in the Accident & Emergency Building (A & E), and the Female Annex (F.A.) was in the Annex of Private Wards (Annex) (Figure 1.14a)

Following Teddlie and Yu's (2007) sampling typologies regarding mixed-methods research design, the sampling strategy of this project was "concurrent" and "multilevel". The recruitment processes of all the main types of hospital occupants, namely doctors, nurses, patients, and visitors, took place while the data collection stage was in progress. Doctors and nurses were asked to participate in both the questionnaire survey and the semi-structured interviews, whereas patients and their visitors were asked to be participants only in the questionnaire survey. The recruitment processes were performed in English and Krio (native language) and involved presentation sessions with hospital staff and the distribution of information letters within hospital premises.

The temporal and spatial aspects of the mixed-methods data collection processes, which were primarily determined by scientifically standardised approaches defined by ASHRAE 55:3013 for existing naturally ventilated buildings and complied with context-specific infection control practises while overcoming infrastructural and safety challenges, were the following (Figure 1.14b):

1. The data loggers and the anemometer were installed at nurse stations or other "safe" locations (close to the nurse stations) in the selected wards. Although it was possible to perform continuous monitoring of the indoor air temperature and relative humidity, recording of the indoor air velocities was repeated sporadically over shorter periods.
2. Photos of the window openings' positions at the facades of interest in the selected wards were taken according to a standardised route around the case study buildings. These photos were taken intermittently at a specific time twice per day, every day, over the fieldwork periods.
3. Semi-structured interviews took place only once, at the time and place suggested by the interviewees to suit their regimes.
4. The thermal comfort survey was a longitudinal survey. Physical and subjective measurements were taken intermittently and repeatedly in a standardised manner in the selected wards on different days, either during the morning or the evening shifts.
5. Mapping of the occupant movement and activities was conducted in a sub-sample of the selected wards only once, covering parts of the morning and evening shifts.
6. The building survey was comprehensive only in the selected wards and was conducted during weekends when these spaces were not crowded.

The applied data collection protocol was co-designed with the ward sisters and the hospital's doctors to eliminate any potential conflicts between scientifically approved recording procedures of environmental and behavioural parameters, infection control, and nursing schedules. At the same time, lack of steady electricity supply and internet access and concerns about the security of the equipment hindered the installation of an extended network of sensors with a digital storage capacity. Functional fans supplemented natural ventilation only in W9 and T.U. In F.A. However, fan operation, which was irregular due to intermittent electricity supply, was not monitored due to lack of financial resources of the necessary equipment[11]. Therefore, all the case-study wards, including

[11] Doctoral researchers at the Department of Architecture do not have access to grants to purchase new equipment. The author had to spend £2,000 from her own money to cover the cost of the necessary extra equipment.

those with functional ceiling fans, were considered free-running. Fan operation was only considered in the analysis of the T.C.Is. data. The T.C.Is., which were conducted close to a personal fan (wall-mounted or standing) in operation, were excluded from the analysis. In addition to the sporadic measurements taken with an anemometer installed at the nurse station, further understanding the natural ventilation performance in the case-study wards consisted of the sporadic recording of indoor air velocities around the participants in the T.C.Is. at scattered indoor locations. Therefore, although these measurements indicated the ventilation rate's strength, they lacked evidence about ventilation efficiency in indoor air filtration through the delusion and removal of airborne contaminants.

Except for the temperature, relative humidity, and wind speed data, which were digitally recorded, all other data were collected manually and required subsequent digitisation. More specifically, the latter included: 1) twenty-one semi-structured interviews (three-hour-long) with doctors and nurses; 2) 750 valid questionnaires (45,000 data) conducted with nurses, patients, and visitors; 3) movement and activity maps with a total duration of seventeen hours and 4) 1,914 photos of the position of the window openings of interest. The digitisation process of the handwritten dataset began in Cambridge after completing my fieldwork in April 2017. Although Connaught Hospital is the largest government tertiary hospital built between 1880 and 2016, only one drawing illustrating the hospital site plan in 1925 survived the fires that destroyed the State Library archives during the civil war (1991-2002). As a result, the general model of the hospital complex and detailed digital reconstruction models of the case-study wards had to be designed from scratch, drawing on archival research conducted at the Freetown State Library, the National Archives in London, and the British Library, and on a thorough building survey. Furthermore, archival information on crucial aspects of the hospital's architectural evolution became available in an online collection of the British Online Archives for the first time in December 2018.

For the selection of the peer-reviewed articles, which composed the main body of the literature review, priority was given to all available thermal comfort and overheating studies of hospital spaces across all climate zones. Secondly, thermal comfort studies in all building types in Africa and thermal comfort studies in non-domestic buildings across the equatorial zone were included. Lastly, all published reviews of adaptive thermal comfort in all building types across the equatorial zone were studied to understand historical aspects of thermal comfort and adaptive behaviours in the tropics. Following the advice by de Dear et al. (2020). comparisons were made with caution due to limitations arisen from diverse operational needs, disciplinary regimes, and occupant profiles between the different building types.

1.5.3.2 Overview of the methods for data analysis

The final collected dataset was comprised of physical measurements, subjective thermal comfort votes, spatial attributes of ventilative cooling, reported and observed interactions with environmental controls, adaptive behaviours at an individual level and personal factors (Figure 1.15). Driven by limitations determined by the sample sizes statistical analysis was restricted to descriptive, non-parametric inferential, predictive correlation and predictive regression methods performed consistently between specific combinations of dependent and independent variables (Figure 1.16). Mann–Whitney U-test or Wilcoxon Rank Sum Test, which is a distribution-free statistical test (Wright and London, 2009), was used to investigate the variation introduced to the dependent variable by differences in the independent variable coded as a binary variable. Spearman correlation was applied as an indication of the strength of a relationship (weak correlation (<=-0.30 and <=+0.30), moderate correlation (-0.50 to -0.30 and 0.30 to 0.50) and strong correlation (-0.90 to -0.50 and 0.50 to 0.90), which is not limited to a linear pattern, between two numerical variables with skewed distributions (Dellinger, 2018). Kendall's coefficient was computed to determine the association's strength, which was measured with similar metrics as the Spearman coefficient, between a numerical dependent variable and a categorical variable as a predictor (Gibbons, 1993). The Cramer's V effect size was taken as an indicator of the strength of the association, which reflected the proportion of the variance of the dependent variable that the predictor could explain (very strong correlation: 0.70-1.0 (49%), strong correlation: 0.50-0.69 (25%-48%), moderate correlation: 0.30-0.49 (9%-24%) and weak correlation: 0.20-0.29 (4%-8%)), between two categorical variables with statistically significant chi-square tests (McHugh, 2018). The pairs of bivariate analysis are illustrated in Figure 1.17.

In models for linear regression, diagnostics for linearity were applied, including examining outliers and checks about the normality and the homoscedasticity of the residuals and multicollinearity between the dependent and independent variables and between the group of predictors (Figure 1.18) (Montgomery, et al., 2012). Regarding the associations between time-series variables, the statistical methods applied for the diagnostics and correction of heteroscedasticity and autocorrelation are illustrated in Figure 1.19. In the first stage, the pair of time-series variables is checked for heteroscedasticity through plots of histograms and scatterplots and the Breusch-Pagan /

Cook-Weisberg test that indicates homoscedasticity with a non-significant p-value (Lim, et al., 2011). Checks for autocorrelation were done through the visual inspection of time-series plots and the calculation of the p-value of the Breusch-Godfrey test with a statistically significant result indicating autocorrelation (Lim, et al., 2011). Stationarity was checked through a time-series plot of each variable's first difference and comparisons between the mean values between two equal sub-samples of each variable. Following the confirmation of stationarity, established statistical techniques for the correction of autocorrelation and heteroscedasticity were applied. These techniques consisted of comparisons between the standard errors and the p-values of the Breusch-Pagan / Cook-Weisberg in ordinary linear regression (OLR) bivariate models, OLR bivariate models with robust errors and weighted Generalised Least Squares (GLS) Multivariate regression (with the extra variable of temporal variation) (Lim, et al., 2011). For autocorrelation correction, the first difference transformation and the Cochrane-Orcutt Prince Winston methodology were applied (ref). In the final stage, coefficients, standard errors, and r-square values were compared between two time-series regression models that were computed as finite distributed lags and Infinite Distributed lags (Lim, et al., 2011).

Probit regression is a widely accepted method for the analysis of small to moderate samples of categorical data from thermal comfort surveys (Nicol, et. al., 2012) and was applied in two thermal comfort surveys in hospital spaces (Khalid, et. al., 2019; Hwang, et al., 2007). Through the application of the probit function, the cumulative proportions of each category of the dependent ordinal variable (thermal comfort votes) that fall within the region of specific cut-points in relation to the independent continuous variable (recorded physical measurements) (Liu, 2016). Multivariate binary logistic regression was applied for the odds ratios between discomfort and rising thermal conditions. The full-model was an extension of the two-predictor model and consisted of the temporal and spatial conditions, personal factors and adaptive behaviours that contributed to variation in the reported thermal comfort votes with very strong and strong effect sizes. Multicollinearity was tested between these independent variables and comparisons between the fitted models were based on the values of the Cragg-Uhler/ Nagelkerke R^2 (Liu, 2016).

1.5.3.3 Thermodynamic modelling

Thermodynamic building simulations were performed with the IESVE 2019 software designed to optimise buildings' environmental performance based on thermodynamic modelling (IESVE, 2015a).

In the IESVE software , thermal conditions are calculated based on steady-state assumptions for the sensible and latent heat flows through the surfaces and air masses within and around the thermodynamic model (IESVE, 2015a). Sensible heat balance is estimated through the combined calculation of the convective heat exchange and the heat exchange through conduction between the layers of the construction elements, air, solar gains and internal heat gains by air movement and internal heat gains and of the heat exchange through conduction from the solar gains in the construction elements and the thermal radiation exchange between surfaces (IESVE, 2015a). The latent heat balance calculations involve the transfer of water vapour by air movement, the transfer of latent heat by casual gains, and the impact of the mechanical humidification or dehumidification processes (IESVE, 2015a).

The development of the thermal model involved the following fundamental actions: a) design of the building geometry, b) assignment of the fabric's materials; c) specification of the space conditions (IESVE, 2017b). Firstly, the architectural model of the ward block accommodating W1 and W2 were imported into the IESVE virtual environment. In ModelIT, problems related to intersecting surfaces and holes in external surfaces were identified and corrected accordingly. Secondly, the necessary modifications in the model's geometry were made consisting of the following actions: a) the central bedded area was separated from the peripheral zones with the addition of doors and windows; b) skylights were added in the roof perimeter; c) the roofs of the peripheral zones were separated from the roof covering the central bedded area and skylights were added in the roofs of the peripheral area. Freetown's damaged weather file had to be replaced with Sabah's weather file that had the most similar climatological conditions and was available in the dataset linked with IESVE (Figure 1.20a). Differences in cloud cover were expected to cause in the thermal model significant deviations in solar exposure from those expected in Freetown (Figure 1.20a).

The development of a more robust thermodynamic model includes the generation of site-specific weather data calibrated according to on-situ measurements. Thermal properties are determined from the properties that specify the thermophysical properties and the metrics of solar absorptivity and emissivity assigned to every single layer of each construction element and are defined by the type of its material using the APcdb tools available in the Apache environment. In Figure 1.20b, the material of each layer of the customised construction types for the external and internal walls, internal floors and ceilings, roofs, external and internal glazing, and roof lights are illustrated. The Apache Systems application was used to specify the space conditions determined by the type of the cooling and ventilation systems and internal heat gains (Figure 1.20c). Through the MacroFlo application, the properties of the window and doors can be assigned. These properties describe the type of the opening, the crack characteristics and the degree of the opening (Figure 1.20d). An operational profile as 'continuously open' is automatically assigned to holes. The results were exported in hourly time intervals for a whole year.

The ApacheSim application performs the thermodynamic simulations. Heat exchange within and around each and between thermal zones driven by weather data and defined by convection, conduction, and radiation is first modelled individually for each construction element based on the mathematical equations described in detail in ApacheSim Calculation Methods (2015a). These calculations are merged with the airflows driven by wind and buoyancy (stack pressure) and influenced by HVAC systems that are calculated by the Macroflow application (IESVE, 2015a) ApacheSim uses the SunCast data and redefines the beam component of solar radiation in external and internal surfaces through glazing, while shading calculations for shading devices in construction elements are also performed in ApacheSim (IESVE, 2015a). In SunCast the incident beams of solar flux while accounting for surface geometry and external shading factor are used to estimate the incident solar radiation in the building's exterior surfaces. In MacroFlow, airflow simulation through windows, doors, holes, and air-cracks is assumed to be driven by pressures arisen from wind and buoyancy effects and mechanical airflows from HVAC systems (IESVE, 2015c). During an ApacheSim simulation, Maroflow exchanges data with ApacheSim having all its data about air and thermal exchanges get fully merged with the ApacheSim simulations (IESVE, 2015c). During the Macroflow simulations, the wind speed and wind direction data from the weather file and the information of the window openings' properties and surrounding microclimate are used to calculate the wind pressure on the external surfaces of the building (IESVE, 2015c).

Meteorological wind speed is modified by differing wind pressure coefficients, which were derived from in situ measurements, CFD studies, and wind tunnel experiments, depending on the terrain and the building's height (IESVE, 2015c)[12]. In MacroFlo, air density in each thermal zone is assumed to be

[12] Macro flow uses three different coefficients that are published in the ASHRAE Handbook of Fundamentals (2001) and correspond to the following urban morphologies: a) a country terrain type with low-rise buildings in open and flat terrain; b) suburbs with low-rise single-family houses; c) city centres with buildings higher than 21m comprising 50% of the sample (IESVE, 2015c).

uniform for the calculation of buoyancy-related pressures, which differ in different heights as air pressure is assumed to have a linear relationship with height, while the stack effect is assumed to be the variation of pressure at different heights of the room and to be driven by temperature differences in these air masses (IESVE, 2015c). Regarding outside air density, both wind and buoyancy-induced pressure are included in the calculations, whilst infiltration from cracks is also considered (IESVE, 2015c). The modification of the flow due to buoyancy effects inside the room is assumed to be determined by an additive constant which is defined by the opening characteristics and contributes to a steady-state flow in the thermal zone (IESVE, 2015c). For the determination of the airflow, the characteristics of the opening and the exerted pressure are considered for double and single-sided naturally ventilated thermal zones. Rayleigh instability characterised by warm air being concentrated below cool air is solved by applying the equations describing the 'behaviour of plumes' (IESVE, 2015c).

Chapter 2
Historical Aspects of Thermal Comfort

Abstract

Historical hospital buildings constructed between the late nineteenth and early twentieth centuries exhibit high potential for low energy cooling. In this chapter, the embodied climate-sensitivity among a sub-sample of the selected Freetown's Connaught Hospital wards built in the 1920s is explored through the historical study of colonial hospital architecture and environmental engineering. In the 1880s, the dominant conceptualisation of the hospital ward as an instrument for efficient ventilation set the foundations for environmental-conscious hospital design. However, the precise connections between colonial hospital design and environmental engineering have yet to be established. In this chapter, it is investigated how the thermal environments for colonial wards at equatorial climates before the 1940s were envisioned and how these ideas were applied in the construction of Connaught Hospital. Drawing on extensive archival materials, site survey and architectural modelling, I trace the history of the Connaught Hospital from 1817 to 1960 and examine the birth and evolution of the Nightingale ward, and in particular how its architecture was adapted for the British colonies in the equatorial zone. The chapter proceeds by providing a systematic analysis of the architecture of a sub-sample of the selected wards, which will demonstrate how, through the lens of environmental engineering, the wards in question display climate-sensitive characteristics. Hence, this chapter functions as a first stage for the diagnosis of the conceptualisation and application of thermal comfort in colonial hospitals in equatorial climates.

2.1 Introduction

At the turn of the nineteenth century, colonial hospital design entangled the political, economic and social spheres of colonial governance with the advancement of medicine and environmental engineering. Over the past decade, the historical examination of hospitals in Ceylon (Jones, 2009) and the network of dispensaries in India (Sehrawat, 2013) have revealed how colonial hospital development contributed to the emergence and consolidation of colonial markets and economies. Although a direct correlation between medical advancement and reforms in hospital design and nursing practices has not been demonstrated (Kisacky, 2017), historical studies have shown that scientific discoveries were crucial drivers in the transformation of hospitals at the time (Black, 2005). In particular, the focus of colonial engineers on ventilation systems encapsulated, applied, and tested several theories regarding disease transmission (Fair, 2014). In the course of the nineteenth century, and up until the emergence of bacteriology in the 1870s, debates about the impact of "fetid" or "vitiated air" on human health in built spaces reached their apex, and became institutionalised in the struggle between contagionists and anti-contagionists (Ackerknecht, 1948). These debates contributed to major shifts in the architectural and engineering design of hospitals, leading to the formation of the pavilion hospital typology by the mid-nineteenth century (Taylor, 1997).

To date we lack a comprehensive history of pavilion-plan hospitals in the British colonies. However, in his recent work, influenced by a broader historical understanding that the "climate as a cause" was part of a ubiquitous pathologisation of space (Naraindas, 1996: 3), Chang (2016a) has retraced the history of the Singapore General Hospital (S.G.H.). Chang explored how the pavilion system was modified for equatorial climates in ways which, rather than merely reflecting interpretations of miasmatic theories at the time, facilitated segregationist practices and hence fostered racial and class inequalities. Moreover, as Kyu-hwan (2017) has shown in his study of the Government Civil Hospital in Hong Kong in the 1880s, the pavilion system reinforced segregationist patient management based on new understandings of disease transmission influenced by germ theory. While these historical studies provide critical insights into the role of hospitals in the social transformation and regimentation of populations at the time of colonialism, my interest lies more with the way in which colonial hospital design and environmental engineering define the function of these hospitals in today's post-colonial condition. However, in order to do this, we first have to examine the historical development of the colonial hospital design as this relates to structural aspects that determine thermal comfort.

This chapter's aim is to provide a first-stage diagnosis of thermal comfort in a sub-sample of the selected Freetown's Connaught Hospital wards built in the 1920s. The chapter thus addresses a key question as regards the inherent climate-sensitivity of this hospital: How were the aspirations in pre-1940s colonial hospitals, which predate the habitual installation of air-conditioning, realised in the construction of Freetown's Connaught Hospital?

Colonial hospitals' role as medical and educational institutions, as well as their status in the colonial health system and their acceptance or not by the local population, has a direct impact on their architectural and engineering evolution (Harrison 2009). In the first part of the chapter, I explore the importance and trace the historical development of Freetown's Connaught Hospital from its foundation in 1817 (when it was known as the Royal Hospital and Asylum) to Sierra Leone's independence from British colonial rule in 1961. In the second part of the chapter, I investigate the development of pavilion hospital typology for equatorial climates. Rather than simply aiming to reconstruct Florence Nightingale's recommendations about ward design, the objective of this section is to examine how she conceptualised thermal comfort through the exploitation of natural ventilation in order to transform the layout, function and operation of wards. While recognising that thermal comfort was not Nightingale's primary focus, I aim to underline how climate-sensitivity and occupant adaptive behaviours were an integral part of ward design. I thus explore how hospital architecture corresponded to the climatic challenges of equatorial climates. In particular, I examine the ways in which, driven by climatic extremes, new environmental engineering norms reconfigured hospital architecture. In the third part of this chapter, I compare archival and "as built" drawings of representative wards (among the selected cohort of the case-study wards) in Connaught Hospital and offer interpretations of the selected ward cohort not only as regards architectural similarities with Nightingale wards, but more importantly in terms of their expected thermal environmental performance. In the end of this chapter a literature review of the historical aspects of thermal comfort in hot and humid conditions is presented.

2.2 Methods of Data Collection and Analysis

Methodologically this chapter draws on the author's archival research, building survey and digital architectural reconstruction modelling. The archival sources of this study are from the National Archives in London, the British Library, and the State Library in Freetown. These sources are complemented by a systematic reading of medical reports between 1897 and 1959, and of reports by the Public Works Department between 1914 and 1961, which were submitted annually by the British colonial government in Freetown. The drawings of the existing conditions at Connaught Hospital were drawn for the first time by the author.[13] Through photos and sketches, the building envelope's geometry and materials, interior layout and shading, ventilation and cooling systems were documented, while detailed interior and exterior measurements were taken in the selected wards.[14] Finally, the digital reconstruction model of the hospital was created with Autodesk Revit 2017.

[13] The Ministry of Health and Sanitation held the only available photocopy of an unscaled ground plan of the Connaught Hospital, which was surveyed in 2012 by the UNOPS team for an unrealised refurbishment project.

[14] The external and internal measurements were made with a "DMiotech 80m Mini Handheld" digital Laser meter.

2.3 The Development of Freetown's Connaught Hospital (1817-1960) in its Colonial Context

In 1817, nine years after the foundation of the British Crown Colony of Freetown, the Royal Hospital and Asylum for Africans commenced its operation at the King's Yard site, where the Connaught Hospital Complex presently stands, as an institution for the provision of medical care and documentation to the newly arrived liberated African slaves (Kup, 1975) (Figure 2.1a). The new settlers entered the Asylum from the King's Yard Gateway (Figure 2.1a). In 1880 the Royal Hospital and Asylum for Africans became the Colonial Hospital (Alldridge, 1910) and in 1910 it was renamed "Connaught Hospital" in tribute to the visit of the Duke of Connaught that same year (Alie, 1990). In 1892, the first Mission Hospital was founded ("Princess Christian Hospital"), and 1899 saw the foundation of the "Colonial Nursing Home for the Europeans" (Alldridge, 1910). Although British colonial authorities tended to prioritise the health of Europeans over that of Africans (Mills, 1998), the priority of authorities in Freetown was for colonial hospitals to accept both Africans and Europeans (Alldridge, 1910). Except for a short period during WWI, the Colonial Hospital had always been a mixed-race and mixed-class medical institution (Young, 1918). Sierra Leonean women were not allowed to be trained as nurses and hence all native nurses were men (Prout, 1902), while Sierra Leonean doctors were also men and received training at the Medical School in Edinburgh (Patton, 1996). Despite the difficulties faced by the British in expanding their colonies across West Africa (Porter, 1999), the British Sierra Leone Protectorate was founded in 1896 (Fyfe, 1968). The Colonial Hospital became the first hospital for the application of Western medicine in British West Africa (Fyfe, 1962). Towards the beginning of the nineteenth century, the surrounding area of the Colonial Hospital developed into a bustling mixed-use and multi-cultural community (Quilliam, 1903) and kept that character for over a century (Figure 2.3). However, up until the 1900s, financial problems and the disorganisation of the colonial government limited public health initiatives in the Protectorate (Griffiths, 2009). As a result, the expansion of hospitals, dispensaries and clinics from urban to rural areas (a typical colonial policy elsewhere; Gish, 1979) was postponed until the 1920s (Fyfe, 1962). Furthermore, whereas in other colonies, like British India, philanthropy supplemented the colonial government's public health budget (Sehrawat, 2013), in Sierra Leone, public funding covered the entire cost of public health measures and healthcare was free of charge (Fyfe, 1962). From 1900 onwards, European physicians employed by the colonial government could also run their private practices in Freetown (Prout, 1902).

The plans of the Colonial Hospital are missing from the National Archives in Kew and the British Library in London, as well as from the State Archives in Freetown, thus limiting my ability to historically reconstruct its exact architectural configuration. Although the exact spatial distribution of the Colonial Hospital's buildings remains unspecified, a close reading of the colonial archives reveals that the hospital was probably the first pavilion-plan in British West Africa. It was composed of a two-storey male ward block, named "Arthur's Ward" and "Hart's Ward", and a two-storey female ward block, known as "King Harma's Ward" and "Grace's Ward", which were connected with an outdoor corridor. The complex also included a prison infirmary, an isolation cottage, an outpatient's block, and a mortuary (Prout, 1902; Prout, 1903; Renner, 1950; Burrows, 1916) (Figure 2.1a).

Interventions in the built environment driven by motives of better sanitation, as well as segregation between colonisers and the colonised, are common across colonial public health history (Chang, 2016a). Such motives possibly drove a series of maintenance works at the Colonial Hospital between 1900 and 1902. Over the first decades of its operation, the needs of staff and patients surpassed its capacity. In 1912, a total of 12,910 male and 9,535 female patients were treated at the hospital (Prout, 1906; Collete, 1913). Contrary to what happened in India, where before the employment of female doctors in the 1840s women avoided the male-dominated colonial hospitals (Harrison, 2009), at the Colonial Hospital in Freetown the twenty-nine-bedded "Grace's Ward" in the block for female patients operated at full capacity (Prout, 1906). It is likely that some of the fifteen male nurses, being trained under the supervision of three European female nurses, worked at "King Harma's" maternity ward (Prout, 1903).

Ronald Ross (1923), the discoverer of the malaria parasite, whose research and teaching are considered by medical historians as foundational to tropical medicine (Arnold, 1996), observed during his 1899 malaria expedition in Freetown that Europeans and Sierra Leoneans lived in similar urban areas (even during the night) without proper sanitation networks, and that their houses were congested, lacking sufficient daylight, ventilation and mosquito nets. A few years earlier, in 1872, Governor J. Pope-Hennessy proposed for the first time the spatial segregation between Europeans and Africans through the development of a European community on the hills, but his idea was dismissed due to technical and financial constraints (Fyfe, 1962). However, in 1902, the area at Hill Station, located at 750 feet altitude and four miles away from central Freetown, was cleaned from vegetation and, two years later, twenty prefabricated bungalows were transferred from England and placed on the hill in columns with a north-south orientation (Spitzer, 1968). Finally, in 1910, an Order in Council certified the Hill Station Reservation as an exclusive residential area for Europeans (Davies, 1968). In 1916, seventeen years after Ross's visit to Freetown, the distribution of mosquito nets began, but only among colonial government officials for private use (Allan, 1917).

By the end of WWI, the Sierra Leone Protectorate was close to financial collapse having coped with a smallpox epidemic in 1915-1916, and an influenza outbreak in 1918 (Rashid, 2011). Moreover, on February 3, 1920 a catastrophic fire destroyed all the buildings of the hospital (which by then was known as the Connaught) except from the isolation cottage at its western side (Lake, 1921). All the services of Connaught Hospital were transferred to the old Law Courts building (Figure 2.3), which was repurposed to accommodate an eighteen-bedded male ward, a four-bedded maternity ward, and three offices for outpatient services, the Medical Officer and the Matron (Wood, 1921). Turnbull and Halls, already employed as assistant engineers at the design branch of the Public Works Department (P.W.D.) in Freetown, undertook the task of preparing the drawings for the new, post-fire, Connaught Hospital (Lake, 1921). By 1921, having won the tender competition, the contractors Thomas and Edge undertook the construction, and began the erection of the two first ward blocks (Lake, 1922) (Figure 2.1b). Their location was probably similar to that of the old Colonial Hospital's male and female ward blocks (Figure 2.1b). By the end of 1922, the P.W.D. demolished the building containing the offices of the Sanitary Department and in its place Thomas and Edge built the third ward block, the operating theatre, the laundry and kitchen, the fumigation block, and the mortuary and post-mortem block (Lake, 1923) (Figure 2.1c). In 1922, the P.W.D. finally completed the construction of the new concrete drainage network, which ran in the perimeter of the wards and collected the wastewater from the baths, toilets and kitchen (Lake, 1923). By 1923, Connaught Hospital reached a capacity of eighty beds and five cots (probably twenty-thirteen beds per ward), while the Old Law Courts Building still housed the administrative and the outpatient services (Peacock, 1924). Only the Nursing Home for the Europeans imposed fees. As a result, in 1923, although the revenue of the Connaught Hospital was lower than the revenue of the Nursing Home for the Europeans, the number of patients treated at the Colonial Hospital was ten times higher (Peacock, 1924). Whereas in British India patients received ophthalmological services at premises like the Eye Ward of the Colonial Hospital in Delhi even before the end of the nineteenth century (Sehrawat, 2013), in Freetown the first specialised medical services appeared only in 1923, in the form of a dentistry, which opened at the old mortuary building of Connaught Hospital (Peacock, 1924), but was replaced two years later by a venereal disease clinic (Inness, 1925).[15]

On March 23, 1925, the colonial government appointed Archer A. Betham (F.R.I.B.A) as architect based at the P.W.D. offices in Freetown (Bradshaw, 1926). The hand-drawn plan titled "Sketch Site Plan, New Hospital Freetown" is signed by him and dated July 31, 1925. The drawing bears the

[15] The archives do not comment on where dentistry was relocated.

signature of receipt of the director of the Public Works Department W.S Lake, dated August 14, 1925 (Figure 2.4). Oriented so that the top points to the North, the plan is drawn using pencil for topographical contours, plot boundaries, landscaping and buildings' names, and ink of three colours: black for the existing building, red for proposed buildings, and green for future extensions (Figure 2.4). It is evident in the site plan that Betham followed the pre-established principles of the parallel position of ward blocks and the spatial dispersion of different uses in free-standing buildings, as these were originally applied at the old Colonial Hospital (Figure 2.4). Whereas from July 1 to July 31, 1925, Betham submitted, in succession, plans and elevations for the proposed Outpatients Block, the Stores, and the Medical, Sanitary and Administrative Block, there is no evidence to suggest that he prepared the drawings for future extensions consisting of three ward blocks, the European nurse quarters, the European Wards, a dentistry with male nurses, and the medical officer's quarters. Betham possibly kept his position as a colonial architect until 1936, when the P.W.D. hired a new architect for the first time since Betham's employment (Brown, 1937). Although limited evidence is available about Betham's studies, career and personal life, his service in 1920 as a junior assistant architect for the colonial government in Madras (British India) early in his career certainly shaped his knowledge about architecture in equatorial climates (Anon., 1920). Indeed, his drawings for an efficiently constructed bungalow, submitted for a competition organised by *The Daily Mail* in 1922, reveal his advanced understanding of building design adapted to equatorial climates (London Associated Newspapers, 1923).

The Outpatients Block (Figure 2.4), the Medical Store Building, and the Administrative Block (Figure 2.6) were completed before the end of 1926 (Figure 2.1d) (Lake, 1927). However, they remained closed throughout 1927, and as a result, hospitalisation demands exceeded the bed-capacity of Connaught Hospital (Inness, 1928). By 1929, a new two-storey ward block for surgical cases with a capacity of twenty-eight beds and eight cubicles, a lift and a veranda for outdoor treatment, partly covered the excess hospitalisation needs (Figure 2.1e) (Brown, 1929, Leitch, 1930). In June 1929, Betham submitted to the P.W.D. a new set of drawings for an eight-bedded children's ward above the operation theatre completed by 1931 (Stewart, 1932). In 1937, the colonial government decided the erection of a new twenty-bedded 'Hospital for the Europeans' and demolished the Nursing Home (Lightbody, 1938). The latter was composed of a wooden bungalow housing the offices and a concrete block containing an operation theatre and a patient-ward and had until then satisfied the hospitalisation needs of Europeans (Inness, 1928) alongside a fourteen-bedded residential bungalow at the Governor's Lodge at Hill Station which since 1924 had provided medical care exclusively to Europeans (Oakley, 1937). In 1937, the P.W.D. designed a new maternity hospital located next to the

Connaught Hospital to supplement the work of the Mission Hospital, which was by then the only maternity ward in Freetown (Stewart, 1939). By 1938, the colonial Medical Department employed 229 healthcare workers, while sixteen government-run and five missionary hospitals were operational (Keller, 1940). Despite the rise to 120 beds by 1938, Connaught Hospital could not accommodate the expected WWII casualties. Therefore, for the duration of the war, the British and the Americans organised first aid stations at schools, hospitals and government buildings in Freetown, while reconstructing Freetown's port with the intention to use it as a naval base (Howard, 2015). In 1948, the Quarters for the Nursing Sisters within the Connaught Hospital complex were ready for occupancy, also housing the new private wards (Figure 2.1f) (Renner, 1950). In 1959, the Colonial Development and Welfare Scheme provided funding for the replacement of old X-ray machine (installed since 1926), and maintenance works at the kitchen and laundry (Boardman, 1960). Until the dissolution of the colonial government in 1960, the proposed buildings of the three extra ward blocks, the European wards, the dentistry and the medical officer's quarters (as illustrated in Figure 2.4) remained unbuilt.

2.4 Design of Pavilion Hospitals for Equatorial Climates and Florence Nightingale's Contribution

The Colonial Hospital in Freetown was among the first colonial hospitals in British West Africa incorporating the basic principles of pavilion-plan typology. Later, the New Colonial Hospital known as Connaught Hospital demonstrated substantial compliance with Nightingale's recommendations as regards the design principles of separation between treatment, diagnosis, administration, accommodation, and isolation, and the parallel location of the ward blocks combined with unobstructed proximity to the waterfront and favoured by its orientation towards the prevailing winds (Figure 2.1g). Despite the evidence from contemporary scientific research that operational Nightingale wards built in the nineteenth and twentieth centuries exhibit climate-responsive attributes and high ventilation rates (Gilkeson, et al., 2013; Lomas and Giridharan, 2012), case studies to date cover only temperate climates. In this chapter, my aim is to compare, on the one hand, the Nightingale ward prototype for British Indian stations, the ward for Europeans at the S.G.H. and hospital buildings in British West Africa and, on the other hand, the architecture of Connaught Hospital in Freetown. This set of comparisons is guided by the following connecting histories. First, the comparison between the Nightingale ward prototype for British India stations and Freetown's Connaught Hospital is meaningful as one of the key Connaught Hospital architects, Arthur Betham, had worked as an assistant architect in Madras before arriving in Freetown. Second, the comparison between the ward for Europeans at the S.G.M. and Connaught Hospital is meaningful as S.G.H. is the best historically documented pavilion-plan hospital in the equatorial zone. Third, the comparison between other hospital buildings in British West Africa and Connaught Hospital is since they overwhelmingly shared the same climatic, political and sociocultural conditions.

2.4.1 The Nightingale Ward Prototype for British India Stations

In 1864, the Commission for the Barrack and Hospital Improvement (B.H.I.C.) issued a report about the necessary improvements for barracks and hospitals in British India (B.H.I.C., 1864). The preparation of the report began in 1863, with extra support from the Army Medical School, the Army Medical Department, and Army Statistics (Vallée and McDonald, 2006). At that time, the governance of British territories in the Indian Subcontinent was handed over from the East India Company to the British Crown following the Indian Rebellion ("Indian Mutiny") of 1857-1858, and more British soldiers were to be transferred to Indian stations (Chang, 2016). Florence Nightingale was a member of this commission and contributed with her work to the reports published in 1861 and 1864 (Vallée and McDonald, 2006). For the preparation of the second report, on-site inspections in Indian stations were not realised (Vallée and McDonald, 2006). Nightingale never visited India, and her sources of information consisted of newspaper articles, government reports, interviews with British officials, and questionnaires created by her and distributed to all 150 barracks and hospitals in the British Raj (Vallée and McDonald, 2006). There, Nightingale built on her extensive work on European hospital design.[16]

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[16] The pavilion hospital is one the earliest building types of the modern era (Adams, 2008). Significant innovation was reflected in the functional organisation, the construction and the heating and ventilation systems (Banham, 1969). The Nightingale ward, which was the primary component of the pavilion hospital, was not Florence Nightingale's original idea (Thompson and Goldin, 1975; Taylor, 1997). According to Goldin (1975), Nightingale's unique contribution was that she took pre-existing ideas, tested them in a scientific manner and modified them according to the results of her trials. Nightingale's work at Scutari in Istanbul from 1854 to 1856 during the Crimean War, gave her the opportunity not only to witness the detrimental effects of poor sanitary conditions, overcrowding and poor ventilation on mortality rates among sick soldiers, but also to observe how her ideas about improvements in sanitary conditions and ventilation contributed to a dramatic rise in survival rates among hospitalised soldiers (McDonald, 2014). In the Crimea, Nightingale developed a systematic methodology of evidence collection and statistical analysis (Fee and Garofalo, 2010), which according to Kisacky (2017) contributed to the standardisation of pavilion hospital design and its export to the colonies during the following years.

Nightingale was a proponent of the miasmatic aetiology of disease transmission (Nightingale 1859). She supported the idea that "Infection acts through the air. Poison the air breathed by individuals and there is infection" (Nightingale 1859: 7). She believed that ventilation rates should be proportional to the rate of carbonic acid being released per person/ per day, which according to her calculations was 0.66 m^3/ per person/ per day (Nightingale, 1859). Billings (1893) reported that 3,000 cubic feet (84.95 m^3) per hour of fresh air in a ward with volumetric space from 100 to 1,000 cubic feet (2.83-28.32 m^3) per person[17] could reduce the concentration of carbonic acid from 6-7/ 10,000 to 3-4/ 10,000. In 1861, the B.H.I.C. published a report about the sanitary conditions and the required improvements of barracks and hospitals in England (B.H.I.C., 1861). Most of the examined spaces failed to comply with the standards set in 1850 by the Royal Commission on the Sanitary State of the Army at 17.00 m^3/ per person in barracks and 34.00 m^3/ per person in hospitals (B.H.I.C., 1861).

Nightingale prudently shared the belief, which was prominent among proponents of miasmatic theories at the time, that the built environment could be modified in order to amplify the healing potential of "nature" through the provision of fresh air and sunlight (Selanders, 2010). Indeed, she believed that the amount of fresh air and daylight supplied to patients should be accurately calibrated (Nightingale, 1863). Nightingale thus believed that the adequate provision of fresh air was feasible through the modification of the ward design (Nightingale, 1859). In so doing, she conceptualised the ward as an instrument for efficient ventilation aimed at diluting the supposedly poisonous vapours generated by infected humans and objects (Kisacky, 2017). The ventilation rates had to be high enough to dilute and extract the supposedly "fetid" or "vitiated" air masses continuously (Nightingale, 1863), often causing uncomfortably low temperatures for occupants (Thompson and Goldin, 1975). Nightingale wards facilitated the surveillance not only of patients but also of the thermal environment surrounding them (Galiano, 2000). A system of spatial attributes representing specific metrics aimed at predefined natural ventilation performance goals, which can be organised according to the following themes: space use, ward layout, solar control, the building envelope's thermal capacity and ventilation (Figure 2.7a).

Regarding hospital design in temperate climates, Nightingale's recommendations covered mostly the ward layout and ventilation. In her influential book *Notes on Hospitals*, Nightingale (1859) insisted on the spatial separation between the bedded space of the ward and the rest of the rooms

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[17] Corresponding to Air Changes per Hour/per person (of fresh air) from three to thirty.

accommodating any other auxiliary services. As illustrated in Figure 2.7a, sanitary facilities were allocated in the west side of the pavilion, while the stairway, the head nurse's office and the scullery occupied the east side (Nightingale, 1859). Though missing from Figure 2.7a, each ward had to have one private room, which could house the terminally ill and the highly infectious patients (Nightingale, 1859). Nightingale (1859) believed that the free volumetric space surrounding each patient's bed had to be large enough for the successful dilution of the polluted air. As a result, the total volumetric space of the ward had to be proportional to the number of beds. In 1857, the Royal standard for volumetric space per bed for European hospitals was $34m^3$ (Hemming, 1900). According to Nightingale's original plan, a thirty-bedded ward with $351m^2$ and $1,020m^3$ surface and volumetric space, respectively could deliver $34m^3$/ per patient and comply with the required standards (Figure 2.7a). A thoroughly studied typical Nightingale ward at the Bradford Royal Infirmary accommodated twenty-five to twenty-eight patients at an open ward providing $20m^2$ per bed (Lomas and Giridharan, 2012). Nightingale (1859) emphasised that the ratio of the width to the length of the ward had to be below 0.23 (Nightingale, 1859). According to experiments conducted at the Lariboisière Hospital, whose architecture Nightingale highly praised, a ratio of 0.23 allowed for high ventilation rates towards the face and the hands of patients, while avoiding draughts (Nightingale, 1859). Beds had to be placed with their heads facing the wall in only two rows at opposite directions, at a distance from 0.95m to 1.55m between each other and only in pairs between each window (Figure 2.7a) (Nightingale, 1859). Under no circumstances could the supervision of patients by the nurse station be obstructed by the installation of partitions between the beds (Nightingale, 1863). With the intention to maximise the opportunities of cross-ventilation, Nightingale devoted a significant part of her book on the construction of continental wards to window design. Approximately 19% of the north and the south facade respectively had to be covered by windows (Figure 2.7a). This window coverage corresponded to a window area of $35m^2$ at either the north or the south facade consisting of nine windows, which had to be installed opposite each other at a distance of 0.90m from the floor, 0.30m from the ceiling, and 3.47m away from each other (Nightingale, 1863). Not only the design of each the pavilion, but also the spatial configuration of the whole hospital had to facilitate cross-ventilation. Each separate pavilion had to be allocated in a north-south orientation, next to each other in parallel positions at distance equal to twice the pavilion's height (Nightingale, 1859). Each pavilion had to have two storeys only, and a basement elevated in arches, while a corridor running along their east side connected the pavilions (Figure 2.7a) (Nightingale, 1859).

Driven by the belief that climatic extremes in the equatorial zones amplified the harmful effects of "miasma", in 1864 the B.H.I.C. described in detail how the capacity of the ward for natural ventilation could be increased (Chang and King, 2011). In this report, although great emphasis was placed on the design of the ward block, the spatial design of the hospital buildings and topographical, climatic and landscape characteristics of the site that were important for Nightingale's conceptualisation of pavilion-plan typology were overlooked. The ward had to be allocated on the first floor, while the ground floor accommodated administrative, leisure and other auxiliary services (Figures 2.7b.1-2) (B.H.I.C., 1864). It was recommended that military hospitals have only two storeys above an elevated and ventilated basement circa 1.50m high (Figure 2.7b.2) (B.H.I.C., 1864). The Royal Commission set the cubic allowance per person in hospitals at equatorial climates at 43.00m^3 and at 45.00m^3 in 1857 and 1900, respectively, whilst emphasising that a healthy amount of air consisted of 21% of oxygen gas, 79% of nitrogen gas, 0.003%-0.009% of carbonic acid, and a maximum 50% of moisture content (Hemming, 1900). The ratio of width to length had to be kept at 0.23 (Figure 2.7b.1). A twenty-four-bedded ward was designed to have a volumetric space of 1,233m^3; thus 51.38m^3 were assigned per bed (Figures 2.7b.1-2). A veranda with a width between 3.00m and 3.70m had to run along the south, west and north sides separating the ward from the winds, with the bathrooms and the toilets at the west side (Figure 2.7b.1) (B.H.I.C., 1864). The east side was attached to the ward and accommodated the sergeant's room and the scullery in two separate rooms placed opposite each other (Figure 2.7b.1) (B.H.I.C., 1864). An operation theatre could occupy the far-east side (Figure 2.7b.1) (B.H.I.C., 1864).

For the Nightingale ward prototype for British India stations, as laid out in the B.H.I.C report (1864), the primary means for solar control on the ground floor of pavilion-ward blocks was the veranda, whereas on the first floor the roof extended to the width of the veranda and shaded it (Figure 2.7b.2) (B.H.I.C., 1864). In addition to vertical shading, horizontal shading was provided by shutters with angled louvres installed between the pillars of the two storeys (Figure 2.7b.2) (B.H.I.C., 1864). Protection against excess heat storage in the thermal mass was supplemented by the construction of cavity walls with empty airspace between them and air bricks, which allowed for the extraction of heat trapped inside the cavities (B.H.I.C., 1864). A suspended lightweight structure connected with the roof through an air-space, with a depth of 0.15m to 0.23m, composed the ceiling of the first floor (Figure 2.8) (B.H.I.C., 1864). An external layer of light-coloured tiles above a double-layered wood boarding increased the roof's reflectivity (B.H.I.C., 1864). In total, twenty-two windows covering 26.88% of the north and south facades of the bedded area, respectively, had to be installed 0.60m to 0.80m above the floor and 0.15m below the ceiling (Figure 2.7b.1) (B.H.I.C., 1864). The veranda's openings covered 42.45% of the external north and south facades respectively, all of them bearing vertical louvered shutters for shading (Figure 2.7b.1). The Commission recommended a casement type window opening inwards, with sliding angled blinds installed at the exterior of the window (B.H.I.C., 1864). The doors had to be covered with a moveable screen so that they could be kept open during the night without creating draughts (B.H.I.C., 1864). Top hinged windows had to be installed above each door, including a rope or pulley to control their position (Figure 2.7b.2) (B.H.I.C., 1864).

A group of combined interventions on the external walls, the roof, the ceiling and the windows comprised the natural ventilation system of the wards. The installed mechanisms had to be easily controlled and maintained by the occupants (B.H.I.C., 1864). Inlets of fresh air with a depth of 0.27m had to be constructed at the top of the external walls and be covered with hinged louvres, so that dust and rain could be kept outside (Figures 2.7b.2-8) (B.H.I.C., 1864). On the ground floor, the extraction of fresh air was augmented with the construction of an airshaft (Figures 2.7b.2-8). For every volumetric interior space between $0.40m^3$ and $0.60m^3$ the required shaft's area was estimated to be $0.00065m^2$ (B.H.I.C., 1864). Hinged louvres had to cover the point of air entry and the point of air extraction along the airshaft (Figure 2.8) (B.H.I.C., 1864). A movable wooden surface had to be installed in front of the louvres at the inlet of the airshaft (Figure 2.8) (B.H.I.C., 1864). On the first floor, accumulated warm air at the top of the room was channelled through openings at the ceiling towards the roof and was extracted from the outlets at the ridge of the roof, while warm air at the ceiling of the first-floor veranda could also be extracted from the ridge (Figures 2.7b.2-8) (B.H.I.C., 1864). As Chang (2016a) has noted, the Commission was against the application of local cooling techniques. The Commission suggested the use of the "thermantidote" for evaporative cooling through the extraction of moisturised air, although it was energy intensive (B.H.I.C., 1864). The work of the B.H.I.C. remained influential until the middle of the twentieth century. In 1938, Ghosh presented a system of natural ventilation consisting of a set of various openable window types installed at different heights, which were supplemented with chimney ventilators and airbricks with openable covers.

2.4.2 The Ward for Europeans at the S.G.H

The S.G.H. is a well-documented hospital not only in terms of its socio-cultural function, but also regarding its environmental engineering. The S.G.H. complex was designed by the London-based architects Major P. Hubert Keys and Frank Dowdeswell; its construction began in 1923 and ended in 1926 (Chang, 2016a). In a presentation given the Fifth Biennial Conference of the Far Eastern

Association of Tropical Medicine held at Singapore in 1923, J. S. Webster, Professor of Medicine at the King Edward VII Medical College (Singapore) and advisor of the board working on the construction of the S.G.H., stressed the importance of cooperation between architects and the medical staff (Webster, 1924).[18] Webster praised the hospital's architect, Major Keys, for having previous experience with hospital construction. The S.G.H. had a capacity of 800 beds distributed at three groups of pavilions, separately for Europeans and non-European patients (Keys, 1923). According to Webster, the topography and climate of the elevated site of the S.G.H. offered good quality of natural light, air and cool temperatures. The design of the wards facilitated maximum levels of natural ventilation and natural daylight similar to an open-air space (Webster, 1924). Webster supported the separation between male and female wards, as well as the hierarchical differentiation of design quality between single and multibed rooms and between rooms for Europeans and native patients. According to Webster's recommendations, the cubic allowance per patient had to be 260.00m^3 at a single room for Europeans and 31.70m^3 at a general ward for natives.[19]

Although Webster did not mention the B.H.I.C.'s report about the Nightingale ward prototype for British India stations (1864), it is evident that the design team was aware of pavilion hospital typology and the recommended modifications for its adaptation to equatorial climates. In one of the pavilions for Europeans, the bedded areas were placed centrally and were surrounded by a veranda with a width of 3.40m to 4.45m, which separated the wards from other rooms with the exception of the stores and the nurses' room (Figure 2.7c.1). Each ward had fifteen beds in a total volumetric space of 810m^3, thus allowing 75m^3 per patient (Figures 2.7c.1-2). The width to length ratio was 0.5, which is approximately twice higher than Nightingale's recommendation of 0.23, indicating that following Nightingale's estimates, a higher stagnation of the air in the middle of the room would occur. The pavilion had two storeys above an elevated basement (Figure 2.7c). A series of arches with shutters situated opposite the ward's openings along the perimeter of the veranda provided free circulation of air and full shading coverage of the ward's walls (Figure 2.7c). The design for natural ventilation of the ward did not include inlets, airshafts and ventilated roofs. High windows (3.40m) with smaller windows at the top comprised the openable window area coverage of 43.48%

[18] King (1966) argued that the conception of the European Nightingale ward and its export to the colonies epitomised the contribution of architects, doctors and nurses in the design of wards.

[19] Webster presented the following metrics about cubic space/ per patient: for a European general ward 11.15m^2 and 47.60m^3; for a single room for non-Europeans 14.90m^2 and 63.40m^3

and 40.08% at the north and south facade, respectively, while the openings at the veranda covered 52.58% of the north and south external facades, respectively (Figures 2.7c.1-2).

2.4.3 Other Hospital Buildings in British West Africa

Despite the pavilion-plan hospital's popularity at the time (Kisacky, 2017), a thorough examination of colonial archives indicates that pavilion-plan hospitals across the British colonies are not well documented. The photographic collection from the colonial archive of British West Africa at the National Archives in London reveals that whereas colonial hospitals built in the Gambia and in Accra (Golden Coast at the time) between 1871 and 1915 were block-type, heavyweight, over-shaded and cross-ventilated structures (Figures 2.9-10), the Colonial Hospital Complex in the Gold Coast built between 1914 and 1930 presented substantial Nightingale influences (Figure 2.11). In 1920 in the British colony of Cape Town, Colonel D. J. Mackintosh, an experienced Scottish hospital architect, designed an 870-bedded pavilion-plan hospital to house the facilities of the Groote Schuur Hospital at a privileged airy location (Digby, et al., 2008). In 1925, J.S. Cleland, the chief colonial architect, totally disregarded Mackintosh's proposal, mainly due to high construction costs (£1,7400,00), and designed an 842-bedded block hospital (Digby, et al., 2008). As Forty (1980) has noted, multi-storey blocks, which superseded pavilion hospitals, could provide integration of diverse hospital services more efficiently and with less cost.

2.5 Historical Environmental Engineering Aspects of the Selected Nightingale Wards in Freetown's Connaught Hospital

As it is illustrated in the "as designed" and "as built" drawing of the representative selection of W2 and W7, their building envelopes' outlines were identical to those design by Betham in 1925, thus indicating the absence of radical interventions following their construction in 1921 and 1929, respectively (Figure 2.4; Figures 2.7d.1-2; Figures 2.7e.1-2). Therefore, it is likely that any alterations in these wards were limited only to maintenance and decorative works that contributed to the preservation of their original spatial and functional arrangements. This continuation of the original spatial distribution might be a result of absence of introduction of extensive use of medical equipment and of radically different nursing models of inpatient care. The slightly different use of the ward space was illustrated in the replacement of the head nurse's office, which was originally located in one of the rooms at the NNW-N front sides, with a sterilisation room in W2, and with a scullery in W7 (Figure 2.7b1; Figures 2.7d.1-2; Figures 2.7e.1-2). At the same time, the design of the bedded areas at the centre of the ward, the scullery at the S-SSE front side, and the auxiliary uses in the two opposite wings at the NNW-N and S-SSE back sides, demonstrated compliance with the recommended functional organisation of the wards in equatorial climates, as these were recommended prototype ward in British India and realised in the landmark ward for Europeans at the S.G.H. in Singapore (Figure 2.7b.1; Figure 2.7c.1; Figures 2.7d.1-2; Figures 2.7e.1-2).

W2 and W7 were probably designed to accommodate patients in their central areas only with capacities from 12-14 and 10-12 beds, respectively (Figure 2.7d.1; Figure 2.7e.1). However, extra beds were added at the peripheral zones of the NNW-N and S-SSE wings, both in W2 and W7, in order to cover the increasing demands for hospitalisation (Figure 2.7d.2; Figure 2.7e.2). It is evident that whereas the open-plan layout resembled that contained in the B.H.I.C.'s (1864) recommendations, the central bedded areas in W2 and W7 were designed and built with volumetric spaces that were remarkably lower by approximately three and two times by comparison to the volumetric spaces of ward prototype for British India stations and the ward for Europeans at the S.G.H., respectively (Figure 2.7b.2; Figure 2.7c.2; Figure 2.7d.3; Figure 2.7e.3). Whereas the width-to-length ratio was designed and built as 0.26 in W2 and 0.37 in W7, and thus allowed for sufficient distances between the beds ranging from 1.60-2.00m, the critical environmental metric of cubic space per bed (m^3) varied between 33.92 m^3 and 42.84 m^3 and was thus significantly lower than the threshold of 51.38m^3 recommended by the B.H.I.C.'s (1864) ward prototype British India stations, and 75.00m^3 realised in the ward for Europeans at the S.G.H., which both aimed at the prevention of overcrowding and insufficient dilution of the accumulated (and potentially "vitiated") air (Figure 2.7).

Thermal mass, constructed by light blocks and reinforced beams and columns of concrete, represented a significant deviation from B.H.I.C.'s (1864) recommendation consisting of hollow blocks with airbricks (Figure 2.7). Although shading was not provided systematically, except for a shading device at the WSW-W facade of W2 and the veranda (with a width of 2m) along with its roof at the ENE-E facades of W2 and W7, their central bedded areas were fully protected from direct solar exposure (Figure 2.7c.3; Figure 2.7d.3). It seems likely that before the enclosure of the spaces currently functioning as private rooms at the respective NNW-N wings in W2 and W7, there existed a transitional zone for the free circulation of air running along the S-SSE and NNW-N facades that provided cross ventilation resembling the natural ventilation system in the prototype ward in British India (Figure 2.7b.2; Figure 2.7d.1; Figure 2.7e.1). The ventilation systems of the central bedded areas in W2 and W7 comprised in fully openable window areas covering between 28.69% and 21.57% in the NNW-N facades, and between 28.91% and 26.82% in the S-SSE facades, which were very close to those recommended in the B.H.I.C.'s report in 1864 and significantly lower than those built in the ward for Europeans at the S.G.H. (Figure 2.7). It seems likely that the wall structures and their openings along the bedded areas both in W2 and W7 were not designed to be thermally separated from the peripheral zones in the NNW-N and S-SSE wings. Although, these peripheral zones at the NNW-N and S-SSE wings provided full protection from direct solar exposure of the central bedded area, they also increased the distance between the opposite windows functioning as inlets and outlets of the airflow through cross-ventilation (Figure 2.7d.3; Figure 2.7e.3). Furthermore, although only the roof in W2 was cross-ventilated, with only two windows installed at the ENE-E and WSW-W facades, their distances was very high and the roof had dark-coloured tiles, which combined with the roof's separation through the suspended ceiling, diminished any potential passive cooling possibility of the roof space through natural cross-ventilation (Figure 2.7d.4; Figure 2.7e.4).

2.6 Historical aspects of human thermal comfort across the equatorial zone

Controversies about the applicability of laboratory-based thermal comfort standards in tropical buildings, the impact of air movement and humidity and the influence of adaptive behaviours have dominated the debate about human thermal comfort in naturally ventilated spaces across the equatorial zone since the first decades of the twentieth century. The ideas presented during the 'Housing and Building in Hot-Humid and Hot-Dry Climates' conference in 1952 indicated the debates about thermal comfort in the tropics at that time (Chang, 2016b). At that conference, G. Atkinson, who played an essential role in the development of building standards for the British colonies in the tropics as a colonial officer within the Building Research Station (BRS) since 1948 and as a Chief Architect in the BRS since 1968, presented the recommended thermal comfort in a 19-24^{o}C range of effective temperature (at a maximum relative humidity level of 70%) in a psychometric chart (Atkinson, 1953). That psychometric chart was developed by the American Society of Heating and Ventilating Engineers (ASHVE) during climate-controlled experiments at the Harvard School of Public Health (ASHVE, 1935). These experiments primarily aimed to advance air-conditioning applications (McIntyre, 1980).

By contrast, Albert Mayer, who had extensive experience as an architect and planner in India, in his presentation at the same conference stressed the importance of understanding the links between thermal comfort and sociocultural norms that could entirely be explored only through fieldwork-based research (Mayer, 1953). Mayer's ideas influenced Otto Koenigsberger, who was a fundamental practitioner, and theorist of tropical architecture. Koenigsberger expanded the importance of regionalism as an efficient strategy for the integration of sociocultural norms in tropical architecture and the mitigation of existing inequalities in low-income countries that could be exacerbated if thermal comfort were solely understood as a function of air-conditioning (Koenigsberger et al., 1973). However, as Chang (2016b) has noted, despite the significant contribution by Koenigsberger, et al. (1973), their views about thermal comfort were influenced by the work of the physiologists H. Vernon and T. Bedford. Although Vernon and Bedford considered the impact of air movement in thermal comfort sensation for the first time and contradicted ASHVE's beliefs about thermal neutrality under steady-state conditions (Vernon and Bedford, 1926), a substantial understanding of the sociocultural modifiers of thermal comfort was missing. By contrast, air movement was associated with evidence about increased productivity that was deduced from studies about the working conditions of workers at munition factories during WWI (Health of Munition Workers Committee, 1918).

Since the first thermal comfort field studies across the tropics in the 1950s (Ellis, 1953; Webb, 1959), empirical evidence suggested that in naturally ventilated spaces, occupants were more tolerant to higher temperatures during summer in warm climates and lower temperatures during winter in cold climates (Nicol and Humphreys, 1973). At the same time, more fieldwork studies revealed significant differences between laboratory-based thermal comfort indexes and reported thermal comforts, with these deviations being higher in case studies in the tropics (Nicol, 2004; Humphreys, et al., 2007; Kwong, et al., 2014; Yau and Chew, 2014). Experimental and empirical studies comprise the significant body of research produced for the correction of these deviations. Fanger and Toftum (2002) developed the ePMV model by integrating an expectancy factor (0.5 during warm periods) assuming lower metabolic rates. Yao et al. (2009) developed an adapted coefficient to account for psychological factors. Both these models have been criticised for lacking empirical proofs by de Dear, et al. 2020. The utilisation of fieldwork data databases has been proved crucial for the development of more robust thermal comfort indexes. De Dear and Brager (1998) developed the first adaptive model based on the analysis of the first global dataset (RP-884, 21,000 participants from 160 buildings). That adaptive relationship, which was defined as a regression between the indoor operative temperature and mean monthly New Effective Temperature (ET*), was used by the ASHRAE Standard 55 (2004). Later, in that adaptive model published in the ASHRAE Standard 55 (2013), the time-weighted, running mean outdoor air temperature replaced the mean monthly outdoor air temperature. To date, the most extensive global database consists of 81,846 sets of physical and subjective field measurements, of which 2,613 were collected in Africa and 9,671 across the equatorial zone[20] with offices and classrooms comprising most of the non-domestic case studies

[20] 6,633 in tropical wet savanna, 2, 075 in tropical monsoon and 963 in tropical rainforest.

(Ličina, et al., 2018). A statistical metanalysis of that database showed that the most widely used thermal comfort index in tropical climates, namely the PMV, had the lowest deviations from reported votes only in offices (Cheung, et al., 2019).

Numerous thresholds of comfortable temperatures lying in the 20-35°C region have been found in fieldwork studies at domestic and non-domestic naturally ventilated buildings across the equatorial zone (Kwong, et al., 2014). However, it became evident that beyond the quantitative definition of the thermal comfort zone, the impact of air movement and humidity, as well as the cumulative impact of adaptive thermal capacity, had to be better understood (Baker and Standeven, 1996; Humphreys and Nicol, 1998; Nicol and Humphreys, 2002). Since the 1970s, fieldwork data showed that in hot-dry parts of India, the reduction of air movement temperatures could reach 4°C (Nicol, 1973). Although the quantitative estimates differ, several empirical and experimental studies have confirmed that heat loss from human bodies through convection and evaporation in hot climates is amplified at higher air velocities making warmer conditions more bearable (Rohles, et al., 1974; McIntyre, 1978; Tanabe, et al., 1987; Gong, et al., 2006; Chowa, et al., 2010; Cândido, et al., 2012). Toftum (2004) found that higher air velocities were required to outweigh the reduction in the evaporative cooling rate at the skin surface level that occurred at higher humidity levels. Changing clothes and personal exposure to air movement have been the most popular adaptive behaviours across climates (Mishra and Ramgopal, 2013). Since the 2000s, significant progress has been achieved with regards to the recording of culture-specific behaviours such as not wearing shoes at home (Rijal, et al., 2010), sitting on the floor at homes (Heidari and Sharples,2002) and taking siestas (Indraganti, 2010). Prevalent recorded behaviours in warm climates include changing the state of the doors, the windows, or the fan, changing clothes, taking showers, consuming cold drinks and moving to cooler places (Nicol, et al., 1999; Wong, et al., 2002; Feriadi, et al., 2004; Tablada, et al., 2005; Hwang, et al., 2009). Humphreys and Nicol (1998) have pointed out that a holistic understanding of adaptive capacity should include investigating the obstructions for the restoration of thermal comfort. Concerns about privacy, security, noise, and vector control force occupants to close the windows (Wong, et al., 2002; Rajasekar and Ramachandraiah, 2010; Indraganti, 2010; Feriadi, et al., 2003). Rodriguez and D'Alessandro (2019) showed in a systematic literature review that adaptive behaviours in warm climates do not include seasonal adaptations of the metabolic rates.

2.7 Conclusion

Connaught Hospital today stands at a historical site, where in 1817 the first liberated African slaves walked through the King's Yard Gateway to the Royal Hospital and Asylum, and in 1880 the first institution for the practice of Western medicine in British West Africa, named the Colonial Hospital, became operational. The Colonial Hospital, which was renamed to Connaught Hospital in 1910, was burned down in 1920. The Pavilion Building (Pav.Buil.), the Outpatient Block (A&E), and the European Nurses' Quarters (Annex), which contained most of the selected (case-study) wards, were built during the reconstruction of the New Colonial Hospital/ Connaught Hospital between 1921 and 1948. Belated and small-scale sanitary interventions in urban space and ad-hoc vaccination campaigns contributed to Connaught Hospital's public health role in the region. This role was further emphasised by the hospital's operation as the main mixed-race and interclass tertiary hospital in Freetown and was reflected in the prioritisation of colonial funding for its development compared to the funding of improvements in the Nursing Homes for the Europeans, and its increasing popularity among Europeans and Africans. The pavilion-plan typology remained influential in the British colonies until the 1930s, despite its decline in the UK, as indicated by the architecture of the Colonial Hospital Complex in Accra, which was built between 1914 and 1930, and the plans for the Groote Schuur Hospital in Cape Town, South Africa, which were designed in 1920 but never realised, as well as the landmark S.G.H. which was constructed between 1923 and 1926. However, due to the lack of available evidence in the colonial archives, the exact reasons for the incomplete implementation of the climate-sensitive principles defining the Nightingale ward prototype for equatorial climates in the construction of the pavilion building in Freetown's Hospital remain unknown.

Despite being driven by erroneous beliefs that climatic extremes in equatorial zones amplified the harmful effects of "miasma", a best practice framework for the design of barrack hospitals in British India produced by the B.H.I.C., in 1864, set the foundations for climate-sensitive hospital design in equatorial climates. As illustrated in the paradigmatic ward for equatorial climates produced by the B.H.I.C (1864), the high coverage of shading and airflow exposure of the bedded area, and the adaptable and manually controlled natural ventilation system in combination with the lightweight and light-coloured structures of the building envelope, the ceiling and the roof, indicated significant capacity of climate-sensitivity. The adaptability of the ward to changing climatic conditions, including climatic extremes, such as monsoons and hurricanes, was reinforced by the diversity in size, position and manual controls of the inlets, outlets and the shaft. However, while an advanced understanding of the physics of warm air was demonstrated in the B.H.I.C.'s report (1864), the problem of undesirable fluctuations in ventilation rates was ignored. Furthermore, the recommendations had an exclusively technical character, and were not concerned with socio-cultural aspects of habitation in hospital barracks.

The selected Nightingale wards (W2, W3, W6 and W7) in Freetown's Connaught Hospital were part of the pavilion-system ward blocks (Pav.Buil.), which kept its original function of accommodating multibed wards. The selected Nightingale wards had advantageous orientation towards the prevailing winds (WSW-SSE). Furthermore, they embodied in their building envelopes climate-sensitive components that resembled the ward prototype for British India stations and with the ward for Europeans at the S.G.H. These similarities consisted in the functional arrangements of clinical, administrative and auxiliary uses, between the central bedded area, the font wings and the back wings. In addition, natural ventilation was reinforced by the advantageous orientation towards the prevailing winds and by extensive window coverage in the NNW-N and S-SSE facades, while the bedded areas were fully protected from direct solar exposure. However, W2 and W7 were built with significantly lower volumetric spaces than those of the ward prototype for British India stations and the ward for Europeans at the S.G.H. The embodied capacity for climate-responsiveness in Connaught Hospital's Nightingale wards was further weakened by the omission of an open-air veranda around the central bedded area, insufficient shading of the building envelope, the disconnection between the ceiling and the ventilated roof, and the extended airflow distance for cross-ventilation.

Chapter 3

Evaluation of Thermal Environmental Performance and Occupants’ Window Opening Behaviours

Abstract

Chapter 3 presents an assessment study of the indoor thermal conditions in eight naturally ventilated wards of Freetown’s Connaught Hospital in Sep.2016 and Mar.Apr.2017. The study includes a building survey, indoor and outdoor environmental monitoring, mapping occupancy frequencies and occupants’ activities, and recording occupant-controlled window operation. The environmental and behavioural data presented in this chapter comprise in: a) indoor measured temperature and relative humidity; b) indoor wind speed data; c) outdoor measured temperature and relative humidity; d) the photographic recording of the position of window openings; and e) maps of occupancy frequencies and activities. Non-parametric inferential statistics (Wilcoxon Rank Sum Test) were applied for the impact of seasonal, temporal, and spatial variation on the temperature and relative humidity values and recorded window-opening behaviours. Predictive correlations (Spearman coefficients, Kendall’s W test coefficients and Cramer’s V effect size) were found between recorded indoor thermal conditions, overheating, and window-opening behaviours, which were defined as dependent variables, and seasonal and temporal variation and spatial characteristics for ventilative cooling. Time-series regression was applied for the exploration of the links between indoor and outdoor recorded environmental measurements.

Although in the case-study Nightingale wards, cross-ventilation was advanced by low width-to-length and low width-to-floor-to-ceiling height ratios coupled with high coverages of openable windows, in all case-study wards, the drivers of environmental performance were similar. Their windows lacked adequate shading devices and double-glazed windows, while internal window curtains trapped solar radiation and, by convection induced higher adjacent air temperatures. At the same time, heat gains by conduction through the heavyweight external and internal walls and by convection through the uninsulated ceilings and floors reduced the potential of nocturnal cooling, contributing to higher night-time overheating. Contemporary operational schedules defined by the busiest time of the day (11:00 to 14:00), when doctors’ and nurses’ rounds were scheduled, coincided with strong levels of solar exposure (being extended until 16:00) and visitors’ presence and activities were intense, continuous and with affective and practical significance for the care of patients. In different ward typologies with a 24-hour operation in hot-humid settings, although overall moderate and strong correlations between indoor thermal conditions and seasonal variations can be expected with rising temperatures (0.32<Kendall’s W coefficient<0.66, p-value<0.001) and falling relative humidity values (-0.65<Kendall’s W coefficient<-0.36, p-value<0.001) over the dry

season, the impact of temporal variations over both seasons between daytime and night-time is likely to be weak. The impact of the spatial attributes on ventilative cooling is likely to be different among diverse building typologies and seasons, with cooler indoor temperatures being associated with higher openable window coverage during night-time in the pavilion plan typology during the rainy season (Spearman coefficient=-0.34, p-value<0.001), while deeper plan layouts could have a protective impact against indoor overheating, especially during night-time over the dry season (Spearman coefficient=-0.63, p-value<0.001) only in the modern building typologies over both the rainy and the dry season indicating the importance of the protection of the bedded areas and the nurse station from direct exposure to solar radiation.

Despite the statistically insignificant correlation with outdoor temperature and relative humidity levels, occupant-controlled widow operation in the case-study wards displayed weak correlations with rising indoor temperature during the rainy season (0.13<Spearman coefficient<0.19, p-value<0.01) and falling indoor relative humidity values (Spearman coefficient=-0.14, p-value<0.01). However, differentiation of the impact of seasonal and temporal variation in the window opening behaviours might be expected to occur between wards (-0.54< Kendall's W coefficient<0.70, p-value<0.001). This is an indication that beyond architectural and engineering aspects, socio-cultural and operational parameters that defined hierarchies and relevant behaviours in each ward's dynamic environment probably played a crucial role in the determination of the window-opening behaviours.

3.1 Introduction

Hospital buildings have high cooling loads, especially those located in the equatorial zone (Escombe, et al., 2019). However, hospitals with limited resources across the equatorial zone struggle with delivering these high cooling loads, and, as a result, expose their occupants more frequently and over prolonged periods to thermally uncomfortable indoor environments (Kigali Cooling Efficiency Program, 2018)[21]. Efficient strategies for the mitigation of overheating in hospital buildings can benefit from better understandings of the adaptive behaviours among hospital occupants, and especially among patients who are more sensitive to uncomfortable changes in the thermal environment (Carmichael, et al., 2013). Monitoring the occupants' adaptive behaviours combined

[21]Howie, et al. (2008) noted that the lack of quality control of donated medical devices results in the accumulation of old, faulty, and probably energy-inefficient medical devices in the wards of African hospitals

with recording indoor thermal conditions in real-time has been proven to provide substantial evidence regarding overheating as this is experienced in indoor spaces (Mavrogianni, et al., 2016). Hospital ethnographies in hospitals in sub-Saharan Africa have shown that healthcare practices deviate from universal perceptions of biomedical models (Livingston, 2012; Brown, 2012). As a result, the study of hospital occupants' behaviours in clinical settings with limited resources becomes more imperative. However, thermal conditions in hospital wards in the equatorial zone have not yet been studied in correlation with occupant adaptive behaviours. This chapter builds on an extensive dataset consisting of monitored environmental and behavioural data collected during my nine-week fieldwork at Freetown's Connaught Hospital. The chapter explores, for the first time, the synergetic impact of the selected wards' thermal performance and their occupants' window-opening behaviours on indoor thermal conditions in operational and naturally ventilated hospital wards in a hot-humid setting with limited resources.

In this chapter, I explore how climatic resilience of hospital wards in the equatorial zone, which is strengthened through applications of climate-responsive design that are in tune with occupant-controlled window operation, can contribute to the maintenance of acceptable thermal environments at multi-patient wards, while accounting for exceptional operational conditions arising from a contextual limitation of resources. In the first part of the chapter, the provision of thermally acceptable conditions in hospital wards located in the equatorial zone is investigated through a systematic literature review regarding established standards for acceptable thermal conditions, occupancy levels, and climate-sensitive design. The second part of the literature review is focused on studies that present recorded overheating in hospitals across different climate zones. In the final part of this chapter, I analyse the fieldwork-collected dataset, comprising in environmental and behavioural data, and compare the recorded seasonal and diurnal fluctuations between the selected wards and their monitored climate-responsiveness in relation to their architectural, engineering and operational characteristics. The recorded overheating is estimated according to static and adaptive thermal comfort and public health indexes. Finally, the chapter proposes a Nightingale ward with improved environmental performance and operational schedule and performs an overheating assessment of this proposed ward.

3.2 Research Questions

The research questions underlining this chapter comprise in the following:

1)How did occupancy frequencies and occupant activities vary throughout the morning and the evening shifts between the monitored wards?

2) How were microclimate characteristics (location and vegetation coverage), aspects of architectural design (building age, typology, storey, bed capacity, floor area, ceiling height, volume, ratio of the width to floor-to-ceiling height, window area, window types, and barriers for window operation), solar control coverage (curtain types), construction (roof, floor, external wall, internal wall, and glazing), building services (ventilation) and operational schedule (ward function, operation, nurse shifts, nursing activities, doctor rounds, and visiting hours) expected to define the environmental performance of the selected wards?

3) What was the scale of the seasonal and diurnal fluctuations in the recorded environmental parameters? How did characteristics of the microclimate, the design, the construction, the building services, and the expected occupancy frequencies and activities impact the recorded indoor thermal conditions? To what extent was the indoor environment responsive to weather changes?

4) What was the role of the occupant-controlled window operation in modifying indoor thermal performances?

5) Which were the spatial, seasonal, and diurnal variations in recorded overheating?

6) To what extent can climate-resilient and occupant-centred environmental engineering restore acceptable thermal environments in naturally ventilated and multi-patient wards in hot-humid settings with limited resources?

3.3 Research Objectives

The research objectives of this chapter consist in the following:

1) To investigate the variations of the occupancy frequencies and occupants' activities throughout daily routines of care provision at three representative wards.

2) To identify which architectural, engineering, and operational aspects of the selected wards impacted their environmental performances.

3) To describe how seasonal and diurnal fluctuations of recorded environmental variables in the selected wards responded to recorded weather changes, while accounting for their architectural, engineering, and operational characteristics.

4) To explore how variations in occupant-controlled window operation responded to fluctuations of indoor and outdoor environmental conditions.

5) To define the spatial, seasonal, and diurnal differences of the estimated overheating risk.

6) To develop and run a naturally ventilated thermodynamic model of an improved multi-patient ward that integrates the best practices for climate-resilient and occupant-centred design adapted to hot-humid climates and limited-resource settings.

3.4 Literature Review

3.4.1 Mitigation of Thermally Uncomfortable Conditions in Hospital Buildings in the Equatorial Zone

3.4.1.1 Acceptable Thermal Conditions and Occupancy Frequencies in Hospitals

In Sierra Leone, the lack of building codes and environmental standards renders impossible the regulation of the quality of the construction and the operation of hospital buildings. Although aspects of the energy performance of healthcare buildings are covered by international green building rating systems, these standards lack sensitivity to contextualised climatic and socio-cultural conditions and thus promote solely technology-oriented low energy design.[22] Natural ventilation is the only mechanism for airborne infection control in hospitals in the Global South where mechanical ventilation is not an affordable option (Escombe, et al., 2007). However, naturally ventilated multi-patient wards have been disregarded by regulatory institutions with international influence, such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2008), and

[22] Even sustainability rating schemes developed for hot-humid climates, such as Singapore's Green Scheme, have been criticised for excluding low energy cooling as a recommended strategy (Lan, et al., 2017).

the American Institute of Architects (AIA, 2001).[23,24] Only the U.K. Department of Health (2013) has published guidance regarding the design of naturally ventilated general wards, according to which the acceptable temperature and ventilation rate stand between 18^{o}C and 28^{o}C and minimum 6 Air Change per Hour (ACH), respectively (Table 3.1).

According to the WHO, acceptable ventilation rates at naturally ventilated wards are 60 l/s/patient (average) with an airflow path from clean to polluted areas and away from infectious agents (Atkinson, et al., 2009). These are minimum ventilation standards and do not guarantee the efficient engineering of infection control, which depends on the understanding of the transmission routes and pathogens' movement (Li, et al., 2015). Far from being praised, the NHS's natural ventilation guidance has received criticism regarding its failure to meet infection-control standards (Beggs, et al., 2008). The safe levels of exposure to air pollutants, which decrease exponentially with airflow rate, set the acceptable ventilation rates (Allard, et al., 1998). Therefore, hospital spaces require high and energy-intensive ventilation rates that correspond to high standards of infection control (Li, et al., 2015). Lower ventilation rates are an energy-saving measure, yet it remains inconclusive whether these are related to a higher concentration of pathogens and thus to a higher infection risk (Li, et al., 2015).[25]

According to a systematic review, inpatient facilities tend to have higher mean total concentrations of aerosols, while naturally ventilated hospital spaces have the highest bioaerosol concentrations by comparison to mechanically ventilated spaces; however, no statistically significant differences in the bacterial bioaerosol concentrations were found (Stockwell, et al., 2019). It is believed that the suitability of buoyancy-driven displacement ventilation, which is the only type of natural ventilation permissible in hospital wards, depends on the bioaerosol's type, size, and movement (Zhao, et al., 2004). Regarding tuberculosis control, displacement ventilation according to on-site measurements in Peru (Escombe, et al., 2007), Hong Kong (Qian, et al., 2010), and Thailand (Jiamjarasrangsi, et al.

[23] For air-conditioned general wards, ASHRAE (2008) and AIA (2001) set the design temperature from 21.00-24.00^{o}C, while the recommended relative humidity values were determined only by ASHRAE (2007) as 30.00% in winter and 50.00% in summer.

[24] The WHO recommended 30^{o}C for working environments of sedentary activities, 28^{o}C for moderate physical work, and 25.50^{o}C for physically intense activities (WHO, 2011).

[25] Efficient low-energy infection-control strategies in hospitals mainly consist in ultraviolet applications (Escombe, et al., 2009).

2009), delivered ventilation rates higher than 2ACH, which is the minimum acceptable wind speed threshold for high-occupancy naturally-ventilated wards guaranteeing protection from TB-infection. A study at a 200m^3 Nightingale ward located at the second floor of the St. Lukes Hospital, Bradford, U.K, which combined experimental measurements with computerised simulations, showed that displacement ventilation through active cross-ventilation delivered ventilation rates that met the NHS's environmental standards (Gilkeson, et al., 2013). At the same time, comparing the concentration of pollutants between an open-plan bedded area and a partitioned part of the ward, each containing six beds, the study found that the addition of partitions protected the patients (Gilkeson, et al., 2013). However, concentration remained high close to the source, and the closure of windows resulted in a fourfold increase to relative exposure, which was in turn mitigated by the addition of extraction fans (Gilkeson, et al., 2013).[26] In an earlier study, measured ventilation rates in Nightingale wards in Edinburgh, Scotland, were higher than in mechanically ventilated wards, which failed to meet the standards for staphylococcal infections (Smylie, et al., 1971).

Guity, et al. (2009) have shown that, in a single-bed ward, displacement ventilation at 4ACH compared to mixed ventilation at 6ACH provided a more comfortable environment, better air quality, and efficient ventilation. However, Li and Nielsen (2011) supported that displacement ventilation is unsuitable for single- and multi-bed hospital wards. During an experiment at a climate-controlled chamber of a single patient room, Olmedo, et al. (2019) found that the number of exhaled contaminants were significantly influenced by the changes in generated heat gains, while the increase of the ventilation rate to 12ACH did not result in more effective protection of health workers.[27] Although knowledge of airborne transmission of pathogens to human hosts remains inconclusive (Morawska, 2006), it is believed that occupancy densities along with occupant activities and adaptive behaviours, such as opening and closing doors and windows, influence the dispersion of pathogens (Eames, et al., 2009). In a study at an ICU room in Taiwan, coarse-sized particle concentrations changed after the continuous presence of visitors in the ward (Tang, et al., 2009).

[26] Airflow patterns and rates varying from 3.4 to 6.5ACH for outdoor wind speeds from 1-4 m/s were investigated by the application of "tracer-gas" methodologies over fifty days, randomly selected from April to September 2010, while ventilation rates of 3.4 to 6.5ACH were simulated with 60% of open windows and the outdoor wind velocities were between 1.0 and 4.0m/s (Gilkeson, et al., 2013).

[27] The team repeated the experiment sixteen times, changing the ventilation rates from 6-12ACH, and using two mannequins to represent the health worker and the patient (Olmedo, et al., 2019).

Coexistence of staff and visitors with infectious patients due to inappropriate triage processes has been confirmed by Yam et al., (2011), especially in wards in limited-resource settings. Furthermore, differences in environmental conditions that affect the survival of airborne pathogens are not reflected in the ventilation standards (Tang, et al., 2009). Regarding hot-humid climates, higher humidity levels influenced the density and movement of large droplets (Yau, et al., 2011) and higher temperatures affected the indoor concentrations of Carbon Dioxide (CO_2) and Total Volatile Organic Compounds (TVOCs) (Chamseddine, et al., 2019), while naturally ventilated spaces were found to have had higher concentrations of fine particulate matter ($PM_{2.5}$) (Jung, et al., 2015).

Acceptable occupancy density levels in hospital wards are only defined in terms of the allowable area per bed (m^2) (Table 3.2), thus directly indicating the number of patients, while leaving the acceptable number of nurses and visitors to be indirectly inferred from the number of patients. According to recommendations of the NHS, one nurse over his/her shift should be responsible for the care between six and eight patients in total (Ball, 2010). Short, et al. (2015) reported that a six-bedded ward at Addenbrookes Hospital, Cambridge, was visited by two staff members every five minutes from 7:00 to 9:00 and from 18:00 to 20:00, and by one staff member and four visitors over the rest of the day. Empirical studies of the NHS's wards have shown that the busiest periods occur during the first hours of the morning shift, when patient hospitalisation levels tend to peak (Karakusevic, 2016). In a study at ten single-patient rooms at a new hospital building in Chicago, Ramos, et al. (2015) found that the density of activities by far exceeded the average number of people per hour visiting the room, which varied between zero and three. Therefore, the average number of visitors in a patient room might not be a representative indicator of the density of activities and their impact on the thermal conditions and air quality in the room.

Although there are a high number of studies about the impact of the ward layout on nurses' productivity, the investigation of that impact has been limited only to hospital wards in the developed world, with a primary focus on the estimation of the optimal number of trips to patient rooms (Choudhary, et al., 2010), the travel pattern and total distance walked by each nurse during his/her shift (Nuffield Provincial Hospitals Trust, 1955), and the total time spent by nurses with patients (Hendrich, et al., 2008). Hospital ethnographies have revealed the limited applicability of these studies' results for understanding healthcare practises in hospital wards in Africa (Brown, 2012; Van der Geest and Sarkodie, 1998). Regarding occupancy-related densities, anthropological studies at hospital wards in Botswana (Livingston, 2012), Papua New Guinea (Street, 2014) and Kenya (Brown, 2012) have shown that scarcity of infrastructural and diagnostic resources and treatment options has led to "improvised" healthcare practises with visitors becoming primary caregivers and therefore being constantly present at the wards.[28] Following a thirty-day time-motion observational study about the efficiency of nursing management systems in Indonesia, Rizkiawan, et al. (2019) have more recently shown the prevalence of very high nurse to patient ratios, with thirty-one nurses being responsible for the care of thirty-eight patients in an open-plan medical ward.

3.4.1.2 Climate-Resilient Design in Equatorial Climates

3.4.1.2.1 Characteristics of Freetown's Climate

Freetown's climate is classified following the Koeppen-Geiger classification system as equatorial-monsoonal (Am) and characterised by a dry season from December to April and a rainy season from May to November (Koettek, et al., 2006).[29] Seasonal variations are minor, with major weather fluctuations being caused by winds and tropical storms (Government of Sierra Leone, 2007). The historical outdoor air temperature ($T.A._{ext.(His)}$) reaches between 17.30 and 41.30^{o}C during the day, dropping to 17.40-36.20^{o}C at night (Figure 3.1). In the rainy season, the diurnal range is between 19.10 and 40.00^{o}C during the day, and between 19.10 and 34.50^{o}C at night (Figure 3.1). In the dry season, the diurnal $T.A._{ext.(His)}$ range is between 17.30 and 41.30^{o}C during daytime, and between 17.40 and 36.20^{o}C during the night (Figure 3.1). The diurnal difference throughout the year lies between 2.55^{o}C in August and 5.22^{o}C in March (Figure 3.1). March has the highest mean daytime $T.A._{ext.(His)}$ (30.54^{o}C), while May has the highest mean night-time $T.A._{ext.(His)}$ (25.89^{o}C) (Figure 3.1). Throughout the year, daytime $T.A._{ext.(His)}$ stays above 25^{o}C from 09:00 to 19:00, peaking at 16:00, while it falls significantly from 03:00 to 06:00 (Figure 3.1). During the hottest months, from December to May, daytime $T.A._{ext.(His)}$ values stay above 33^{o}C between 13:00 and 18:00 (Figure 3.1).

Historical outdoor relative humidity values ($R.H_{.ext.(His)}$) remain high throughout the year, reaching between 35% and 100% during the day and 51%-100% during the night (Figure 3.2). In the rainy

[28] Khodakarami and Knight (2007) have demonstrated how common was the presence of visitors in hospital wards in Iran, despite the lack of problems related with scarcity of resources for the provision of healthcare.

[29] Site climatic analysis based on historical weather data. The period of 1961-1990 is covered by the temperature and relative humidity data and rainfall. The period of 1981-2000 is covered by the radiation, cloud cover and wind speed data. Meteonorm 6.1 was used for access to the temperature, relative humidity, solar radiation, cloud cover and wind speed data. The rainfall data were downloaded from the Climate Change Knowledge Portal of the World Bank Group.

season, the diurnal range is between 46% and 100% during the day, and between 56% and 100% at night (Figure 3.2). In the dry season, the diurnal range varies from 35% to 100% during the day, and from 51% to 100% at night (Figure 3.2). The highest twenty-four-hour mean $R.H_{.ext.(His)}$ values, around 87%, are expected in Sep.2016 and August, while the lowest values, around 74%, are expected in January and March (Figure 3.2). Throughout the year, $R.H_{.ext.(His)}$ values peak from 03:00 to 08:00, while their lowest point is reached between 14:00 and 17:00 (Figure 3.2). During the raining season, the mean monthly rainfall ranges from 92.39mm in November to a peak of 513.63mm in August (Figure 3.2). Due to the low latitude, solar radiation, which peaks between August and October (Figure 3.3), is significantly higher on the east and west walls than in the north and south walls of built structures. The sky cover falls below 30% only in April, while for the rest of the year, the twenty-four-hour mean sky cover stands between 32.43% in February and 65.20% in August (Figure 3.3). The most frequent direction of the historical outdoor wind speed ($W.S._{(His)}$) is SSW, with their values varying between 2m/s and 6m/s (Figure 3.4). Throughout the year, the hourly $W.S._{(His)}$ values stay above 4m/s between 14:00 and 19:00 (Figure 3.5). $W.S._{(His)}$ values tend to be high from 13:00 to 18:00 over the year with mean values varying between 4.68m/s at 13:00 and 5.36m/s at 16:00, when $T.A._{ext.(His)}$ and historical solar radiation peak. However, after a short period with rising values from 02:00 to 04:00, $W.S._{(His)}$ tend to drop from 05:00 to 08:00, when $R.H_{.ext.(His)}$ tends to peak. As illustrated in Table 3.3, according to different $T.A._{ext.(His)}$ and $R.H_{.ext.(His)}$ thresholds applied in the only available dataset of relevant historical weather data, the potential for natural ventilation in Freetown is overall limited, with outdoor $T.A._{ext.(His)}$ ranging from 25 to 28°C and $R.H_{.ext.(His)}$ from 30% to 70% over less than 1% over the year (Table 3.3).

Regarding the optimal operation of cross-ventilation, it is recommended that the width of individual rooms should not exceed the floor-to-ceiling height by more than five times, whereas the width of the room should not be higher than 2.5 times of the floor-to-ceiling height ratio in the case of single-sided naturally ventilated spaces (CIBSE, 2014). In both cases, the stack effect could be enhanced through the application of double openings with large vertical distances between them (CIBSE, 2014). In hot-humid climates, where limited temperature differences between interior and exterior spaces render stack ventilation inefficient, wind-driven natural ventilation might be more efficient (Haw, et al., 2012). Precooling is required in areas where the climatic conditions do not allow for night-time ventilation due to high humidity levels (Brandemuehl, et al., 1990). In hot-humid climates, the operation of fans might not increase the air-change rate[30] (Atkinson et al., 2009), while screens with mosquito nets can significantly decrease the airflow, with cotton nets having an impact of 70%, while nylon nets a lower impact of 35% (Koenigsberger, et al. 1959).

The psychometric chart of Freetown shows that the combination of high levels of moisture in the outdoor air with low diurnal and radiant differences render natural ventilation and evaporative and radiant cooling significantly inefficient. This results in high demand of mechanical cooling for the provision of thermally comfortable conditions, which were defined from 23.20 to 29.40^{o}C, and shading, which was determined to be essential from 10:00 to sunset over the whole year (Figures 3.6-7). Early research on naturally ventilated buildings in hot humid climates showed that indoor vapour pressure tended to be higher than the one outdoors when airflow rates were low and occupancy levels were high (Givoni, 1969). It becomes evident that in Freetown the recommended environmental standards for naturally ventilated hospital wards of 28^{o}C, 6ACH and acceptable humidity levels are very unlikely to be achieved in naturally ventilated and overcrowded multi-patient wards over prolonged periods both during the rainy and dry seasons.

3.4.1.2.2 Principles of Climate Resilient Design at Equatorial Climates

Halawa, et al. (2017) have noted that savings for cooling energy over the dry season derived from natural ventilation and passive cooling were surpassed by the mechanical dehumidification demands over the rainy season. Particular attention has been directed to the improvement of passive cooling in hot-humid climates by the reinforcement of nocturnal ventilation through the decrease in the thermal storage capacity of the building envelope[31]. Nocturnal ventilation and thermal mass of lower conductivity generated the highest cooling energy savings according to a study of residences

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[30] Based on seventy-eight full-scale laboratory tests, Raftery, et al. (2019) found that the average air speed in the room got higher with the use of fans of higher speed and diameter. Furthermore, applying high resolution air speed measurements and airflow visualisation via smoke in a climatic chamber, Liu et al. (2018) found that airflow patterns were affected both by the distance between the fans and the air speed of each fan.

[31] The application of internal insulation supplemented by vapour retarders and air gaps and of highly reflective materials on external surfaces which were recommended in earlier studies (de Waal, 1993) are still considered effective solutions for the reduction of the thermal conductivity of the building envelope.

across different equatorial zones in Mexico (Oropeza-Perez and Østergaard, 2014)[32]. Nocturnal ventilation combined with improved double-glazed facades in office spaces in Singapore[33] reduced energy consumption for cooling (Hien, et al, 2005). Interventions in indoor spaces in Madras[34] in southern India, which combined highly reflective glazing with insulated external walls, showed that internal heat gains were decreased by approximately 20% (Kumar, et al., 2017). Although the application of materials with low thermal conductance at residential and commercial buildings in Thailand[35] contributed only by 25% to energy reduction, the improvements in the energy efficiency of the systems for mechanical cooling and the appliances had the highest contribution to energy reduction (Rattanongphisata and Rordprapat, 2014). Comparative simulations between double and triple glazed windows in buildings in Malaysia[36] showed that triple glazing generated the highest energy savings, varying between 5.5 and 8.5% (Tahmasebi, et al., 2011)[37]. The construction of local materials in an air-conditioned rural health centre in Tabasco, Mexico[38] performed mean temperature and relative humidity values of 22.5°C and 70% and 27°C and 30%, an ample air supply of 1.08 m3/h provided thermally comfortable conditions resulting in consuming 63% of the annual electricity for air-conditioning and 17% of the annual electricity for lighting (Alpuche, et al., 2004).

There are a limited number of studies that assess the combined impact of the reduced thermal mass and improved ventilation in naturally ventilated spaces located in the equatorial zone in Africa. Based on ninety-six scenarios for the location of Uganda[39], Hashemia (2017) found that the addition of external insulation in walls, the combination of internal insulation in walls and floors, and the combination of internal insulation on the roof and in the brick walls deteriorated the indoor thermal

[32] Each house was modelled as a single thermal zone (Oropeza-Perez and Østergaard, 2014).

[33] climate zone: Af
[34] climate zone: Aw
[35] climate zone: Aw
[36] climate zone: Af
[37] Across the temperate zone, modifications in the building's envelope solar reflectance capacity by the application of highly reflective materials and glazing on the external surfaces of the building envelope gave 44% in energy savings (Haberl and Cho, 2004). Roof with thermal resistance of 0.31mK/W performed the optimal thermal conductivity for a steady albedo value of 0.6 (Arumugam, et al., 2015).

[38] climate zone: Am
[39] climate zone: Aw

conditions.[40] For the location of Cameroon[41] , Nematchoua, et al. (2015) estimated that an insulation thickness of 0.10m was the best solution for earth blocks. In a study that combined on-site measurements and computer-based simulations for the location of Ghana[42], for a steady 10ACH, the peak indoor temperature had the highest reduction when the thermal mass was modelled by concrete blocks while the reduction of window size and the addition of shading devices had a small impact on the peak temperatures, which remained below 0.9°C. A study of a typical office building in Ghana, which combined simulation and experimental methods, demonstrated that spaces with concrete walls displayed lower peak indoor temperature, standing at 32.60°C, with a five-hour delay after the peak of outdoor temperatures, whereas the peak indoor temperature of 35.60°C, with a two-hour delay from the peak of the outdoor temperature, was recorded in spaces with walls built from sandcrete blocks (Abanyie, et al., 2013). Abanyie, et al. (2013) showed that nocturnal ventilation supported by fans could further reduce peak indoor temperatures by 4.3°C only in the prototype built with concrete walls, while lower window-to-wall ratios contributed to lower indoor temperatures in both the prototypes with heavyweight and lightweight thermal masse. Contrary to the results of Abanyie, et al. (2013), heat gains generated by window coverages ranging from 20% to 30% contributed to 45%-60% of the required cooling loads (Lee, et al., 2013). An experimental study in Akure City[43], Nigeria, which compared indoor environments between a shaded and an unshaded building, demonstrated that the unshaded building displayed a peak indoor temperature that exceeded the peak outdoor temperature by 5.4°C, whereas the other building that was shaded by trees displayed a temperature higher by 2.4°C than the peak outdoor temperature (Morakinyo, et al., 2013).

3.4.1.2.3 Studies of On-Site Environmental Performance in Hospitals in the Equatorial Zone and Other Climate Zones in Africa

There are a limited number of on-site environmental performance studies of hospitals located in the equatorial zone across continents and other climate zones in Africa (Table 3.4). Nimlyat, et al. (2018) found that orientation of the windows had stronger impact than any other design parameters on the indoor environment of an urban hospital at Jos, Nigeria. Following the completion of numerous

[40] Internal insulation is protected from rainwater infiltration during the monsoonal periods (Sudhakara, et al., 2019).

[41] climate zone: Am

[42] climate zone: Aw

[43] climate zone: Am

building surveys at fourteen dispensaries and seven health centres in Machakos, Kenya, Njogu, et al. (2018) found that 79% had ceilings lower than 3m, 52.50% provided air volume per worker lower than $10m^3$, and 61.50% lacked cross-ventilation. In a study about energy consumption in twelve cities in Madagascar, which combined on-site environmental monitoring with occupant surveys in 1,272 domestic, fifty-one commercial buildings and one hospital over the dry and the rainy seasons, Nematchoua, et al. (2019) found that modern buildings had the highest energy demand for cooling and the highest occupant dissatisfaction rates as regards thermal comfort, while buildings with local materials had better indoor air quality and staff productivity. Indoor environmental monitoring at the waiting rooms of eight rural health centres in Giyani, South Africa, showed that summer temperatures (December to February) were higher than autumn temperatures (March to May) with the temperature threshold of 38^{o}C being exceeded by maximum daily temperatures in some spaces on average by differences ranging between 2 and 4^{o}C (Wright, et al. 2017).

Through environmental monitoring of air-conditioned waiting rooms, nurse stations and examination rooms across five outpatient departments in two block type hospitals built in 1992 and 2005 and located in Bangkok, Sattayakorn, et al. (2017) found that average temperatures and relative humidity values ranged from 20.00 to 29.30^{o}C and from 43 to 85%, respectively, in waiting rooms, and from 18.7 to 29.6^{o}C and from 40.00 to 93.00%, respectively, in examination rooms and nurse stations. Through a mixed-method environmental assessment of a historic hospital in Indonesia, which was mechanically ventilated only in 38% of its spaces, Sudarma (2019) found that the average temperature was 30.60^{o}C, and the average humidity was 64.40% for wind speeds lower than 0.41m/s. Lan, et al. (2017) have shown that high ventilation rates could be achieved through natural ventilation in areas close to the windows in a multi-bed ward of an urban block type hospital in Singapore with average airflow at the centre of the beds standing at 0.48m/s (fans operating at an average speed of 0.29m/s), indoor temperatures rarely exceeding outdoor temperatures and indoor wind speeds fluctuating less than outdoor ones.

3.4.1.3 Occupant-Controlled Window Operation in Hospital Spaces

Although, there is a significant body of work about diverse aspects of window design in patient wards including patients' preferences (Thompson and Goldin, 1975), window view and hospitalisation length (Verderber, 1986), and daylight performance and its therapeutic impact on patients' recovery (Park, et al., 2018), there is limited evidence as regards occupant-controlled window operation in hospital wards. Security, safety and maintenance concerns have determined window design and operation in hospitals (Hosking, 1999), especially as regards the operation of nocturnal ventilation (Roetzel, et al., 2010), and have resulted to installations of non-openable windows or openable windows with small permitted openings[44] and to the removal of windows designed for intense natural ventilation from historic hospitals.[45] Similar to other type of buildings, the occupants' lack of awareness about proper window control is one of the main barriers for the operation of natural ventilation systems in hospitals (Atkinson, et al., 2009). Furthermore, the existence of windows and doors do not guarantee frequent use by occupants (Hobday and Dancer, 2013). At two multi-bed wards and at a private room in the Hairmyres Hospital in Glasgow, Scotland, Baird (1969) reported that the windows' state rarely changed, while fluctuations in the outdoor temperature mainly triggered changes in the position of the windows. Short, et al. (2012) observed that, at a multi-bed ward at Addenbrookes Hospital, Cambridge, UK [46] during periods of warm weather, occupants opened the windows, but tended to leave them at the same position (maximum opening area) over long periods during both the morning and evening shifts.

Monitoring window-opening behaviours at two multi-bed naturally ventilated surgical wards in a hospital in Nanjing, China[47], Shi, et al. (2018) found that, whereas seasonal variations were significant, no significant differences were observed over the same day or week. Their findings revealed that the opening positions were different in the two wards with the "fully open" state and the ajar' state, accounting for the 70% and 91% of the time when they remained open, respectively, (Shi, et al., 2018). Furthermore, while both wards had the highest percentages of open windows during the spring, both summer and winter were the seasons with the lowest percentages of open windows (Shi, et al., 2018). These differences contributed to diverse recorded levels in air temperature, and relative humidity and CO_2 concentration at the two wards (Shi, et al., 2018). Algorithms predicting occupant-controlled window operation in response to changes in indoor and outdoor temperature and according to the time of the day (Yun, et al., 2009) have been developed for diverse types of non-domestic buildings at various climate zones. However, such an advanced level of research has not yet been achieved in the field of window operation in hospitals. At the

[44] Open window openings should not have a gap deeper than 100mm, according to the Department of Health and Social Care (DHSC) (2013).

[45] Lomas and Giridharan (2012), noted that at an operational Nightingale ward at the Bradford Royal Infirmary, the original windows, which were "Crittal" type with steel frames with one hopper opening and two or three top-hung openings, were replaced by thermally broken aluminium-framed double-glazed windows with smaller openings.

[46] climate zone: Cfb

[47] climate zone: Dwa

same time, a considerable gap exists in terms of the psychological aspects, which are crucial drives of occupant adaptive behaviours (Borgeson and Brager, 2008)[48]

3.4.2 Recorded Overheating in Hospitals

For the estimation of the overheating risk in hospitals, both static and adaptive thermal comfort standards have been applied (Tables 3.5-3.6). Adaptive thermal comfort standards integrate the combined impact of air speed, air and radiant temperatures, humidity, and clothing and physiological adaptation, which are the most crucial determinants of the human thermal comfort, while accounting for occupants' physiological and behavioural adaptive capacity (Zero Carbon Hub, 2015). The category I of the EN15251 (BSI, 2008)[49] adaptive thermal comfort standard has been presented as a suitable overheating assessment tool for occupied and free-running hospital buildings with accessible and openable windows. However, its applicability for hospital wards in the equatorial zone is limited by the allowable range of the running mean outdoor temperature defined between 8.00 and 25.00°C. The ASHRAE Standard 55 (2013) was revised according to 21,000 fieldwork data from 160 offices in four different continents including the equatorial-monsoonal zone, in order to redefine the thermal comfort algorithms through the integration of the impact of acclimatisation and air movement (de Dear and Brager, 2002). However, the dataset for the revision of the ASHRAE Standard 55 did not contain any data of thermal comfort surveys in hospitals. Although specific recommendation regarding the applicability for hospital buildings are not made in the ASHRAE Standard 55 (2013), the application of the low limit for 90% acceptability was recommended for buildings with populations with vulnerability to heat-related discomfort.

As it is shown in Table 3.7, there are only two overheating studies of hospital spaces located in Africa, which however did not include the study of patient wards, while the rest of the published research covers hospital spaces of the NHS estate including patient wards. Through the estimation of apparent temperatures based on on-site indoor monitoring of the indoor temperature and relative humidity in the waiting rooms of eight rural health centres in Giyani, South Africa, Wright, et al. (2017) found that apparent temperatures exceeded the recorded temperature by 4°C, indicating discomfort that was probably caused by high levels of humidity due to low ventilation rates. The

[48] In naturally ventilated working environments, these psychological drivers are further influenced by established hierarchies, social norms, and the fear of causing discomfort to co-workers (Borgeson and Brager, 2008).

[49] Revised as EN 16798-1:2019 (BSI, 2019).

estimated apparent temperatures tended to peak to categories classified as heat-related health hazards over the occupancy period from 08:00 to 16:00 (Wright, et al., 2017). Assessing the relationship between indoor and outdoor mean monthly temperatures through linear regression, Wright, et al. (2017) found that the models explained 86.00% of the indoor recorded temperature and 81.00% of the estimated apparent temperature, with values of the coefficients standing at 0.80 for the recorded temperatures and 0.90 for the apparent temperatures. Beccali, et al. (2018) designed and run a thermodynamic model of a new mixed-mode and energy autonomous primary healthcare facility in Maputo, Mozambique, with stone walls of U-values from 0.8-1.5W/m^{2}K, adobe walls of U-values from 1.8-2.6W/m^{2}K, and with double-glazed windows covering from 4.1% to 6.9% of the external wall surfaces and a ventilated roof. Their modelling of overheating assessment according to the EN15251 and ASHRAE 55 adaptive thermal comfort standards showed that longer periods of discomfort particularly over the cold season were estimated from the ASHRAE 55 algorithm (Beccali, et al., 2018).

Following the study of two naturally ventilated Nightingale wards at Bradford, UK, during the particularly cool summer of 2010, Lomas, et al. (2012) found that there was no evidence of overheating according to the EN15251 Cat I standard, while the threshold of 26^{o}C during night-time was exceeded for less than three hours. No overheating was estimated following the application of the EN15251 Cat I standard in the recorded temperatures in multi-bed wards and nurse stations at a block-type medium-rise hospital built in the 1960s (Short, et al., 2012). However, when the 28^{o}C threshold was applied, it was exceeded by 0.1% to 0.5% in the wards and by 1.4% to 10% in the nurse station (Short et al., 2012). During night-time, overheating peaked in the nurse station, where the threshold of 26^{o}C was exceeded by 44.60% to 73.70% of the monitoring period (Short, et al., 2012). In a study of two multi-bed wards, two private rooms and one nurse station at a nucleus type hospital located in Leicester, UK, the EN15251 Cat I was exceeded by 255 hours in the multi-bed wards and between 59 and 206 hours in the private rooms, while the 26^{o}C threshold was exceeded by 110 hours in the multi-bed wards and between 35 to 112 hours in the private rooms (Giridharan, et al., 2013). Based on a study of spaces in the maternity department of Addenbrookes Hospital, Cambridge, Short, et al. (2015) reported that both the multi-bed and the single bed wards got overheated when all standards were applied, whereas the nurse station demonstrated a low four-hour period exceeding the 28^{o}C threshold. Finally, in a study at multi-bed and single-bed wards at Bradford, UK, Fifield, et al. (2018) found that the adaptive standard was exceeded in all the wards, the threshold of 28^{o}C was slightly exceeded only at the multi-bed wards (0%-1%), and that at night-time the nurse stations were most severely overheated with temperatures being above 26°C over 21% of the monitoring period.

Indoor humidity is impacted by the occupancy levels and by the operation of windows, which controls the impact of outdoor relative humidity on the indoor relative humidity and therefore its potential impact is stronger for naturally ventilated buildings (Vellei, et al., 2017). According to the potential impact of indoor relative humidity in human health, Sterling, et al. (1985) provided the following three categories: a) high with R.H.>59.00%, b) medium with R.H. between 37.00% and 59.00% and c) low with R.H.<=37.00%. For the protection of human health Sterling, et al. (1985) defined the range of relative humidity values between 40 and 60%. According to a metanalysis of a debase of thermal comfort studies in naturally ventilated buildings composed by sixty-three field studies (eighteen from the ASHRAE RP-884 database and forty-five from twenty-four papers that were published after the publication of the ASHRAE RP-884 database), they developed multivariate model having as a dependent variable the regression gradient and as independent variables indoor temperature (dry bulb, globe temperature, operative), mean daily outdoor, relative humidity, total insulation, air speed, metabolic rates, gender) (Vellei, et al., 2017). Vellei, et al (2017) noted the following: a) The estimated comfort temperatures were higher than those estimated by the ASHRAE model; b) High levels of humidity were linked with lower (and narrower) range of comfort temperatures; c) The difference of acceptable temperatures between the different categories of the levels of relative humidity reach 4°C; d) ASHRAE adaptive models comfort zone coincided with the comfort zone of the new models for medium levels of relative humidity.

3.5 Methods of Data Collection and Analysis

3.5.1 Mapping of Occupancy Frequencies and Occupant Activities in Hospital Wards

Mapping of the occupancy frequencies in Freetown's Connaught Hospital was performed at a critical sub-sample of the cohort of the selected wards consisting in a ward for female surgical patients (W2), a ward for female patients suffering from infectious diseases (W9), and a ward for male and female emergency cases (T.U.) (Table 3.8). In so doing, the impact of functional differences in occupancy frequencies and occupant activities between the selected wards could be assessed. Determined by the permission given to the author by the head nurses, the mapping exercises were executed on three different weekdays between September 20 and 27, 2016, covering continuously the periods of six hours and seventeen minutes in W2, four hours and sixteen minutes at W9 and six hours at T.U., over either the morning or evening shifts (Table 3.8). The author, out of observations devised a group of symbols to represent the type of occupants and their activities, and the main space facilities (Figure 3.8). These symbols were manually drawn at a five-minute interval as a system of nodes on printed copies of the ground plan of the selected wards. The group of representative occupant types was composed of nurses, doctors, patients, visitors-carers, and other types of hospital staff and visitors (Figure 3.8). The main occupant activities consisted of walking, standing, sitting (lying in bed was also coded as sitting) and were centred around the hand hygiene and waste disposal facilities, the beds, and medical trolleys (Figure 3.8). The hand-drawn maps (Figure 9-11) were firstly transformed to digital maps through the application of the graphic design software Adobe Illustrator. Secondly, a database of activities by different types of occupants (per five-minutes) was developed with Microsoft Excel (version 2017). Thirdly, this database was imported to STATA (version 14.2), and a basic descriptive statistical analysis was performed.

3.5.2 Environmental Monitoring in Indoor and Outdoor Spaces

Environmental monitoring in the selected indoor and outdoor spaces was conducted during a twenty-day period over the rainy season in Sep.2016 and a twenty-seven-day period over the dry season in Mar.Apr.2017. Diagnostic methods consisting in indoor and outdoor environmental monitoring are an integral part of investigative processes for the understanding of the thermal environmental performance of existing buildings (Allard, et al., 1998). The equipment should be accurate, easy to use and with a measurement frequency of at least one hour and be installed away from sources of humidity as well as from heating and cooling energy, while representative locations should be selected for the measurement of air velocities (Allard, et al., 1998). To achieve the standards prescribed by ASHRAE 55:2013 (Table 3.9) the indoor air temperature ($T.A._{(in)}$) and relative humidity ($R.H._{(in)}$) were monitored on five-minute intervals, which were transformed into hourly intervals during the data analysis, Before installation, the data loggers were synchronised. However, with this type of data-loggers the recording of the air temperature was influenced by components of radiant temperature, a problem also encountered in the Design and Delivery of Robust Hospital Environments in a Changing Climate (DeDeRHECC) project (Lomas and Giridharan, 2012). Contrary to DeDeRHECC's data collection processes, in my project, head nurses of the selected wards did not give me permission to install multiple loggers at different locations and different heights. Furthermore, lack of steady electricity supply and internet access (both perennial in Freetown) and concerns about the security of the equipment hindered the installation of an extended network of sensors with a digital storage capacity. Therefore, the main criteria for the selection of the location for the indoor and outdoor data-loggers were security, convenience, and avoidance of direct or reflective sunlight and cooling devices (Table 3.10).

After the pilot period, and with the consent of the staff in each ward, the table provided for the nurse station was selected as the most suitable location for the installation of the indoor data-loggers (Figure 3.12). The exact locations of the indoor data-loggers are illustrated in Figure 3.13. As Short, et al. (2012) have noted regarding environmental monitoring at operational hospital wards, given that the location of the data-loggers required the nurses' approval, the monitored data are indicative but not comprehensive as regards the thermal environment at the monitored wards. There is only one study of a hospital in the Netherlands (Derks, et al. 2018), where the most representative locations were found following a series of pilot environmental measurements in the patient rooms and around the nurse stations. Common practices also applied in my project regarding the installation of data-loggers and the prevention of their removal, include the use of hangers (Lomas and Giridharan, 2012) and of tape and zip ties (Wright, et al., 2017). Although weather stations and wireless sensors have been used for outdoor environmental monitoring at hospital sites[50], one data-logger type Gemini Tinytag Ultra (TGU-1500) was installed outside one of the windows of the S-SSE facade on the first floor of the Technicians Building and was covered with a solar radiation shield; a practice previously used in outdoor environmental monitoring without the installation of weather stations (Mavrogianni, et al., 2016). Indoor wind speed values ($W.S._{(in)}$) were measured with a TROTEC TA 300 Anemometer (Table 3.9).

The historical weather data covering the period of 1961 to 1990 for $T.A._{ext.(His)}$ and $R.H_{.ext.(His)}$ values and the period of 1981 to 2000 for solar radiation were downloaded from the Meteonorm version 6.1, which was the only available source for the historical weather data of Freetown (Table 3.11). The only meteorological station of Sierra Leone is located at Lungi Airport, 26.10km away from Connaught Hospital. The station became fully functional in November 2016, and for the period of November 2016 to April 2017 it did not collect any solar radiation data (Tables 3.11-12)[51]. During the monitoring periods, the temporal coverage of $T.A._{(in)}$, $T.A._{ext.(His)}$, outdoor air temperature recorded on-site at location S1 ($T.A._{ext.(S1)}$) and at the meteorological station ($T.A._{ext.(Meteo)}$), $R.H._{(in)}$, $R.H_{.ext.(His)}$, outdoor relative humidity recorded on-site at location S1 ($R.H_{.ext.(S1)}$) and at the meteorological station ($R.H._{ext.(Meteo)}$) was different to that of $W.S._{(in)}$, with the former being taken continuously while

[50] Published details of indoor and outdoor environmental monitoring at hospital wards in other projects are presented in Table 3.1 in Appendix 2.1.

[51] The limited number and capacity of weather stations across Africa and Latin America were noted by the World Meteorological Organization (2015) and WBG (2017).

the latter only sporadically (Table 3.13) (Figures 3.14-15)[52]. In Sep.2016, despite detailed discussions about the objectives of the project and technical specifications of the data-loggers, the nurses were extremely reluctant and suspicious about the function of the data-loggers. Believing that the data-loggers were voice and video recorders, they delayed the permission for their installation at W9, Physio., T.U. and F.A. (Table 3.14). In addition, data-loggers were removed and destroyed three times during the fieldwork in Sep.2016, and they had to be replaced, resulting in discontinuities in the monitoring of the selected spaces (Table 3.14). Such problems were avoided during the second phase of the fieldwork in Mar.Apr.2017 (Table 3.14). The relationship of trust that had developed between the researcher and hospital staff may have contributed to the prevention of subsequent damage and removal of the installed data-loggers.

STATA (version 14.2) and Microsoft Office Excel (version 2017) were used for the analysis of the temperature and relative humidity values. Statistical indicators for the range, central tendency, dispersion, and variability were used for the description and comparison of the collected climatic variables. The mean, minimum, maximum and the 25th, 50th and 75th percentiles and standard deviations were tabulated and graphically displayed in the form of time series, boxplots and bar graphs for the description and comparison of hourly twenty-four-hour, daytime, and night-time temperature and relative humidity values. Although the nurses working in the monitored wards were advised to keep notes of the date and time, when the position of the installed data-logger was different from the recommended one, no such report was made. Therefore, at the stage of data analysis, the author was obliged to thoroughly check the data and remove data that were deemed unreliable. The environmental data were recorded in occupied wards. Hence, while a small number of the outliers in the final dataset could be attributed to possible removals of data-loggers from their recommended location, the exact conditions that caused these outlier values cannot be identified with precision. Non-parametric inferential statistics (Mann–Whitney U-test or Wilcoxon Rank Sum Test) were applied for the impact of seasonal, temporal, and spatial variation on the $T.A._{(in)}$(^oC) and $R.H._{(in)}$(%)values and recorded window-opening behaviours. Predictive correlations (Spearman coefficients, Kendall's W test coefficients and Cramer's V effect size) were found between recorded indoor thermal conditions, which were defined as dependent variables, and seasonal and temporal variation and spatial characteristics for ventilative cooling. Time-series regression was applied for the exploration of the links between indoor and outdoor recorded environmental measurements.

[52] The exact monitoring periods in the selected ward in Sep.2016 and Mar.-Apr. 2017 are presented in Table 3.2 in Appendix 2.1.

3.5.3 Recording of Occupant-Controlled Window Operation

The photographic recording of the state of the window openings in the selected wards was performed according to a standardised protocol of data collection repeated at a specific time of the day daily, both in Sep.2016 and Mar.Apr.2017. The protocol was designed by the researcher and was executed accordingly with the help of trained assistants. The diary of the state of the window openings was kept by taking a series of photographs with the exact angle of the facades in the selected wards at preselected locations along a predefined route (Figure 3.16a). These photographs were taken from 10:00 to 11:00 during the morning shift and from 17:00 to 18:00 during the evening shift. Rather than simply recording the state of every window's openings, the overall aim was to keep a systematic record of the windows that impact the thermal environment of specific areas of the wards where the environmental monitoring and the thermal comfort survey were performed. Unfortunately, a small number of windows of the facades of interest were not captured due to obstructions from surrounding buildings and landscaping (Figure 3.16b, Tables 3.15-16). Brager, et al. (2004) also used a photographic recording of the window openings' positions in a thermal comfort study of workers in naturally ventilated offices. More technologically advanced collection methods were used by Shi, et al. (2018) and Fifield, et al. (2018), who used data-loggers that registered the state of the window as either closed or open. Although the study of occupant behaviours in naturally ventilated buildings involves additional aspects of environmental control, such as the change of the curtains' positions (CIBSE, 2014), these aspects were not part of this project.

The analysis of the windows photo-diary was performed according to the following steps:

1. Photographs were organised chronologically following the route sequence using Photoshop CS6 (Figure 3.16b).

2. Each photographed facade was checked thoroughly, and the number and the percentage of open apertures were calculated and added using Microsoft Office Excel (version 2017). Depending on the angle of each aperture, its position was recorded as follows: 0% if closed, 100% if entirely open, and 25%, 50% and 75% for intermediary positions.

3. The range, dispersion and variability of the recorded values were computed using STATA (version 14.2). The differences between the morning and the evening values were calculated by subtracting the morning from the evening.

3.5.4 Calculation of the Recorded Overheating Risk

Although operative temperatures are recommended for the estimation of the overheating risk, in this project the recorded $T.A._{(in)}$ values were applied for comparisons with the static temperature thresholds illustrated in Table 3.5 and the equations of the adaptive thermal comfort shown in Table 3.6. The use of the $T.A._{(in)}$ values was based on the assumption that operative temperatures in the selected wards at Freetown's Connaught Hospital were similar to the recorded $T.A._{(in)}$ values. This assumption has been proven to be valid in spaces with airflows lower than 2m/s and with differences between the air and radiant temperatures lower than 4K (Lomas and Giridharan 2012). The temperature threshold of 28^{o}C was applied in the twenty-four-hour $T.A._{(in)}$ values, while the night time (20:00 to 6:00) $T.A._{(in)}$ values comprised the dataset in which the temperature threshold of 26^{o}C was applied. The applicability of the adaptive comfort EN15251 and ASHRAE 55 standards was checked by the calculation of the running mean of outdoor temperature through the application of Equation 7 (Table 3.6). The $T.A._{ext.(S1)}$ values were used in Equation 7 for the estimation of the running mean of outdoor temperature ($T.A._{rm.ext.(S1)}$). The use of the $T.A._{ext.(Meteo)}$ would result in an underestimation of the running mean and therefore an overestimation of the overheating risk. The constant with a value of 0.9, as it is recommended for hot-humid climates in the equatorial zone, was applied. The estimated $T.A._{rm.ext.(S1)}$ values in Sep.2016 stood between 28.17 and 28.54^{o}C and in Mar.Apr.2017 varied from 28.34 to 28.45^{o}C, thus allowing for the application only of the adaptive comfort models according to the ASHRAE 55 standard (Table 3.6). The low limit of the ASHRAE 55 with 90% acceptability, which is recommended for overheating assessment of indoor spaces with high expectations of thermal comfort ASHRAE 55 (2013), was applied as an overheating threshold. Both in Sep.2016 and Mar.Apr.2017, the impact of the operation of the fan was not considered in the modelling of the overheating risk in W9 and T.U., which were the only selected wards with functional ceiling fans. Due to intermittent electricity supply the operation of these fans was sporadic with limited effect on the ambient environments in W9 and T.U. The estimated $T.A._{rm.ext.(S1)}$ values were also applied in the adaptive comfort models developed by Vellei, et al., (2017) for the three different levels of health risk (Table 3.6). The frequency and the severity of overheating were accessed through the application of the methodology presented in the TM52 Standard CIBSE (2013) through the calculation of the percentage of recorded temperatures above the limits of comfortable temperatures over the monitoring period and the estimation of the frequencies of different values of the calculated differences above the limits of comfortable temperatures. Finally, the health impacts of recorded overheating was assessed through the application of the $T.A._{(in)}$ values and $R.H._{(in)}$ values in apparent temperature index according to the Equations 10 and 11 (Table 3.6).

Although Wright, et al. (2017) assumed zero values for wind speed values for the calculation of the apparent temperatures in their project, the value of 0.25m/s represented the median of the $W.S._{(in)}$.

3.6 Results

3.6.1 Occupancy Frequencies and Occupant Activities Recorded in W9, W2 and T.U.

3.6.1.1 Key Statistics of Occupancy Frequencies and Occupant Activities Recorded in W9, W2 and T.U.

Monitored median occupancy frequencies stood at high levels varying between 11.00 in W2, 10.00 in W9, and 08.00 in T.U. (Figure 3.17). All selected wards operated with most of their beds being occupied on the day of the mapping exercise, with patients displaying the highest mean occupancy frequencies of 55.73% in W9, followed by T.U. with 51.82%, and W2 with 45.43%, whereas nurses comprised the majority of occupants in W2, with mean occupancy frequencies at 29.28%, followed by 33.40% in T.U., and 30.38% in W9 (Figure 3.17). Overall, while the number of nurses and visitors vividly fluctuated in all selected wards, the number of patients remained constant with few changes in T.U. (Figures 3.19-3.21). Despite the continuously varying number of nurses (Figures 3.19- 3.21), the mean patient-to-nurse ratios remained high, varying between 2.00 in W9, 1.69 in W2, and 1.64 in T.U. (Figure 3.17). Contrary to the relatively stable number of patients, in W9, W2, and T.U., visitors tended to arrive at and depart from the wards constantly and beyond the visiting hours, leading to the most extreme changes in their numbers (Figures 3.19-21). W2 accommodated the highest median number of visitors (9.00), constituting on average 25.28% of the total number of occupants per five minutes, followed by T.U. (14.79%), and W9 (13.88%) (Figure 3.17). The median recorded number of total occupants per five minutes peaked at 37.00 occupants in W2, followed by 33.00 in W9, and 24.00 in T.U. (Figures 3.19-21).

The nursing schedule was organised around the morning (8:00-14:00), evening (14:00-20:00), and night shifts (20:00-8:00) (Figures 3.19-3.21). Although, different parts of the morning and evening shifts were covered by the mapping exercises, it became evident that giving medication and monitoring the patients’ vital signs comprised the main nursing activities taking place at specific times of the day, namely at 6:00, 10:00, 12:00, 18:00, 22:00 and 24:00 hours. The doctors’ rounds took place between 11:00 and 14:00, while the permitted visiting hours were between 16:00 and 18:00 during weekdays. Sitting was the dominant occupant activity with the median number of occupants being seated ranging between 23.00 in W9, 22.00 in W2, and 15.00 in T.U., with a mean prevalence of 71.69% in W9, 62.77% in W2, and 59.72% in T.U. (Figure 3.18). By contrast, standing was the less preferred activity and only exceeded walking during hectic periods, especially in T.U. (Figures 3.19-3.21).

3.6.1.2 Discussion about the Occupancy Frequencies and Occupant Activities Recorded in W9, W2 and T.U.

Although clear patterns were not evident, the coincidence of the doctors' rounds with the nurses' rounds and the transition from the morning to the evening shift, as it occurred in W9 (Figure 3.20) and T.U. (Figure 3.21), contributed to the highest occupancy densities and activities. The patients mainly remained seated on their beds (Figures 3.19-3.21). It seems likely that the fluctuation in the occupancy levels was primarily driven by the changes in the numbers of nurses and visitors entering and exiting the wards (Figures 3.19-3.21). It is evident that, contrary to reported occupancy densities at NHS wards (Ball, 2010), the selected wards were significantly more overcrowded over long periods of the day. Despite the strongly fluctuating numbers of nurses and visitors, the change in the number of patients was extremely low. This might be attributed to more extended hospitalisation periods and a lower rate of daily discharges.

The observed abundance of nurses being present in the selected wards drove the mean patient-to-nurse ratio to approximately two patients per nurse during his/her shift, which was three times lower than that of the NHS (Ball, 2010). Despite the contextual differences compared to the wards studied by Ramos, et al. (2015), a similar discrepancy between occupancy frequencies and the frequency of occupant activities was also evident at Connaught Hospital's wards. Therefore, the observed occupancy frequencies cannot be considered a representative indicator of the intensity and diversity of the occupants' activities and, more importantly, of their impact on the ambient environment in the wards and the dispersion of infectious pathogens. The continuously high number of visitors and their intense movement within the selected wards corroborated the observations of existing anthropological studies regarding visitors' significant role as caregivers (Livingston, 2012; Brown, 2012). Therefore, rather than being dismissed as a significant source of multiple disturbances, visitors' presence in the ward needs to be controlled while maintaining its affective and practical significance for patients' care.

3.6.2 Architectural, Engineering and Operational Aspects of the Selected Wards.

3.6.2.1 Overview of the Architectural, Engineering and Operational Aspects of the Selected Wards.

The two oldest blocks, built in 1921, contained W2 on the first floor, and W3 on the ground floor and the third block, constructed in 1922, on the first floor, and the fourth block, built in 1929, on the ground floor, housed W6 and W7, respectively (Figure 3.22). The A&E, built in 1926, on the ground floor, and the Annex, on the first floor, accommodated T.U. and F.A., respectively, while the Med.San.Adm.Buil., which was constructed between the 1960s and 1970s, contained Physio., on the ground floor, and W9, on the first floor (Figure 3.22). The Med.San.Adm.Buil. with a NNW-SSE orientation and the Pav.Buil., the A & E and the Annex with a S-SSE-NNW-N orientation could catch the prevailing winds with SW and SSW directions (Figure 3.22). Vegetation was scattered in an unplanned manner within the site of Connaught Hospital, with the Nightingale wards and W9 having tall trees in front of the WSW-W and NNW facades, respectively, while soil and grass covered most of the land within site (Figure 3.23). All selected wards were occupied by nurses, patients, and visitors, while all except Physio. were used for overnight hospitalisation of patients, and only the T.U. and Physio. accepted mixed-sex patients (Figure 3.24). The inpatient facilities in question treated exclusively medical cases in W6, surgical cases in W2, W3 and W7, and infectious disease cases in W9, while in F.A. both medical and surgical cases were admitted and at Physio. physiotherapy treatment was provided both to inpatient and outpatient cases (Figure 3.24). All the inpatient wards had similar operational schedules except for Physio., which functioned as a gym only during weekdays from 09:00-18:00 (Figure 3.24).

The Nightingale wards had the most spacious bedded areas with volumes ranging from 428m^3 in W7 to 475m^3 in W2 and W3, and width to floor-to-ceiling height ratios varying between 2.69 in W3, and 2.84 in W2 and W6 (Figure 3.24). The highest value of width to floor-to-ceiling height ratio of 3.85 was observed in F.A., while the lowest values of 2.00 and 2.12 were observed in Physio., and W9 (R1), respectively (Figure 3.24). The Nightingale wards had the highest number of windows, with window coverages lying between 59.48% in W7, 73.31% in W2 and W3, and 76.61% in W6, and being followed closely by 58.05% in F.A. By contrast, T.U. had the lowest window coverage of 9.77% (Figure 3.24). W9 and Physio. with openable window-coverage of 25.96% and 27.69%, respectively, had aluminium thermally broken windows with single horizontal sliding, while metal-framed windows with complete operable two outward openings covered the openings of the rest of the selected wards (Figure 3.24). The only non-operable windows were the top windows in T.U. and W9, while railings and mosquito nets were installed at the windows of all selected wards except for the windows on the SSE facade of Physio., and on all the facades of W9 (Figure 25). Although mosquito nets were openable inwards in all selected wards, F.A. had irremovable mosquito nets on its windows (Figure 25). Except for the window of the WSW-W facade of W2, none of the windows in the selected wards had any solar or rainwater protection on their outer surfaces, while curtains were available indoors in all selected wards except for T.U., W9, and the SSE facade of Physio. (Figure3.25). Despite differences in the year of construction, the selected wards had similar characteristics in the construction of roofs, floors, external and internal walls, and glazing (Figure 3.24). As regards ventilation, all selected wards had cross-sided natural ventilation, except for T.U., which had single-sided natural ventilation (Figure 3.24).

3.6.2.2 Discussion about the Architectural, Engineering and Operational Aspects of the Selected Wards.

Lower width to length and width to floor-to-ceiling height ratios are indications that a given space has more beneficial geometrical characteristics to harness natural ventilation potential (CIBSE, 2014). Contrary to the confined and poorly ventilated spaces reported by the only published study about a building survey in a hospital built in the 1920s in Africa (Njogu, et al., 2018), all selected wards except for F.A. had beneficial geometrical characteristics for the harnessing of natural ventilation. However, the Nightingale wards, the oldest wards of the cohort, seemed to have a more critical combination of climate-sensitive characteristics and a higher passive cooling capacity. This observation is in line with the findings by Nematchoua, et al. (2019) that older buildings across twelve cities in Madagascar had better indoor air quality with less required energy consumption. As illustrated in Figure 3.26, the indicative environmental performance in the selected wards was driven by the following thermodynamic relationships. The buildings were subject to direct solar gain, higher at the north and south elevations, through unshaded single-glazed large window areas.

Additional heat gains by conduction through the heavyweight external walls reduced the potential of nocturnal cooling due to the lack of insulation and shading, thus contributing to night-time overheating, caused by the gradual generation of heat stored in the fabric, peaking late at night. Nocturnal heat, generated from the load-bearing uninsulated internal walls proximate to the wards' beds, further reduced patients' sleep quality. This heat was trapped inside the curtain tracks around each bed. While reducing glare, internal window curtains, which were in widespread use, absorbed solar radiation and induced higher adjacent air temperatures through convection. The likelihood of considerable heat gains, combined with higher moisture levels being transferred through incoming air, was higher in the windward facades. However, insect screens weakened incoming wind velocities and their moisture contents. Heat gains trapped in the attic through the uninsulated ceiling significantly increased internal heat gains, while uninsulated floor slabs contributed to unintended convective heat exchange. Finally, while internal heat gains from computers, medical devices and lighting were low, occupancy levels were high, resulting in high internal gains. Physio. and W9 had a higher potential of natural ventilation as compared to Nightingale wards and F.A. However, in all selected wards, the airflow pattern was likely to follow a horizontal path close to the ceiling due to the lack of multiple occupant-controlled windows openings at various heights, which through fine-tuned operation could actuate extra buoyancies. Although having no cooling impact, existing functional fans contributed to humidity reduction through evaporation in the air moisture content.

3.6.3 Recorded Thermal Environmental Performance and its Associations with the Seasonal, Temporal and Spatial Variations

3.6.3.1 Key Statistics of the Seasonal and Diurnal Fluctuations in the Recorded Temperature Values

Sep.2016 was slightly warmer than a typical September in Freetown, with $T.A._{ext.(S1)}$ values ranging between 23.90 and 32.74^oC at daytime and 24.07 and 32.74^oC at night-time (Table 3.17). Throughout the monitoring period, in Sep.2016, all selected wards had mean twenty-four-hour $T.A._{(in)}$ values in the 27.29-29.33^oC range, minimum twenty-four-hour $T.A._{(in)}$ values from 25.32^oC (in W6) to 27.24^oC (in T.U.) and maximum twenty-four-hour $T.A._{(in)}$ values from 33.05 ^oC (in W7) to 31.22^oC (in W2) (Table 3.17; Figure 2.27). $T.A._{(in)}$ values with the highest dispersion and variability were recorded in W2 (SD=1.45), W6 (SD=1.50), and W9 (SD=1.45), whereas T.U. (SD=0.30) and Physio. (SD=0.50) had the lowest dispersion and variability of the recorded values (Table 3.17; Figure 3.28). All the mean daytime $T.A._{(in)}$ values were higher than the mean night-time $T.A._{(in)}$ values, except for the recorded values in Physio., T.U., and F.A. with the night-time $T.A._{(in)}$ values exceeding the daytime $T.A._{(in)}$ over the monitoring period by 40.00% at Physio., 50.00% in T.U., and 72.73% in F.A. (Table 3.17; Figure 3.28).

Although the recorded night-time $T.A._{(in)}$ values exceeded the daytime $T.A._{(in)}$ with percentages standing at 22.22% in W2, 50.00% in W3, 7.69% in W6, 16.67% in W7, 25.00% in W9, 40.00% in Physio., 50.00% in T.U., and 72.73% in F.A., the difference was never higher than 3K (Table 3.17). The mean daytime $T.A._{(in)}$ values stood in the 27.29- 28.42 ^oC range in Pav.Buil. and at 27.98 ^oC in T.U., 28.75 ^{o}C in F.A., 27.77 ^{o}C in Physio., and 29.33 ^{o}C in W9 (Table 3.17; Figure 3.27). The mean night-time T.A.$_{(in)}$ ranged from 27.16 to 27.97 ^{o}C in Pav.Buil. and stood at 27.84 ^{o}C in Physio., 28.83 ^{o}C in W9, 28.69 ^{o}C in F.A., and 28.03 ^{o}C. in T.U. (Figure 3.27). Over daytime W2, W6 and Physio. had the highest percentages of T.A.$_{ext.(S1)}$ values exceeding the T.A.$_{(in)}$ values with the mean differences between the T.A.$_{ext.(S1)}$ values and the T.A.$_{(in)}$ values standing at 0.40K in W2, -0.07K in W6, and 0.12K in Physio (Table 3.17). Over night-time the percentages of the T.A.$_{ext.(S1)}$ values exceeding the T.A.$_{(in)}$ values were higher than those recorded over daytime in all selected wards, with the highest percentages being recorded in W9 (97.00%), Physio. (96.15%) and F.A. (78.00%) (Table 3.17). Although differences exceeding 3K were not recorded in W2, W3 and Physio., percentages standing at 41.00% in F.A., 35.00% in W9, 6.09% in W6, and 5.05% in T.U. accounted for night-time periods with T.A.$_{ext.(S1)}$ values higher than T.A.$_{(in)}$ values by more than 3K (Table 3.17).

In Sep.2016, around 09:00, all selected wards began to warm up and reached peak T.A.$_{(in)}$ at different times of the day over the period from 12:00 to 18:00 (Figure 3.29). In W9, the median hourly T.A.$_{(in)}$ of 30.84 ^{o}C peaked at 16:00 and stayed at the highest level from 12:00 to 23:00 (Figure 3.29). At Pav.Buil., W6 had the highest median T.A.$_{(in)}$ from 12:00 to 17:00, peaking around 14:00 when it reached 29.74^{o}C (Figure 3.29). At the same time of the day, the median T.A.$_{(in)}$ of F.A. rose at its highest point, 29.16^{o}C (Figure 3.29). At 11:00, W3 was the first ward with A recorded median T.A.$_{(in)}$ lower than T.A.$_{ext.(S1)}$ (Figure 3.29). Unfortunately, the peak of median T.A.$_{(in)}$ values in W6 and W7 occurring at 18:00 cannot be explained based on the available data (Figure 3.29). After 19:00, the wards started to cool down , but rather than following a continued downward trend, they slightly fluctuated until 03:00, when the greater part of the stored heat in the fabric was released (Figure 3.29). The period between 08:00 and 09:00 was the coolest period of the day in all selected wards (Figure 3.29).

Over the monitoring period in Mar.Apr.2017, T.A.$_{ext.(Meteo)}$ values recorded at the meteorological station, which was located within the national airport at a rural and sparsely populated area, were significantly lower than recorded T.A.$_{(in)}$ within the Connaught Hospital site, which were close to typical temperature values in March-April with a range of 25.70 to 34.15^{o}C at daytime and 25.32 to 29.77^{o}C at night-time (Table 3.18). In Mar.Apr.2017, all selected wards had mean twenty-four-hour T.A.$_{(in)}$ values in the 28.61-30.60^{o}C range, minimum twenty-four-hour T.A.$_{(in)}$ values from 25.63^{o}C (W2) to 29.63^{o}C (T.U.) and maximum twenty-four-hour T.A.$_{(in)}$ values from 30.68^{o}C (F.A.) to 33.65^{o}C (W9) (Table 3.18; Figure 3.30). All selected wards had mean daytime T.A.$_{(in)}$ values in the 28.98-30.93^{o}C range, minimum daytime T.A.$_{(in)}$ values from 25.63^{o}C (W2) to 29.64^{o}C (T.U.) and maximum daytime T.A.$_{(in)}$ values from 30.68^{o}C (F.A.) to 33.65^{o}C (W9), while the mean night-time T.A.$_{(in)}$ values stood in the 28.16-30.73^{o}C range, minimum night-time T.A.$_{(in)}$ values between 25.98 (W2) and 29.86^{o}C (W9 and Physio.) and maximum night-time T.A.$_{(in)}$ values from 30.45 (W3) to 32.12^{o}C (W9) (Table 3.18; Figure 3.30).

Similar to the recorded T.A.$_{(in)}$ in Sep.2016, in Mar.Apr.2017 the Nightingale wards, whose standard deviation values ranged from 0.81 to 1.31, and W9, whose standard deviation value stood at 1.19, had T.A.$_{(in)}$ values with the highest variability and dispersion, probably because of higher exposure to outdoor wind speeds (Table 3.18; Figure 3.31). Diurnal fluctuations within each ward were low, with mean diurnal differences varying from 0.81 to 1.15K in the selected Nightingale wards and between 0.03K and 1.22K in the rest of the selected wards (Table 3.18). Physio. had the highest percentage of night-time T.A.$_{(in)}$ values being higher than those recorded during daytime that stood at 96.00% followed by the percentages in T.U. (50.00%) and F.A. (42.31%), while significantly lower were the percentages of night-time T.A.$_{(in)}$ values exceeding the daytime T.A.$_{(in)}$ values in W9 and the Nightingale wards accounting for periods of the monitoring time that stood at 11.54% in W9, 12.00% in W2 and W7 and 8.00% in W3 (Table 3.18).

In Mar.Apr.2017, over daytime, only the Nightingale wards and F.A. had slightly lower T.A.$_{(in)}$ values than the T.A.$_{ext.(S1)}$ values, whereas their mean differences standing at 0.21K in W6, 0.78K in W7, 0.88K in W3, 1.03K in W2 and 0.54K in F.A., daytime periods with T.A.$_{ext.(S1)}$ values exceeding T.A.$_{(in)}$ values by more than 3K accounting for only 1.55% of the monitoring time in F.A. with a total prevalence of cooler T.A.$_{ext.(S1)}$ values varying between 35.36% and 37.64% of daytime monitoring in the selected Nightingale wards while standing at 37.21% of the daytime monitoring in F.A. (Table 3.18). Whereas W9 had the longest daytime periods with T.A.$_{ext.(S1)}$ values lower than the T.A.$_{(in)}$ values, with their percentages standing at 72.62% followed by the percentages recorded in Physio. (54.98%) and in T.U. (53.85%), differences never remained below 3K in W9 while accounting for 12.35% and 13.08% of the monitoring periods in Physio. and T.U., respectively (Table 3.18).

Over night-time, the lowest mean difference between the T.A.$_{ext.(S1)}$ values and the T.A.$_{(in)}$ values were recorded in the selected Nightingale wards varying between -0.70 (W2) and -1.29K (W7), while with the highest difference between the T.A.$_{ext.(S1)}$ values and the T.A.$_{(in)}$ values were recorded in Physio. standing at -3.14 and being followed by those recorded in T.U. (-2.87), W9 (-2.47), and F.A. (-1.93) (Table 3.18; Figure 3.30). The T.A.$_{ext.(S1)}$ values remained higher than the T.A.$_{(in)}$ values over the whole night-time period in Mar.Apr.2017 in all selected wards except for W2, W3 and W6, where the $T.A._{(in)}$ values exceeded the $T.A._{ext.(S1)}$ values during short intervals of the monitoring time that stood at 9.55% in W2, 1.82% in W3, and 5.91% in W6 (Table 3.18). The highest percentages of $T.A._{ext.(S1)}$ values being cooler than the $T.A._{(in)}$ values by more than 3K stood at 60.29% in Physio., 41.82% in T.U., and 11.82% in W9 (Table 3.18; Figure 3.30).

In Mar.Apr.2017 except for Physio. and T.U., the median $T.A._{(in)}$ values followed an upward trend from 10:00 to 17:00. They reached their peak levels between 16:00 and 17:00 (Figure 3.32). In W9, the highest median $T.A._{(in)}$ value of 32.43^{o}C was recorded at 17:00, while one hour earlier at 16:00 the median $T.A._{(in)}$ values at the Nightingale wards culminated to 29.99^{o}C in W7, and 31.81^{o}C at W6 (Figure 3.32). The fluctuations in the median $T.A._{(in)}$ values per time of the day recorded at Physio. and T.U. stayed below 0.5K (Figure 3.32). From 11:00 to 19:00, W6 remained the warmest Nightingale ward, although, it started cooling down at 16:00 (Figure 3.32). The median $T.A._{ext.(S1)}$ values remained lower than the $T.A._{(in)}$ values throughout the twenty-four-hour period, and they were significantly lower (Figure 3.32). Except for Physio., T.U. and F.A., all selected wards began to cool down after 17:00 at different starting points varying between 17:00 for W9 and 18:00 for the selected Nightingale wards (Figure 3.32). Although all selected wards had the lowest median $T.A._{(in)}$ values from 06:00 to 08:00, only the Nightingale wards had the fastest cooling rate and most extended periods of cooler median $T.A._{(in)}$ levels over night-time (Figure 3.32).

3.6.3.2 Key Statistics of the Seasonal and Diurnal Fluctuations in the Recorded Relative Humidity Values

In Sep.2016, all selected wards had mean twenty-four-hour $R.H._{(in)}$ values in the 75.82- 90.37% range, minimum twenty-four-hour $R.H._{(in)}$ values from 64.87% (W9) to 80.47% (Physio.) and maximum twenty-four-hour $R.H._{(in)}$ values from 82.59% (T.U.) to 96.20% (Physio.) (Table 3.19). Overall, W7 and W3 were the most humid wards, while T.U. and W9 were the less humid wards (Figure 3.33). he highest dispersion and variability levels were observed in W2, W3, W6 and W9, while T.U. had the lowest levels of variability and dispersion (Figure 3.33). All selected wards had mean daytime $R.H._{(in)}$ values in the 75.38-89.96% range, minimum daytime $R.H._{(in)}$ values from 64.94% (W2) to 76.36% (W7) and maximum $R.H._{(in)}$ values from 82.59% (T.U.) to 96.20% (Physio.) (Table 3.19). Overall, the diurnal swings in the recorded $R.H._{(in)}$ values were low, varying between -0.46% in Physio. and 1.41% in W2, while the diurnal swing of the $R.H_{.ext.(S1)}$ values was 4.92% (Figure 3.34). The mean night-time $R.H._{(in)}$ values were in the region of 75.55% (T.U.) to 90.34% (W7) (Table 3.19). The minimum night-time $R.H._{(in)}$ values varied from 68.20% (in W9) to 84.59% (Physio.), while the maximum night-time $R.H._{(in)}$ values ranged from 81.98% (T.U.) to 94.63% (W7) (Table 3.19).

In Sep.2016, between 10:00 and 19:00, the median $R.H._{(in)}$ values followed a relatively downward trend in the Nightingale wards and in W9, whereas F.A. and Physio. had a relatively steady course of median $R.H._{(in)}$ values, and T.U. had a fluctuating trend (Figure 3.35). The downward trend in W9, W2, W3, and W6 coincided with the peak period of solar radiation and likely high $W.S._{(His)}$ values, as indicated by the historical weather data (Figure 3.35). However, W7, T.U., and F.A. displayed less responsiveness to the impact of solar radiation and wind exposure over the same period (Figure 3.35). Except for Physio. and T.U., median $R.H._{(in)}$ values began to rise erratically after 19:00, reaching their highest levels between 22:00 and 24:00 and between 5:00 and 8:00, while in W7 the peak period was extended beyond 08:00, until 11:00 (Figure 3.35).

During the monitoring period in Mar.Apr.2017, all selected wards had mean twenty-four-hour $R.H._{(in)}$ values in the 58.41%-73.06% range, minimum twenty-four-hour $R.H._{(in)}$ values from 31.84% (W9) to 52.93% (T.U.) and maximum twenty-four-hour $R.H._{(in)}$ values from 62.65% (T.U.) to 84.24% (W3) (Table 3.20). Overall, W3 was the most humid ward, while T.U. was the least humid ward (Figure 3.36). Recorded mean night-time $R.H_{.ext.(S1)}$ value was higher than the daytime one, whereas the mean daytime $R.H._{ext.(Meteo)}$ value exceeded the night-time one, indicating the strong impact of different microclimates between a rural and an urban location, respectively. All selected wards had mean daytime $R.H._{(in)}$ values in the 58.38-72.90% range, minimum daytime $R.H._{(in)}$ values from 31.84% (W9) to 51.16% (W2) and maximum daytime $R.H._{(in)}$ values from 62.65% (T.U.) to 83.66% (W3) (Table 3.20). The mean night-time $R.H._{(in)}$ value was higher than the daytime one in W2, W3, W6, W9, and T.U. (Figure 3.36). The diurnal swings were small, varying between 0.48% in W2 and 1.68% in W6 for higher night-time $R.H._{(in)}$ values and between 0.16% and 1.45% for higher daytime $R.H._{(in)}$ values (Figure 3.37). The mean night-time $R.H._{(in)}$ values lied between 58.45% (T.U.) and 73.26% (W3), the minimum night-time $R.H._{(in)}$ values ranged from 39.07% (W9) to 84.24% (W3) (Table 3.20).

In Mar.Apr.2017 apart from the steady course of the median $R.H._{(in)}$ values at T.U., the rest of the selected wards followed a similar general pattern of change in the median $R.H._{(in)}$ values per time of the day (Figure 3.38). This might indicate that throughout the dry season, the combined impact of solar radiation with ventilation could be more substantial on influencing the variations of the $R.H._{(in)}$

values, whereas their influence over the rainy season was affected by the impact of the monsoonal rainfalls. In the Nightingale wards, W9, Physio., and F.A., at 17:00, the median $R.H._{(in)}$ values concluded a downward trend, which began between 11:00 and 12:00 and was probably influenced by the potentially strong winds varying between 5.70 and 6.40 m/s, as indicated by the historical weather data (Figure 3.38). Whereas after 17:00 a strong upward trend began that lasted until 24:00, became weaker and continued until 6:00 (Figure 3.38). The period before the culmination of the solar radiation (between 7:00 and 10:00), was another peak period for the median $R.H._{(in)}$ values in the selected wards except for T.U. (Figure 3.38).

3.6.3.3 Key Statistics of the Recorded Wind Speed Fluctuations Between Seasons and Shifts

Throughout the monitoring period in Sep.2016, the recorded $W.S._{(in)}$ values were in the 0.01-3.75m/s range, the minimum values varied from 0.01m/s (W7, W9 and T.U.) to 0.08m/s (F.A.), and the maximum values ranged between 0.94m/s (F.A.) and 3.75m/s (W9) (Table 3.21). F.A. and W7 had the lowest range and dispersion of recorded $W.S._{(in)}$ values, while the range and dispersion of recorded values were the widest in W2 and W6 (Table 3.21). As illustrated in Figures 3.39a-d, $W.S._{(in)}$ values from 0.00-0.50m/s demonstrated the percentages of highest occurrence in the 76.28-95.87% range in all selected wards except for W7, where the 1.01-1.50m/s interval was most prevalent reaching 74.50%.

As indicated by the recorded wind speed values at Freetown's meteorological station ($W.S._{ext.(Meteo)}$), over the monitoring period in Mar.Apr.2017, the mean $W.S._{ext.(Meteo)}$ value was typical compared to the historical values, standing at 3.59m/s (Table 3.21). The mean $W.S._{(in)}$ values were in the 0.42-0.88m/s range, minimum recorded $W.S._{(in)}$ values stood at 0.01, and maximum recorded $W.S._{(in)}$ values ranged between 2.98m/s (W6), and 4.18m/s (W9) (Table 3.21). W2 and W6 had the highest occurrence percentages in the interval with wind speed values from 0.51 to 1.00m/s, which accounted for 34.51% and 34.04% of the monitoring period in W2 and W6, respectively, while the interval with the wind speed values from 0.00 to 0.50m/s accounted for most of the monitoring time in the rest of the selected wards except for W9, where the most prevalent frequencies stood at the intervals with wind speed values from 0.00 to 0.50m/s (28.54%) and from 0.51 to 1.00m/s (Figures 3.39a-d). The strongest and most fluctuating wind velocities were recorded in the Nightingale wards and especially at those wards located on the first floor; however, the impact of natural ventilation was very weak in F.A (Table 3.21).

3.6.3.4 Associations between the Recorded Environmental Measurements and Seasonal, Temporal and Spatial Conditions

Recorded $T.A._{(in)}$ and $R.H._{(in)}$ values during different seasons and times of the day and between the Pavilion building and the rest of the case-study buildings displayed non-normal distributions (Figure 3.40a). The application of the Wilcoxon Rank Sum Test showed that differences between different seasons and between the Pavilion building and the rest of the case-study buildings introduced statistically significant variation in both the $T.A._{(in)}$ and $R.H._{(in)}$ values, whereas only in $T.A._{(in)}$ values differences between daytime and daytime were statistically significant (Figure 3.40b). Seasonal differences had strong positive correlation coefficients (0.52-0.66, p-value<0.001) with the recorded $T.A._{(in)}$ values only in W3 (samples of daytime and night-time periods), in Physio. and T.U. (samples of 24-hour, daytime, and night-time periods) and F.A. (samples of 24-hour period and daytime periods) (Figure 3.40c). Variation in the recorded $R.H._{(in)}$ had strong negative correlations (-0.65-(-0.56), p-value<0.001) in all case-study wards except in W2 (-0.40, p-value<0.001) and W6 (-0.36, p-value<0.001) where the estimated correlations were moderate, and in Physio, where strong positive correlation (0.56, p-value<0.001)) was found in the daytime values and in F.A., where positive strong correlations were found in the sample of the daytime values (0.62, p-value<0.001) and night-time values (0.64, p-value<0.001) (Figure 3.40c).

Weak correlations with variation between daytime and night-time periods (-0.28-0.21, p-value<0.01 and p-value<0.001) were found in the $T.A._{(in)}$ and the $R.H._{(in)}$ values in most case studies wards both in Sep.2016 and in Mar.Apr.2017, while no correlations were found in the $T.A._{(in)}$ and the $R.H._{(in)}$ values during both seasons in T.U. (Figure 3.40d). Furthermore, the only strong correlation (0.64, p-value<0.001) between the indoor thermal conditions and the spatial conditions was found in the variation created in the $T.A._{(in)}$ values between the Pavilion building and the rest of the case-study buildings during night-time over Mar.Apr.2017 (Figure 3.40e). Correlations between the twenty-four-hour, daytime and night-time $T.A._{(in)}$ values comprising the total sample, the sample collected at the pavilion building and the sample collected in the rest of the selected buildings, and the spatial characteristics for ventilative cooling were weak or moderate both in Sep.2016 and in Mar.Apr.2017 (Figures 3.41a-b). Moderate protective impact against the rise in $T.A._{(in)}$ values with higher influence during night-time was found in higher values of width-to-length ratios in the sample collected in the case-studies outside the Pavilion building in Sep.2016 (Spearman coefficient: -0.55-(-0.39), p-value<0.001) and in higher percentages of operable windows in the sample collected in the Pavilion Building in Sep.2016(Spearman coefficient: 0.34, p-value<0.001) and both in higher width-to floor-to-ceiling height ratios and percentages of openable windows in the sample collected in the case-study outside the Pavilion building in Mar.Apr.2017 (Spearman coefficient: -0.62, (-0.32), p-value<0.001) (Figures 3.41a-b).

Normal distributions were found only in the $T.A._{(in)}$ values in W2 in Sep.2016, while heteroscedasticity was found in the recorded $T.A._{(in)}$ and $R.H._{(in)}$ values during both seasons in the rest of the case study wards with a polynomial transformation having small impact on the correction of the distributions (Figures 3.42.1-2). Regarding possible correlations between the $T.A._{(in)}$ and $T.A._{ext.(S1)}$ values and $R.H._{(in)}$ and $R.H._{ext.(S1)}$ values, scatterplots revealed weak and moderate positive correlations in most selected wards during both seasons with W3, F.A. and Physio. displaying no or weak negative correlations (Figures 3.43.1-2). Only W6 and W9 experienced a rise in $T.A._{(in)}$, consistent with the increase in $T.A._{ext.(S1)}$ in Sep.2016 (Figures 3.44a-b). Time series plots indicated autocorrelation between the $T.A._{(in)}$ and $T.A._{ext.(S1)}$ values and $R.H._{(in)}$ and $R.H._{ext.(S1)}$) values in most selected wards during both seasons except for Physio. and T.U. (Figures 3.45.1-2), while all recorded $T.A._{(in),}$ $T.A._{ext.(S1)}$, $R.H._{(in)}$ and $R.H._{ext.(S1}$ values displayed attributes of stationary time-series variables (Figures 3.46.1-2). Autocorrelation between the $T.A._{(in)}$ and $T.A._{ext.(S1)}$ values and the $R.H._{(in)}$ and $R.H._{ext.(S1)}$ values was decreased in all the selected wards during both seasons with the application of the first difference time-series regression, whereas the application of the GLS, the infinite distributed lag model and the robust standard error regression were less effective with very few exceptions (Figures 3.47a-b). The application of weighted GLS (regarding temporal variation) eliminated heteroscedasticity only in the regression models between the $T.A._{(in)}$ and $T.A._{ext.(S1)}$ in W7, T.U. and F.A. over Mar.Apr.2017 (Figures 3.47a-b).

3.6.3.5 Discussion about the Recorded Thermal Environmental Performance and its Associations with the Seasonal, Temporal and Spatial Variations

Hospital spaces in warm climates without air-conditioning and proper design for the exploitation of natural ventilation tend to have high indoor temperatures, especially during high occupancy periods, as it was shown in the only published evidence by Wright et al. (2017) in waiting rooms in Giyani in South Africa where maximum mean temperature peaked at 31.4^{o} C. In the case-study wards at Connaught Hospital the insufficient protection against indoor overheating resulting from the insufficient cooling impact of the outdoor microclimate, the architectural and engineering components of the building envelopes, the operational schedules, the occupancy patterns, and the occupants' activities were indicated in the monitored indoor thermal performances. The ground-floor Nightingale wards were more prone over Sep.2016 to receive the excess moisture stored in the surrounding soil and vegetation that was transferred indoors through the open windows. In Physio., during both seasons the operational schedule, which imposed the closing of the windows at 18:00 during weekdays and over the whole weekend, contributed to significantly elevated night-time $T.A._{(in)}$ and $R.H._{(in)}$ values. In T.U., especially over Mar.Apr.2017, the single-sided ventilation, the protective impact of shading from surrounding buildings and the dense mosquito screens on the windows probably mitigated the impact of outdoor airflows contributing to steadier indoor thermal conditions. F.A., which had the deepest plan and the most inaccessible window apertures, displayed the slowest cooling rate over night-time. Despite all these differences, in all the ase-study wards, during both seasons, the peak of solar radiation coincided with high occupancy frequencies and activities.

During these periods that can be broadly defined from 11:00 and 16:00, high levels of internal heat gains impeded the diminished ventilative cooling potential of high outdoor wind speeds (as indicated by the historical weather file). W9 experienced the strongest exposure to unprotected solar exposure that was reflected in the delay of its cooling process over night-time. In multi-bed wards in hot-humid settings similar to the case-study wards, although moderate and strong correlations between indoor thermal conditions and seasonal variations can be expected with rising temperatures and falling relative humidity values over the dry season, the impact of temporal variations between daytime and night-time is likely to be weak. Indoor thermal conditions are anticipated to be linked with the building and ward typology with the strongest protective impact against overtime rise in temperatures to be performed by the pavilion-plan typology. The impact of the spatial attributes on ventilative cooling is likely to be different among diverse building typologies and seasons, with cooler indoor temperatures being associated with higher openable window coverage both in pavilion plan and other contemporary typologies over both the rainy and the dry seasons. In contrast, deeper plan layouts could have a protective impact against indoor warming only in the modern building typologies over both the rainy and the dry season indicating the importance of the protection of the bedded areas and the nurse station from direct exposure to solar radiation.

3.6.4 Recorded Occupant-Controlled Window Operation and its Associations with the Environmental, Seasonal, Temporal and Spatial Variations

3.6.4.1 Key statistics of the Recorded Occupant-Controlled Window Operation

Apart from W6, all selected wards experienced a moderate rise in the median percentages of open apertures during Mar.Apr.2017 (Figure 3.48). However, during both seasons, the median of the differences in the percentages of open apertures between the morning and the evening shifts remained around 0.00% except in Physio., where significantly more window apertures were open over the evening shift (Figure 3.49). Mean percentages of open apertures stood around 50.00% in the studied facades of all the case-study buildings during both seasons, with the window openings at their WSW-W facades that were behind the nurse stations at the Nightingale wards displaying the highest variation (Figures 3.50-53). However, similarly, active window-opening behaviours were not observed in the windows behind the nurse station at the S-SSE façade in F.A. (Figures 3.54-55).

3.6.4.2 Associations between the Recorded Occupant-Controlled Window Operation and the Environmental, Seasonal, Temporal and Spatial Variations

Window-opening behaviours displayed strong correlations with seasonal variability only in W6 (Kendall's W test coefficient: -0.54, p-value<0.001), in W9 (Kendall's W test coefficient: 0.70, p<0.001) and Physio. (Kendall's W test coefficient: 0.56, p-value<0.001) while only in W9 occupant-controlled window operation had a weak link (Kendall's W test coefficient: 0.19, p-value<0.001) with temporal differentiations between the morning and the evening shifts (Figure 3.56). Window opening behaviours displayed weak correlations with spatial variations between building and ward typologies (Kendall's W test coefficient: -0.17-0.10, p-value<0.01) (Figure 3.56). Distributions of the total percentages of open apertures were non-normal between different seasons, the morning, and the evening shifts and between the Pavilion building and the rest of the case-study buildings (Figure 3.57a). However, seasonal, temporal, and spatial differentiation had no statistically significant impact on the variance of the total percentages of open apertures (Figure 3.57b). The recorded percentages of open apertures had no correlations with the $T.A._{ext.(S1)}$ and the $R.H._{ext.(S1}$ during both seasons while they had weak correlations with the $R.H._{(in)}$ values (Spearman coefficient: -0.14-(-0.13), p-value<0.01) and with the $T.A._{(in)}$ values (Spearman coefficient: 0.13-0.19, p-value<0.01) (Figure 3.57c).

Furthermore, window-opening behaviours had weak correlations (Spearman coefficient: -0.24-0.24, p-value<0.001) with the spatial attributes for ventilative cooling that became strong (Spearman coefficient: -0.42, p-value<0.001) over Mar.Apr.2017 when lower percentages of open aperture were linked with higher width-to-floor-to-ceiling height ratios and higher coverages of openable windows (Figure 3.57c). The lack of responsiveness of the window-opening behaviours to outdoor and indoor environmental changes is illustrated in Figures 3.58a-h with weak indications that occupants in Sep.2016 in the Nightingale wards, in W9 and in F.A. tended to open more window-openings when the $T.A._{ext.(S1)}$ and $T.A._{(in)}$ values rose and in Mar.Apr.2017 in all selected wards tended to close window openings when $T.A._{ext.(S1)}$ values and the $T.A._{(in)}$ values exceeded 30.00^{o}C.

3.6.4.3 Discussion about the Recorded Occupant-Controlled Window Operation and its Associations with the Environmental, Seasonal, Temporal and Spatial Variations

Regarding the observed differences in the percentages of open window-apertures between the morning and the evening shifts, Shi, et al. (2018) also found differences in the window-opening behaviour in wards in China between different times of the day. However, overall low frequency of changes in the positions of the window openings, as observed by Baird (1969) and Short, et al. (2012), was also evident in observations collected at Freetown's Connaught Hospital, especially regarding the daily differences between the morning and the evening shifts. Contrary to the irresponsiveness of the window-opening actions to the indoor accumulation of heat found by Raja, et al., (2001), occupants in Sep.2016 in the Nightingale wards, in W9 and in F.A. tended to open more window-openings when the $T.A._{ext.(S1)}$ and $T.A._{(in)}$ values rose and in Mar.Apr.2017 in all selected wards tended to close window openings when $T.A._{ext.(S1)}$ values and the $T.A._{(in)}$ values exceeded 30.00^{o}C.

However, similar to the findings by Hobday and Dancer (2013), the absence of possible correlations between larger window areas and more frequent window-opening actions was found in the recorded window-opening behaviours at Connaught Hospital. It is likely that occupants' inclination to open or close the windows more often and in a more responsive manner to the changes of the indoor and outdoor thermal conditions was prevented by the lack of accessibility and easiness regarding the operation of the window openings that were created through the unavoidable installation, due to security and safety concerns, of the railings and the mosquito nets covering the most significant part of the window areas in the selected wards. However, the lack of railings and mosquito nets did not seem to contribute to more frequent changes in the positions of the window openings in W9 and Physio. Therefore, beyond architectural and engineering aspects, socio-cultural and operational parameters that defined hierarchies and relevant behaviours in each ward's dynamic environment probably played a crucial role in the determination of the window-opening behaviours in Connaught Hospital's selected wards.

3.6.5 Recorded Indoor Overheating and its Associations with Seasonal, Temporal and Spatial Variations

3.6.5.1 Key Statistics of the Recorded Indoor Overheating

In Sep.2016, the recorded T.A.$_{(in)}$ values in all selected wards exceeded the overheating threshold of 28^{o}C, resulting in overheating in all of them, with the most severe impacts being experienced over a twenty-four-hour period in F.A. (84.95%), W9 (83.62%) and T.U. (63.52%) (Table 3.22). During night-time, the overheating threshold of 26^{o}C was exceeded over the whole monitoring period in all selected wards except for very short periods with T.A.$_{(in)}$ values below 26^{o}C only in W2 (9.14%), W3 (1.11%), and W6 (5.71%) (Table 3.22). In Mar.Apr.2017, it is evident that the overheating threshold of 28^{o}C was exceeded in all selected wards during a twenty-four-hour period of approximately the whole monitoring period with the selected Nightingale wards experiencing the lowest overheating incidence that stood at 66.50% in W2, 89.39% in W3, 76.05% in W6, and 97.11% in W7 (Table 3.22). Throughout night-time, the temperature threshold of 26^{o}C was exceeded over the whole night except for only one hour in W2 (Table 3.22).

The low limit of the ASHRAE 55 standard was exceeded in all the case-study wards during the whole monitoring period, both in Sep.2016 and in Mar.Apr.2017 (Figures 3.59-3.62). In Sep.2016, the rise above the low limit of the ASHRAE 55 standard was higher with mean values in the 3.22- 6.68K range, minimum values from 1.19 (W2) to 4.74K (W9) and maximum values between 5.88 (F.A.), and 8.90K (W7) (Table 3.23). The recorded overheating was lower at the selected Nightingale wards, especially during night-time, whereas night-time overheating was most severe in T.U. and F.A (Figures 3.63-3.64). In Sep.2016, the mean differences in the T.A.$_{(in)}$ values exceeding the low limit of the ASHRAE 55 standard during daytime ranged between 3.13 (W3) and 6.68K (W9), the minimum values varied between 1.29 (W2) and 4.74K (T.U.), and the maximum values were between 3.84 (W3) and 9.48K (W9) (Table 3.23). Over night-time, the mean differences in the T.A.$_{(in)}$ values above the low limit of the ASHRAE 55 standard were in the 3.18- 6.26K range, the minimum values were from 1.25 (W3) to 4.92K (T.U.), and the maximum values varied between 1.25 (W6) and 7.94K (W9) (Table 3.23). In Sep.2016, W9 was the only selected ward, where the recorded T.A.$_{(in)}$ values exceeded the low limit of the ASHRAE 55 standard by a difference between 8.00 and 9.00K over

4.17% of the twenty-four-hour monitoring period with most of the remaining overheating period displaying differences between 5.00 and 5.99K (Figure 3.67). W9 was followed by T.U., where 93.78% of the recorded T.A.$_{(in)}$ values exceeded the low limit of the ASHRAE 55 standard by 6K (Figure 3.67). Whereas overheating levels were less severe in F.A., it experienced T.A.$_{(in)}$ exceeding the low limit of the ASHRAE 55 standard by 4K and by 5K over 61.20% and 30.40% of its twenty-four-hour monitoring period, respectively (Figure 3.67). Similar to the hospital case-studies of the DeDeRHECC project, in the selected Nightingale wards of Freetown's Connaught Hospital, the lowest levels of overheating were recorded with differences from 2.00 to 2.99K and from 3.00 to 3.99K accounting for monitoring intervals that stood at 59.78% in W2, 100% in W3, 56.18% in W6, while in W7 differences between 3.00 and 3.99K and between 4.00 and 4.99K accounted for 73.78% of the twenty-four-hour monitoring period (Figure 3.67).

In Mar.Apr.2017, the rise above the low limit of the ASHRAE 55 standard had mean values between 4.68 (W2) and 6.48K (Physio.), minimum values between 2.13 (W2) and 5.49K (Physio.) and maximum values from 5.37 (T.U.) to 8.50K (W2) (Table 3.24). Overall, the dispersion, variability and severity of overheating were lower during night-time than during daytime in all selected wards except for T.U., F.A. and Physio. (Figures 3.65-3.66). During daytime, the differences between the low limit of the ASHRAE 55 standard and the T.A.$_{(in)}$ values had mean values from 4.77 (T.U.) to 6.38K (Physio.), minimum values in the 2.42-5.49 K range, and maximum values from 5.37 (T.U.) to 8.50K (W2) (Table 3.24). During night-time, T.A.$_{(in)}$ values above the low limit of the ASHRAE 55 standard had mean values in the 0.88-6.63K range, minimum values between 2.13 (W2) and 5.78K (Physio.) and maximum values from 1.89 (F.A.) to 7.30K (Physio.) (Table 3.24). Recorded T.A.$_{(in)}$ values with differences above the low limit of the ASHRAE 55 standard standing from 6.00 to 6.99K accounted for twenty-four-hour intervals that stood at 80.00% in Physio., 14.71% in W9 and W6, 10.56% in W2, and 8.61% in W3, while differences from 5.00 to 5.99K accounted for twenty-four-hour intervals that stood at 73.61% in F.A., 21.11% in T.U., 22.50% in W9, 33.61% in W7, 18.61% in W6, 24.44% in W3, and 21.68% in W2, while differences between 2 and 4.99K covered most of the remaining monitoring periods in all selected wards except Physio. (Figure 3.68). In Sep.2016, T.A.$_{(in)}$ values with differences above the low limit of the ASHRAE 55 standard approximately between 4 and 5K continuously over consecutive days occurred in F.A. over the whole monitoring period and in T.U. over sporadic days (Figure 3.69). By contrast, in Mar.Apr.2017 Physio., T.U. and F.A. had continuously over consecutive days T.A.$_{(in)}$ values with differences above the low limit of the ASHRAE 55 standard that stood approximately between 5.50 and 7.00K in Physio, from 4.50 to 5.00 in T.U., and between 4.00 and 6.50 in F.A. (Figure 3.70).

Applying the adaptive thermal comfort model developed by Vellei, et al. (2017) for $R.H._{(in)}$ values higher than 60% being recorded in Sep.2016, lower levels of overheating were found in all selected wards, with W2, W3 and W6 having the highest percentages of $T.A._{(in)}$ values remaining below the maximum comfortable temperature, which stood at 51.08% in W2, 68.68% in W3, and 48.33% in W6, while differences higher than 0 and lower than 2K prevailed in the rest of the selected wards with the highest percentages of differences from 0 to 2K being recorded in Physio. (68.47%), W7 (48.75%), and W9 (33.50%), and of differences from 1 to 2K being recorded in F.A. (60.00%) and W9 (27.50%) (Figure 3.71). In Mar.Apr.2017, the application of the adaptive thermal comfort model developed by Vellei, et al., (2017) for $R.H._{(in)}$ values higher than 60% showed that W2 and W6 had the highest percentages of $T.A._{(in}$ values below the limits of the comfortable temperatures, which stood at 38.26% in W2 and 29.90% in W6, while differences above 0 and below 3K prevailed in the rest of the selected wards with the highest percentages of differences from 2 to 3K being recorded in T.U. (100%), Physio. (80.15%), and W7 (68.97%), and of differences between 1 and 2K being recorded in F.A. (72.66%) and W9 (43.15%) (Figure 3.72). Regarding comparisons made with the adaptive model developed by Vellei, et al., (2017) for $R.H._{(in)}$ values between 40% and 60% the most prevalent percentages indicated differences between 0 and 2K in all selected wards with W9 having the highest percentage of differences from 2 to 3K, which stood at 23.60% (Figure 3.72). The adaptive model developed by Vellei, et al., (2017) for R.H.(in) values lower than 40% was not applied in the very limited number of monitoring hours in W6 (one hour) and in W9 (two hours) with recorded R.H.(in) values lower than 40%. Apparent temperatures indicated an overheating level of "extreme caution" (32-39^{o}C) over the whole monitoring periods in Sep.2016 and Mar.Apr.2017 in Physio., W9, T.U., and F.A., and in W7 in Mar.Apr.2017 (Figures 3.73-3.74). The Nightingale wards had the most frequent experience of apparent temperatures that stood at the lowest level of caution (27-32^{o}C), especially in Sep.2016 with the most frequent incidences occurring during night-time in W2 and W6, and during daytime in W3 and W7 (Figure 3.73). At the same time, Nightingale wards except for W3 had apparent temperatures classified as "danger" (39-51^{o}C), with the highest percentages occurring during daytime in Sep.2016 and standing at 2.07% in W7, 0.91% in W2, and 0.60% in W6 (Figure 3.73).

3.6.5.2 Associations between the Recorded Indoor Overheating and the Seasonal, Temporal and Spatial Variations

Correlations between the recorded overheating and seasonal variation were positive and strong in W3 (Kendall's W test coefficient: 0.57, p-value<0.001) and in T.U. (Kendall's W test coefficient: 0.66-0.68, p-value<0.001), negative and strong in W9 (Kendall's W test coefficient: -0.62, p-value<0.001) only during night-time and weak or moderate (Kendall's W test coefficient: -0.18-0.30, p-value<0.001) in the rest of the selected wards (Figure 3.75a). Correlations between the recorded overheating and temporal variation between daytime and night-time were weak or statistically insignificant (Kendall's W test coefficient: -0.24-0.27, p-value<0.001) except for W6 in Mar.Apr.2017 (Kendall's W test coefficient: -0.32, p-value<0.001) (Figure 3.75a). The Nightingale typology showed a strong protective association against 24-hour (Kendall's W test coefficient: 0.54, p-value<0.001) and night-time overheating (Kendall's W test coefficient: 0.66, p-value<0.001), while links with diverse building typologies and ward typologies were weak or moderate (Kendall's W test coefficient: 0.14-0.46, p-value<0.001) (Figure 3.75b). Regarding the correlations between overheating and spatial attributes of ventilative cooling (width to length, the width to floor-to-ceiling-height ratios and the percentage of openable window area), the most significant protective links against overheating were in relation to the openable window coverage collected in the Pavilion building in Sep.2016 (Spearman coefficient: -0.60, p-value<0.001) and in relation to higher width/floor-to-ceiling height ratios collected in the case-studies outside the Pavilion building (Spearman coefficient: -0.47, p-value<0.001)(Figure 3.75c).

3.6.5.3 Discussion about the Recorded Indoor Overheating and its Associations with Seasonal, Temporal and Spatial Variations

Critical levels of overheating regarding severity, duration, and frequency, especially during night-time were estimated according to static and adaptive thermal comfort thresholds. Overheating estimated according to the apparent temperatures thermal index revealed critical public health risks, which is probably common in crowded hospital spaces in the Global South, which lack air-conditioning and proper passive cooling design, as indicated by the only available overheating evidence from the waiting rooms in the rural health centres in Giyani, South Africa (Wright, et al., 2017). Overall, the Nightingale wards experienced slightly lower levels of overheating. However, the application of the adaptive model according to the ASHRAE 55 standard carried significant limitations since outdoor temperatures were a weak predictor of indoor thermal conditions. Furthermore, this model is not recommended to understand thermal comfort among non-healthy adults, or adults seating or lying on beds (such as the patients) or being physically very active (such as the nurses). Indoor overheating was found to be less severe following the application of the adaptive thermal comfort model, as modified by Vellei, et al. (2017) for different levels of indoor relative humidity. Differentiation between building and ward typologies can exacerbate or mitigate indoor overheating in different ways between seasons and times of the day or the night, with the pavilion-plan typology displaying the strongest mitigative function. Similar to the correlations found between indoor thermal conditions and the spatial attributes for ventilative cooling among the case-study wards, in ward typologies with higher capacity for the exploitation of natural ventilation and better protection from extensive direct solar radiation higher openable window coverage can reduce overheating during the rainy season, whereas in ward typologies lacking both optimal design for natural ventilation and protection from extensive direct solar radiation deeper plans can be protective against overheating.

3.6.7 A Tropical Nightingale Ward with Improved Environmental Performance

An indicative set of interdependent interventions in the thermal mass, the ventilation and shading design and the operational schedule were applied in a thermodynamic model of W2, and their impact on indoor overheating was assessed (Figure 3.76). The interventions aimed to reduce the accumulation of internal heat gains by reducing the rate and range of heat exchanges between the internal and external surfaces of the fabric. The window areas of the NNW-N, S-SSE and WSW-W facades were kept the same, while rooflights with shading at the roofs of the NNW-N and S-SSE peripheral areas and windows with shading at the top of NNW-N and S-SSE facades with direct impact at the cross-ventilated attic were added. Regarding the operational profiles, windows in the WSW-W, NNW-N and S-SSE facades and the rooflights were modelled to be open when the indoor temperature was higher than outdoor temperature and outdoor relative humidity was lower than 80.00%. The internal glazed doors, which were added between the bedded area and the peripheral areas, were modelled to be open when the temperature in the bedded areas was higher than the temperature in the peripheral areas, while added internal windows, which were added exactly above the glazed doors, were modelled to be open when the temperature in the bedded areas was higher than the temperature in the peripheral areas and the winds came from the relevant prevailing directions. This model's thermodynamic simulations demonstrated that only the percentage of $T.A._{(in)}$ values exceeding the static threshold of $28^{o}C$ in Mar.Apr.2017 were lower by 48% than those in Sep.2016 (Table 3.25). Both in Sep.2016 and Mar.Apr.2017, the differences between the low limit of the ASHRAE 55 standard and the night-time $T.A._{(in)}$ values were overall lower, with narrower ranges and with higher concentration in the lower ranks of temperature differences (Figure 3.77).

3.6.8 Conclusion

Similar to the category I of the EN15251, which is the sole adaptive thermal comfort standard recommended for the calculation of indoor overheating in naturally ventilated wards, the low limit of the adaptive thermal comfort standard ASHRAE 55 might also have limited applicability in hospital buildings with limited resources in hot-humid climates. In these settings beyond climatological similarities, clinical care with remarkably restrained resources is likely to be practised in hospital estates comprising diverse building and ward typologies with their construction ages ranging from the nineteenth to the twentieth-first centuries. Although hospital buildings built before the 1940s according to climate design principles before air-conditioning might have a higher capacity to exploit natural ventilation, this capacity might have been impaired by contemporary interventions being driven by higher hospitalisation needs, different expectations of healthcare and more hectic operational schedules. In this way, indoor thermal conditions in historical and modern hospital buildings might be driven by similar drivers. As it was shown, high thermal mass, insufficient solar control, single-glazed windows, which were controlled with difficulty, and high occupancy levels contributed to the reduction of any potential cooling capacity driven by natural ventilation. Furthermore, mapping of the occupancy frequencies and occupants' activities showed that delivery of care might significantly deviate from established assumptions and models.

Mapping of occupancy frequencies and occupants' activities in a sub-sample of the case-study wards revealed the diversity of occupant types and activities and extremely high numbers of occupants. Although the abundance of nurses kept the patient-to-nurse ratio at low levels, visitors' presence was continuous and intense with affective and practical significance for the care of patients. Despite the accepted practice of deducing the intensity and diversity of activities in inpatient spaces with the number of occupants, the observations at Connaught showed that this practice might result in the underestimation of the impact of nursing and other activities on internal heat gains and, more importantly on the potential of natural ventilation to protect against airborne infection through the control of the directions and dispersions of viral air contaminants. The investigation of the synergetic impact of the building's thermal environmental performance, the operational schedules, and occupant adaptive behaviours revealed that the busiest time of the day (11:00 to 14:00) when doctors' and nurses' rounds were scheduled, coincided with strong levels of solar exposure (being extended until 16:00) and irresponsive occupant-controlled window-operation (Figures 3.78-79).

This synergetic impact is expected to be linked with seasonal, temporal, and spatial variations with diverse influence between different building and ward typologies. This is an implication that in naturally ventilated inpatient spaces, responsiveness of the building's envelopes' environmental controls and their operation by the hospital occupants as well as the schedules of the clinical activities and the visiting hours need to be adapted to diverse environmental conditions across seasons and between daytime and night-time, despite the fact that in equatorial- monsoonal (Am) climates (similar with Freetown's climate) seasonal and diurnal fluctuations of outdoor weather are low. The pavilion-plan typology can probably have a protective impact against night-time rise in indoor temperatures compared to other hospital building typologies that were not conceptualised as instruments for the optimal exploitation of natural ventilation. In these ward typologies with a higher capacity to exploit natural ventilation and better protection from extensive direct solar radiation, higher openable window coverage can contribute to stronger ventilative cooling, especially during the rainy season. In contrast, in other ward typologies, the protection from extensive direct solar radiation in deeper plans can be more effective in mitigating overheating. In hospital wards, where occupant-controlled window-operation is the primary environmental mechanism for cooling and infection control, hospital occupants need to be trained to operate the windows according to indoor and outdoor environmental changes.

Chapter 4

Adaptive Thermal Comfort and Occupants’ Adaptive Behaviours

Abstract

In Chapter 4, the impact of seasonal, temporal, spatial and environmental conditions and participants’ characteristics, adaptive behaviours, and satisfaction levels with existing environmental controls on the votes of thermal sensation and comfort, preferences and acceptability are explored. The thermal comfort survey, which was realised with the participation of 750 nurses, hospitalised patients, and visitors for the first time in naturally ventilated multi-patient wards in a hot-humid setting with limited resources, consisted of the collection of subjective and environmental measurements according to standardised procedures (ASHRAE 55:2013) that complied with infection control protocols while avoiding disruptions of the nursing care routines. In addition, semi-structured interviews were conducted with nine head nurses and twelve doctors to further explore common adaptive behaviours at an individual level and in relation to patient care.

Non-parametric inferential statistics (Wilcoxon Rank Sum Test) were applied to investigate the impact of seasonal, temporal, and spatial conditions and personal factors on the variation of the physical measurements. Predictive correlations (Kendall’s W test coefficients and Cramer’s V effect size) were estimated between the thermal comfort votes and seasonal, temporal, and spatial conditions, personal factors, and adaptive behaviours and between different types of the thermal comfort votes in the separate samples of nurses, patients, and visitors. Simple bivariate linear regression was used to determine the links between the thermal comfort votes and physical measurements. The impact of indoor airflows on indoor temperature and relative humidity levels was explored through time-series regression. Investigation of the context-specific acceptable indoor thermal conditions was conducted through probit regression, while binary logistic regression was used to define the risk of higher thermal discomfort to rising temperatures and relative humidity levels. Thematic content analysis was applied in the semi-structured interviews’ scripts.

Indoor airflows had a statistically significant impact on the $T_{op.(spot)}$ values around nurses in Mar.Apr.2017 and on the $R.H._{(spot)}$ values around patients in Mar.Apr.2017 with high levels of autocorrelation. Comparisons between reported and observed individual adaptive behaviours showed that nurses drank water, visitors moved to cooler places, and patients asked for help. Nurses' responses revealed that actions for the restoration of patients' thermal comfort were an integral part of nursing care and in line with doctors' advice and patients' needs. Although nurses were in control of the existing environmental controls' operation, opportunities for interaction with

existing controls in close distance occurred to all occupant types. The reported thermal sensation votes were not a good indicator of comfort and acceptability of the thermal conditions. Therefore, sensation votes had to be paired with comfort votes and preference votes (reported by the same participant). Temperature-related- preference votes were strong predictors of the temperature-related sensation and comfort votes (Cramer's V effect size: 0.51-0.60, p-value<0.001), however the direction of their effect was different among nurses, patients, and visitors. Perceptions of thermal discomfort were driven by perceptions of high indoor relative humidity levels in Sep.2016, of elevated indoor temperatures in Mar.Apr.2017 and low levels of indoor airflows during both seasons. Therefore lower tolerance levels to elevated temperatures during the warm season ($T_{op.(spot}$: 28.20-29.38^{o}C), and to higher relative humidity levels during the rainy season (R.H.$_{(spot)}$: 66.25-67.50%) defined thermal comfort while occupants' preferences for higher indoor airflows (W.S.$_{(spot)}$: 0.90 m/s) displayed minor seasonal variation.

The group of spatial attributes, which were defined by diverse building and ward typologies and by different levels of proximity to existing environmental controls, personal factors, which were determined by gender, and adaptive behaviours, which were described by the operation of the existing environmental controls and behaviours that change thermoregulation at an individual level, had the strongest effect size (Cramer's V effect size: 0.50-0.69, p-value<0.001) on the variation of thermal comfort votes only among interviewed patients. More specifically, allocation of patients in the case-study Nightingale wards (coded as "0") had a strong alleviating impact on thermal discomfort during the rainy season (Cramer's V effect size: 0.50-0.66, p-value) while acceptability of the indoor airflows among patients was higher across all ward typologies when they could control window operation (Cramer's V effect size: 0.54, p-value<0.001). Furthermore, in the case-study wards, whereas temperature-related comfort votes were linked in linear regression models with Top.$_{(spot)}$ values among all occupant types ($0.44<R^2<0.72$, p-value<0.001), the impact of indoor airflows found to be more critical only around patients (R^2= 0.66, p-value=0.001). Overall, patients were more sensitive to rising indoor temperatures by 1.3 times more than nurses and by two times more than visitors. Outdoor thermal conditions were a weak predictor of the experienced thermal discomfort, as is indicated by the linear regression models between the reported temperature-related votes and the recorded T.A.$_{ext.(S1)}$ and R.H.$_{ext.(S1)}$ values. Comparisons between reported thermal comfort and modelled thermal comfort according to PMVs (ASHRAE 55:2013) and Griffins models showed that although thermal discomfort was overestimated, the sensitivity of thermal distress to rinsing indoor temperatures was underestimated. If exposure to the critical cooling force through natural ventilation is not adapted to indoor microclimate and occupant's capacity for thermal adaptability (both behavioural and physiological), thermal distress will probably differentiate disproportionally to thermal vulnerability among the occupant types. Climate-responsive operation of the building controls can become part of nurses' training in naturally ventilated hospital wards with restrained resources. Nurses' training can be supplemented by real-time visual evidence about outdoor and indoor environmental changes, while posters and other visual aids can guide window operation to patients and visitors. The provision of cool water and accessibility to cool outdoor places can strengthen the adaptive capacity at a personal level among all occupant types. Informal nursing practices for the amelioration of thermal discomfort can be integrated with established care and infection control protocols. The integration of critical aspects of thermal adaptability at a personal level in relation to indoor microclimate that extend the criteria for bed allocation beyond clinical outcomes can significantly improve patients' limited thermal adaptability while strengthening the indoor environment's healing potential, whose attributes are exploited towards a personalised type of health care.

4.1 Introduction

In the last fifty years, architects and engineers have been producing a growing body of work on human thermal comfort. However, to date the research landscape lacks comprehensive thermal comfort surveys in occupied naturally ventilated in-patient wards. Furthermore, despite significant differences in the physiological thermoregulation capacity (Parsons, 2002), the permitted adaptive behaviours (Verheyen, 2009) and the individual characteristics that influence human thermal comfort (Skoog, et al., 2005), no distinctions are made in the established thermal comfort standards between the acceptable range of environmental conditions for hospital staff, patients, and visitors. Apart from the effect of thermal environments on operative and post-operative care, a significant knowledge gap exists regarding the impact medical conditions and treatments on thermal comfort among patients (Özsaban and Acaroğlu, 2020). As a result, any potential healing impact on patients' recovery through modifications of the thermal conditions, has not yet been investigated (Khodakarami and Nasrollahi, 2012), while an additional research gap exists about thermal comfort among patients during sleep (Lomas and Giridharan, 2012). By contrast, a significant number of studies exist on the healing potential of diverse aspects of the interior design of hospital spaces in high-income countries (Salonen, et al., 2013; Salonen and Morawska, 2013; Nimlyat and Kandar, 2015).

It is widely accepted that comprehensive understanding of human thermal comfort consists in the integrated modelling of the physiological, behavioural, psychological, and microclimatic processes that interact simultaneously. These dynamics are influenced by long-term and short-term acclimatisation, demographical characteristics, state of health, adaptive behaviours at individual level and in relation to mechanisms of environmental controls in the built environment (Hanna and Tait, 2015). Regarding the restoration of thermal comfort at individual level, whereas the vital role of air movement in cooling through evaporative heat loss on the skin surface is widely accepted, the impact of ambient humidity has been widely overlooked. Recent evidence suggests that ambient humidity has a crucial impact on thermal comfort that needs to be thoroughly examined (Berglund, 2002) especially in naturally ventilated buildings where its influence on thermal comfort might be stronger through the incoming air (Vellei, et al., 2017). In this chapter, I present the findings from 750 T.C.Is., which were realised in the selected wards of Freetown's Connaught Hospital and consisted of the collection of subjective and environmental measurements.

The impact of seasonal, temporal, spatial and environmental conditions and participants' personal characteristics, adaptive behaviours, and satisfaction levels with existing environmental controls on the votes of indoor temperature, relative humidity and wind speed-related thermal sensation and comfort, preferences and acceptability were investigated. Furthermore, the most prevalent adaptive actions for the restoration of thermal comfort among occupants were explored through comparisons between the reported adaptive behaviours and the realised actions for the restoration of thermal comfort at personal level and in relation to patients care. The data collection and analysis processes were informed by a comprehensive literature review that is presented in Part A of this chapter. This review aims at understanding the critical aspects of existing thermal comfort surveys in hospital spaces across climate zones. These include characteristics of the case-study hospital spaces, their thermal conditions and reported or modelled thermal comfort. Ranges of comfortable temperatures and adaptive behaviours and the impact of participants' personal characteristics are further explored in published thermal comfort surveys in naturally ventilated, non-domestic buildings across the equatorial zone, and in all types of buildings in Africa.

4.2 Research Questions

The research questions underlining this chapter are the following:

1. How did monitored thermal conditions around nurses, patients and visitors vary between different locations within the same ward and between selected wards throughout the morning and evening shifts across the rainy and dry seasons?

2. What was the scale of the effect of the variations in the seasonal, the temporal and the spatial conditions, the demographic and the health-related characteristics and the satisfaction levels in the reported thermal comfort votes of the nurses, the patients, and the visitors? How did these differences impact the range and variation of the reported neutral, comfortable, and preferred thermal votes regarding monitored temperatures, relative humidity values and air movement?

3. Which were the perceived behaviours for the restoration of personal thermal comfort among doctors, nurses, patients, and visitors? To what extent did these reported adaptive actions reflect the observed window-opening behaviours in selected wards? How were doctors' instructions and nursing practices integrated with nurses' reported behaviours for the adjustment of acceptable thermal comfort conditions among patients?

4. Which were the ranges and variations of neutral, comfortable, and preferred temperatures, relative humidity values and wind speed between nurses, patients and visitors across diverse seasonal, temporal, and spatial conditions, personal factors, and adaptive behaviours?

5. To what extent can established thermal comfort indexes predict the recorded discomfort and dissatisfaction levels?

4.3 Research Objectives

The research objectives of this chapter are the following:

1. To estimate the range and variations of the temperature, relative humidity and wind speed measurements taken during the T.C.Is. around each participant in multiple locations in each selected ward, while examining their associations with indoor and outdoor environmental measurements.

2. To identify how seasonal, temporal, and spatial variations influenced the monitored differentiations in the temperature, relative humidity and wind speed measurements taken during the T.C.Is. and the reported satisfaction levels with existing environmental controls.

3. To understand how nurses and doctors cope with their personal, as well as with patients' thermal discomfort, and which are their recommendations for changes in the wards that would strengthen their adaptive capacity.

4. To define the ranges of neutral, comfortable, and preferred temperatures, relative humidity values and air movement between nurses, patients, and visitors, while accounting for significant variations arising from differences in seasonal, temporal and spatial variations and demographic and the health-related characteristics.

5. To compare the reported thermal sensation, acceptance and preference votes of nurses, patients, and visitors with established thermal comfort indexes with applicability in hot-humid clinical spaces.

Part A: Literature Review

4.4 Literature Review

4.4.1 Overview of the Characteristics of the Case studies Across Equatorial and Temperate Zones

Evidence about thermal comfort in hospitals has been published only to fifteen studies covering the period of the last fourteen years with only six of them being conducted across the equatorial zone (Tables 4.1-2). Among the studies across the equatorial zone, four were performed in hospital spaces in Malaysia, one was realised in Madagascar and one in Thailand (Table 4.1). A lack of evidence exists regarding thermal comfort in naturally ventilated and operational multi-patient wards in the tropics, which is reflected in the published studies: the naturally ventilated spaces in Madagascar studied by Nematchoua, et al. (2017) functioned as waiting rooms, whereas environmental monitoring was not included in the field survey conducted by Kushairi, et al. (2015) in naturally ventilated multi-patient and open-plan wards in Malaysia (Table 4.1). Although a variety of mechanically conditioned administrative and clinical hospital spaces were case studies of thermal comfort surveys across the equatorial and temperate zones, thermal conditions of in-patient facilities have been dominated by thermal comfort surveys in single-patient rooms, with only one survey being realised in general wards across three hospitals in Malaysia (Khalid, et al., 2019) (Tables 4.1-2). Furthermore, whereas the function of the in-patient hospital spaces, where thermal comfort surveys were performed in the temperate zone, demonstrated high levels of diversity, comprising in both surgical and medical wards with specialisation in gynaecology, oncology, internal medicine, neurology, orthopaedics, paediatrics, infectious diseases, non-communicable diseases, geriatrics, and emergency medicine, only general wards (without functional specialisation) have been the case studies of thermal comfort surveys in tropical hospital spaces (Tables 4.1-2).

Seasonal variations were explored in all the studies performed in tropical hospitals, with the only two exceptions being the studies conducted by Yau and Chew (2009; 2014) and Kushairi, et al. (2015) (Table 4.1). Only Skoog (2006), Pourshaghaghy, et al. (2012), and Derks, et al. (2018) investigated differences in thermal comfort in hospital spaces between cold and hot seasons across the temperate zones (Table 4.2). Patients were the type of hospital occupants with the highest participation rates in thermal comfort surveys, both in the equatorial and the temperate zones, followed by hospital workers (Tables 4.1-2). However, distinctions between different types of hospital workers were overlooked in all the studies, except for the study in three wards in central Italy and four operation theatres in Belgium, which included the diversification between nurses' and doctors' needs (Tables 4.1-2) (De Giuli, et., 2013; Van Gaever, et al., 2014). From this literature review, it becomes evident that across existing studies so far, visitors have had overall the lowest participation rates, with their participation being limited only to thermal comfort surveys in tropical hospital spaces (Tables 4.1-2). In the tropics, acclimatisation in a thermal environment might last twenty minutes (Mishra, et al., 2017).[53] Khodakarami and Knight (2007) reported that 80.50% of the nurses, who participated in their thermal comfort survey, were working between seven and twelve hours. Khalid, et al. (2019) reported that 93% of the patients who participated in the survey were in the hospital over less than seven days, while the patients at the waiting rooms who were interviewed by Sattayakorn, et al. (2017) were present there on average over two hours. Khodakarami and Knight, (2007) reported that among the patient-participants 39.20% were hospitalised between one and three days, 31.60% were hospitalised from four to six days, and 17.70% between seven and ten days.

4.4.2 Thermal Environmental Performances During Thermal Comfort Surveys in Hospital Spaces

[53] Acclimatisation to warm thermal conditions was tested by Parsons (2002) by exposing six male participants to neutral and slight warm conditions over two consecutive days, following that experiment the six male participants had to perform a series of activities that consisted in exercising in a hot and humid environment (45°C, 40%) for two hours every day and over four consecutive days. However, small levels of acclimatisation were observed (Parsons, 2002).

Robust comparisons between the thermal conditions recorded during thermal comfort surveys in hospitals are limited due to inconsistencies in the reporting of monitored environmental metrics (Tables 4.3a-b). Thermal comfort surveys in hospitals were conducted under an extensive range of outdoor temperatures, which varied between 25.40 and 35°C in Kuala Lumpur, Malaysia (Yau and Chew, 2014; Kushairi, et al.,2015; Khalid, et al., 2019), while they ranged from -0.40 to 18.70°C in the Netherlands (Derks, et al., 2018), between 0 and 12°C in Fukuoka, Japan (Hashiguchi, et al.,2008), and stood above 29°C in Belgium (Verheyen, et al., 2011) (Tables 4.3a-b). The reported evidence about outdoor relative humidity levels was limited to two studies only across the temperate zone: the first one was conducted in Fukuoka, Japan, where outdoor relative humidity stood between 42.30 and 89.30% (Hashiguchi, et al., 2008) while the second, in Belgium, where outdoor relative humidity varied between 74.00 and 86% (Verheyen, et al., 2011) (Table 4.3b). Among the studies being undertaken in tropical hospitals, the air-conditioned waiting rooms in Thailand had wider temperatures, which varied from 20 to 29.30°C (Sattayakorn, et al., 2017) than the recorded temperatures in the naturally ventilated waiting rooms in Madagascar, which ranged from 25.50 to 27.50°C during the dry season, and from 24.50 to 25°C during the rainy season (Nematchoua, et al., 2017) (Table 4.3a)[54].

Overall, thermal conditions in hospital buildings and their differentiation between seasons, shifts, occupant types and hospital spaces have been more thoroughly studied across the temperate than the equatorial zones (Tables 4.3a-b). In particular, a considerable gap exists in the reported evidence about the sporadic environmental measurements been collected around the participants in tropical hospitals, with only Khalid, et al. (2019) reporting the value of the mean spot-temperature, which stood at 23.50°C, in air-conditioned general wards across three hospitals in Kuala Lumpur, Malaysia (Table 4.3a). Whereas weak fluctuations between the morning, the evening and the night shifts during summer and autumn were recorded in the mechanically conditioned hospital spaces in the Netherlands, where the mean continuously recorded temperatures ranged from 20 to 25°C, and the continuously recorded relative humidity values displayed significant seasonal variations, with mean values ranging from 52.50 to 54.10% over the summer and from 38.90 to 40.30% during autumn (Derks, et al., 2018) (Table 4.3b). Similarly, significant differences were observed in the continuously monitored relative humidity values between summer and winter and between the patients' rooms and the nurse stations in the mechanically conditioned hospital spaces in Sweden (Skoog, 2006). In

[54] Nematchoua, et al. (2017) did not report the measurements separately in the hospital spaces from those in the shopping malls that were also part of their project.

these hospital spaces, the mean relative humidity value in patient rooms was 46.20% during summer and 22.00% during winter, while the mean relative humidity value in nurse stations was 43.00% during summer and 16.20% during winter (Table 4.3b) (Skoog, 2006). The diversity in the reported sporadic temperature measurements around different types of hospital occupants consisting only in patients and visitors in the mechanically conditioned hospital spaces in Sweden and Japan was very low with differences (in the mean values) remaining below 0.50ºC (Table 4.3b) (Hashiguchi, et al., 2008; Skoog, 2006). The spatial and functional variations in the study of the mechanically conditioned hospital spaces in Italy conducted by De Giuli, et al. (2013), although it affected the range of the recorded wind speeds, it did not have a significant impact on the in the range of the monitored mean temperature and relative humidity values (Table 4.3b).

4.4.3 Key Statistics of Thermal Comfort Votes During Thermal Comfort Surveys in Hospital Spaces

In the thermal comfort surveys in air-conditioned hospital spaces in Kuala Lumpur in Malaysia, staff and visitors who were interviewed in non-clinical spaces reported an Actual Mean Vote (A.M.V.) of 0.75 (Azizpour, et al., 2013a; 2013b), while patients and visitors in general wards expressed lower A.M.Vs., which stood at -0.90 among patients, and at -1.10 among visitors, with patients reporting that they preferred even cooler temperatures (Khalid, et al., 2019) (Table 4.4). These differences in the A.M.Vs. may be partly attributed to the fact that both dry and rainy seasons were included in the field surveys by Azizpour, et al. (2013a) and (2013b), whereas Khalid, et al. (2019) conducted the field-survey only during the cool season. As it is shown in Table 4.4, reported and predicted votes and dissatisfaction rates displayed significant deviations in the thermal comfort surveys in hospitals, in both the equatorial and the temperate zones. In the field survey by Azizpour, et al. (2013a), predicted neutral votes were higher by 0.76 units than the reported ones, while the Predicted Percentages of Dissatisfied (P.P.D.) were lower by 20% than the Actual Percentages of Dissatisfied (A.P.D) (Table 4.4). Although the P.P.D. among the thermal comfort votes reported in hospital spaces across temperate zones were lower than those reported in the tropical hospital spaces, higher levels of thermal discomfort were indicated by the thermal comfort votes from staff and patients (Table 4.4). The highest A.M.Vs. (for summer and winter combined) standing between 3.50 and 4.00 were reported in the surveyed hospital spaces in Sweden with patients expressing the highest A.M.Vs. both in summer (4.00) and winter (3.90) (Table 4.4) (Skoog, 2006). In the wards in central Italy, P.M.Vs. among all the participants were more than three times higher than the A.M.Vs., with the group of patients aged above 65 years displaying the highest deviations (Ferraro, et al., 2015).

Although the impact of air movement on thermal comfort was generally overlooked, in a field survey of air-conditioned clinical and out-patient areas in a hospital in Taiwan, Wang, et al. (2012) reported that the feeling of low air movement among staff and patients determined the high percentages of dissatisfaction (64.28%) and unacceptability (52.61%) of indoor thermal conditions. In the only thermal comfort survey in an air-conditioned operation theatre across four hospitals in Belgium among surgical staff, only surgeons reported neutral thermal comfort votes, whereas anaesthesiologists' and nurses' votes leaned towards cold thermal sensations (Gaever, et al., 2014). Skoog (2006) reported that low relative humidity levels adversely affected thermal comfort during periods of high temperatures[55].Derks et al. (2018), who explored seasonal differences in discomfort levels, found that statistically significant differences existed in the reported thermal sensation, acceptability and productivity between summer and autumn, with levels of discomfort, unacceptability and unproductivity being higher over the summer. Although variations in the thermal comfort votes between different types of hospital occupants were not explored in a systematic way, in the mechanically conditioned wards in central Italy, staff reported higher percentages of warm thermal sensation votes, whereas both staff and patients expressed similar percentages of satisfaction rates during summer and winter (Skoog, 2006). In Pourshaghaghy, et al., (2012), more discomfort votes were reported in the morning shift during winter, while the evening shift collected the highest percentages of discomfort votes during summer. Nematchoua and Orosa, (2016) noted that during the morning shift higher dissatisfaction rates of occupants with the indoor environmental conditions were caused by higher relative humidity levels especially in modern office buildings and most of the votes expressing cold thermal sensations were reported.

4.4.4 Range of Neutral, Comfortable and Preferred Temperatures During Thermal Comfort Surveys in Hospital Spaces

In the thermal comfort surveys across the equatorial zone, the operative temperatures corresponding to "neutral" A.M.Vs. varied between 26.40 and 26.80^{o}C exhibiting very low differences between air-conditioned nurses' stations, offices, and other non-clinical spaces in Malaysia (26.40-26.80^{o}C) and naturally ventilated waiting rooms in Madagascar (26.41^{o}C) (Table 4.5a) (Yau and Chew 2009, 2014; Azizpour, et al. 2013a, 2013b; Nematchoua, et al., 2017). Similarly, while accounting for less than 20.00% of the dissatisfaction rates among the participants, the range of the mean comfortable operative temperatures corresponding to "slightly cool", "neutral" and

[55] Low levels of humidity have been associated with respiratory problems, while high levels of humidity have been dryness of the skin and nose and throat irritations (Reinikainen, 1991).

“slightly warm” A.M.Vs. was in the 23.70-27.70°C range in the monitored hospital spaces in Malaysia and in the 23.20-26.80°C region in the monitored hospital spaces in Madagascar (Table 4.5a) (Yau and Chew 2009; 2014; Nematchoua, et al., 2017). The operative temperatures corresponding to neutral Predicted Mean Votes (P.M.Vs.) were lower than the operative temperatures corresponding to neutral A.M.Vs. in all the surveyed hospital spaces across the equatorial zone with their differences varying from 1.80 to 2.60°C in air-conditioned hospital offices, nurses stations and other clinical spaces (Table 4.5a) (Azizpour, et al. 2013a, 2013b; Yau and Chew 2009; 2014), while they reached values higher than 3°C in patient rooms (Table 4.5a) (Sattayakorn, et al., 2017). P.P.D. reported only for air-conditioned hospital spaces displayed low deviations from the A.P.Ds. (Table 4.5a) (Azizpour, et al. 2013a, 2013b; Yau and Chew 2009, 2014).

In the thermal comfort surveys across the temperate zone, the recorded operative temperatures corresponding to neutral A.M.Vs. in a mechanically conditioned orthopaedical ward in Sweden that stood at 22.60°C during summer, and at 22.40°C during winter were significantly lower than those recorded in air-conditioned hospital spaces in the tropics (Skoog, 2006) (Tables 4.5a-b). Similarly, low air temperatures varying between 20.30 and 23.30°C corresponded to thermal sensation votes of slightly cold, neutral, and warm among nurses in the selected hospital spaces in the Netherlands (Table 4.5b) (Derks, et al., 2018). By contrast, in air-conditioned hospital spaces in Iran, the range of operative temperatures that were voted as comfortable were from 19.00 to 26.00°C among staff, between 22.50 and 28.00°C among patients covered with blankets and from 27.00 to 31.50°C among patients without blankets (Table 4.5b) (Khodakarami and Knight, 2007). Compared to the high deviations between P.M.Vs. and A.M.Vs. in the tropical hospital spaces, the differences between the P.M.Vs. and A.M.Vs. remained lower and below 1.5°C in heated medical and surgical wards in Taiwan (Tables 4.5a-b) (Hwang, et al., 2007).

4.4.5 Adaptive Comfort in Naturally Ventilated Buildings in Africa and in Non-Domestic Buildings in the Equatorial Zone

Published evidence about thermal comfort in naturally ventilated buildings in equatorial climates in Africa is limited to four studies in total, with Cameroon being the location of three of these studies and Nigeria for the remaining one (Table 4.6) (Ogbonna and Harris, 2008; Djongyang and Tchinda, 2010; Nematchoua, et al., 2014; Nematchoua, et al., 2015).[56] The case studies of these thermal comfort surveys comprise exclusively in residences, university classrooms and other spaces of non-domestic use (excluding clinical uses), with those located in Cameroon reaching 3,084 participants, while only 200 participated in the survey in Nigeria (Table 4.6). In Cameroon, comparisons made between the ranges of neutral and preferred temperatures in the monitored traditional and modern residences showed that traditional houses were warmer within a broad range of temperatures (24.81-27.32°C) (Djongyang and Tchinda, 2010) (Table 4.6). Furthermore, although the monitored temperatures in the modern houses (25.14-25.98°C) had a very narrow range, the preferred temperatures had wider range (21.50-25.61°C) that was similar with the range of the preferred temperatures in traditional houses (21.22-26.76°C) (Djongyang and Tchinda, 2010) (Table 4.6). In the second thermal comfort study on residences in Cameroon, traditional residences, which had lower temperatures (19.50-27.80°C in the dry season and 15.30-28.40°C in the rainy season), higher humidity levels (55.20-85.80%) and wind speed (0.06-0.51m/s) gained higher levels of acceptability regarding temperature levels (51%) and air movement (100%) and lower demands for lower humidity (28%), compared to the selected modern residences (Table 4.6) (Nematchoua, et al., 2015). The reported range of neutral temperatures in the naturally ventilated university classrooms stood from 25.87 to 27.28°C (Table 4.6) (Ogbonna and Harris, 2008).

Correlations in naturally ventilated buildings between indoor comfortable temperatures and outdoor temperatures have been expressed by linear regression models, with reported or predicted comfortable indoor temperatures being applied as dependent variables, and with outdoor temperatures being applied as independent variables (Nicol, et al., 2012). The steepness of the regression line between the comfortable indoor temperatures and the outdoor temperatures indicates the extent of sensitivity and the rate of discomfort among occupants to fluctuations in outdoor temperature (Vellei, et al., 2017). Therefore, it has been established that a gradual gradient between comfortable indoor temperatures and outdoor temperatures of a linear regression model demonstrates low sensitivity levels among occupants to discomfort which is caused by variations in outdoor temperatures (de Dear, et al. 2015), while indicating of a wider thermal comfort zone (Nguyen, et al., 2012; Humphreys, et al., 2013; Indraganti, 2010). Occupants of naturally ventilated buildings tend to be more tolerant to thermal discomfort (Brager and De Dear, 1998) and this might

[56] Overview of the characteristics of the published thermal comfort surveys in naturally ventilated buildings Africa and in no-domestic buildings in the equatorial zone is presented in Table 4.1a in Appendix 3.1

be an indication of acclimatisation to outdoor diurnal and seasonal fluctuations (De Dear and Brager, 2002). Therefore, naturally ventilated buildings have more gradual linear gradients representing the relationship between the comfortable indoor temperatures and the outdoor temperatures (de Dear and Brager, 1998; Manu, et al. 2016; Yang and Zhang, 2008; Luo, et al. 2015).

Regarding established linear associations between comfortable indoor temperatures and indoor temperatures, a descending regression coefficient in relation to ascending variation (illustrated in the standard deviations) in indoor temperatures indicates that occupants have higher adaptive capacities to varied thermal conditions (de Dear, et al. 2015; Humphreys, et al., 2007). However, in non-domestic buildings, the observed linear gradients between indoor comfortable and indoor recorded temperatures tend to be steeper than those estimated for domestic buildings (de Dear and Brager, 1998). These differences were attributed to limited adaptive actions that could be taken by the occupants for the restoration of thermal comfort (de Dear and Brager, 1998). In warm climates, more gradual gradients between the neutral temperatures and indoor temperatures have been found in spaces with higher indoor air velocities (Givoni, et al., 2006) with the impact of elevated air movement on the restoration of thermal comfort to be higher during periods with particularly extreme weather conditions (Song, et al., 2015; Liu, et al., 2013; Dhaka, et al., 2013). In the study by Kwok, et al. (1998), approximately half of the participants who found the thermal conditions as comfortable voted for preferred higher indoor air velocities.

High humidity levels significantly obstruct the process of sweat evaporation, and thus contribute to thermal discomfort (Vellei, et al., 2017). McIntyre (1980) believed that air humidity did not affect occupants’ perception of thermal comfort when the ambient indoor temperatures remained within the limits of the comfort zone. However, Fountain, et al. (1999) showed that humidity levels standing from 60.00 to 90.00% in spaces with a temperature range from 20 to 26°C adversely affected perspiration among the participants with low activities levels causing thermal discomfort. In a climate-controlled experiment with healthy adults, Kong, et al. (2019) showed that long-term physiological acclimatisation affected thermal comfort perception with individuals who had spent more years living in a more humid location being less sensitive to humidity fluctuations and expressing discomfort only at humidity levels above 70%. Higher humidity levels contributed to steeper linear regression gradients between comfortable indoor temperatures and indoor recorded temperatures, thus contributing to the rise in sensitivity levels towards occupants’ thermal discomfort (Indraganti, et al., 2013). Indoor air sensation depends on the existing thermal conditions defined by the air velocity and movement, temperature, and relative humidity, and on personal attributes such as metabolic rates and clothing insulation (Toftum, 2004).[57] In naturally ventilated buildings, the direct impact of outdoor wind speed on occupants' thermal comfort perception is moderated by occupant-control window and fan operation (Vellei, et al., 2017). Kwok, et al. (1998) documented discrepancies between thermoneutrality and preferred thermal conditions in classrooms, especially those that were naturally ventilated during the warm season as it was indicated by the 62% of participants who gave a neutral thermal comfort vote while at the same time expressing their preferences for cooler temperatures. Kwok, et al. (1998) reported acceptability percentages were higher than 80%, which marked the maximum of the prescribed level of acceptability by the ASHRAE standard (version 1992), although only 62% of the measured temperature and relative humidity levels were within the prescribed comfort zone.

4.4.6 The Impact of Gender, Age, Health Status, Clothing Insulation and Activity Levels on Thermal Comfort in Hospital Spaces and in Non-Domestic Buildings in the Equatorial Zone

4.4.6.1 The Impact of Gender and Age[58]

Regarding the gender distribution in the samples of thermal comfort survey in hospitals, female subjects have been prevalent in all the field-surveys across climate zones, with the survey conducted by Yau and Chew (2009, 2014) being the only exception. The dominance of female participants prevailed particularly among nurses thus, contributing to a significant lack of evidence about thermal comfort among male nurses. However, the distribution of sexes was less asymmetrical among patients and visitors. Regarding the age distribution among participants in thermal comfort surveys in hospitals, the widest age range (10-80 years) was observed among patients. By contrast, nurses' and visitors' age distribution exhibited a significantly narrower age range (20-50 years) with highest participation rates among nurses and visitors in their twenties, thirties, and forties. According to the findings of a systematic review about gender differences in thermal comfort across different building types and climate zones, women's reactions were more responsive to the temperature fluctuations and they were more willing to assume individual control of the ambient environment (Karjalainen,

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[57] Cabanac (1971) defined allisthesia as the process through which latent and sensible heat is removed from the human body by air movement, and through the physiological process, the sensation of comfort temperature is restored. In higher temperatures, higher air speeds help occupant to remain in thermally comfortable states through excess heat generation from their bodies to the environment by convection and evaporation (Tanabe and Kimura, 1994).

[58] Distributions of gender and age among the participants in the published thermal comfort surveys in hospital spaces across diverse climate zones are presented in Table 4.1b in Appendix 3.1.

2012). Laboratory studies and field surveys have investigated the effect of gender as a modifier of individual thermal experience. Through climate-controlled experiments, Fanger (1970) demonstrated that although the observed differences in thermal comfort were not statistically significant between the male and female participants, women were more sensitive to fluctuations from the optimal temperature. In a climate-controlled chamber, compared to men's thermal comfort votes, women preferred and felt comfortable in higher temperatures (Griefahn and Kunemund, 2001). Similarly, more women felt cooler when they got exposed in lower temperatures under controlled thermal conditions (Parsons, 2002)[59].

Limited evidence is available about the impact of gender on thermal comfort during field surveys in hospital spaces. Only Hwang, et al. (2007) reported that among interviewed patients in mechanically conditioned wards in a hospital in Taiwan, differences in the thermal comfort responses between male and female patients were not statistically significant. Female patients who participated in the thermal comfort survey in mechanically conditioned hospital wards in central Italy were more sensitive to elevated temperatures, with their mean A.M.V. (0.74) being higher by 0.13 units (Ferraro, et al., 2015). During on-site surveys in mixed-mode offices in the humid subtropical zone in Brazil, the differences in the acceptable and preferred thermal conditions between men and women were higher when air-conditions were in operation, whereas differences in votes about thermal sensations and preferred thermal conditions became higher during periods of natural ventilation (Kuntz, et al., 2018). In mixed-mode, air-conditioned and naturally ventilated offices in India, comfortable temperatures for women were 0.6^{o}C higher than those for men indicating, according to the authors, the better acclimatisation capacity of women that was attributed to the type of clothes (Indraganti, et al., 2015). However, beyond acclimatisation, Indraganti, et al. (2015) pointed out that under the influence of the dominant culture of patriarchy, female participants were hesitant to express thermal discomfort. Whereas sex-based differences in the acceptability of thermal environments were not found in naturally ventilated offices in Tokyo (Indraganti, et al., 2013), higher dissatisfaction percentages along with higher discomfort levels among the female participants were found by Karjalainen (2007).

Although lower activity levels among the elderly participants contributed to lower P.M.V.s., during laboratory experiments, Fanger (1970) did not find significant differences in the neutral temperature

[59] The sample consisted of sixteen men and sixteen women with similar clothing insulation and activity levels who had to spend three hours in identical thermal environments (Parsons, 2002).

between elderly and younger participants. However, over the past decades, increasing evidence suggest that age is a crucial modifier of individual thermal experience, to such an extent that different thermal comfort standards are required for old people (van Hoof, et al., 2017). During a climate-controlled study, P.M.V.s. were higher than the A.M.V.s. by 0.5 units among the participants from sixty-seven to seventy-three years old, whereas no deviations were found between the P.M.V.s. and the A.M.V.s. among younger participants (22-25 years) (Schellen, et al., 2010). Furthermore, during the same experiment under identical thermal conditions older people reported thermal sensation votes that were lower by 0.5 units compared to younger participants' votes (Schellen, et al., 2010). During another climate-controlled experiment with six 71-77 years old male participants and six 21-30 years old male participants, Natsume, et al. (1992) demonstrated that older people reported comfortable temperatures with wider variations and were more sensitive to fluctuating temperatures especially to high temperature falls during summer. In agreement with the findings by Natsume, et al. (1992), van Hoof et al. (2017) has shown that older people are in higher risk of thermal discomfort in extreme thermal environments due to their slow capacity to fluctuating thermal conditions attributed partly to their impaired thermoregulation system as a result of their deteriorating health status.[60] Uniformity in the thermal environment where older people are exposed was also recommended by Tweed, et al (2015). Older participants reported lower neutral and preferred temperatures (Bills, 2016), while Tweed, et al. (2015) found that the range of neutral temperatures was narrower among older people during both summer and winter. However, adaptive behaviours for the restoration of thermal comfort seem not to be affected by old age, with most elderly participants reporting that they tended to switch on/off environmental controls, open windows and change clothes (van Hoof, et al. 2017), as well as to avoid exposure to outdoor temperatures, changing clothes, consuming drinks, and adjusting their physical activities (Hansen, et al., 2014).

Limited evidence is available about the impact of age on thermal comfort during field surveys in hospital spaces. Only Hwang, et al. (2007) reported that among the interviewed patients in mechanically conditioned wards in a hospital in Taiwan, age did not have a statistically significant impact on the variation of the reported thermal comfort votes. By contrast, patients older than sixty-five years who participated in the thermal comfort survey in mechanically conditioned hospital

[60] Medication changes the thermoregulatory capacity of the human body; for example, beta-blockers that are used for cardiovascular problems adversely affect thermoregulation (Heintzen and Strauer, 1994).

wards in central Italy reported mean A.M.Vs. that were the lowest (0.60) (Ferraro, et al., 2015). According to evidence collected during thermal comfort surveys in non-domestic buildings across the equatorial zone, in Madagascar and India older people tended to accept more easily lower temperatures (Nematchoua and Orosa, 2016; Indraganti et al., 2015). The mean comfort temperature among older participants stood at 26.5°C, which was lower by 0.7°C compared to the mean comfortable temperature among the younger participants (with age lower than twenty-five years old), with younger female participants reporting a mean comfortable temperature higher by 1°C than those reported by older men (Indraganti, et al., 2015). Descending trends between thermal sensations and age were also found in a thermal comfort survey in air-conditioned care centres for the elderly in Singapore, where for participants with age higher than sixty years the thermal comfort sensation fell by one unit for every rise of 25.3 years (Wong, et al., 2009).

4.4.6.2 The Impact of Health Status

Steady-state and dynamic models have been developed to describe the physiological aspects of human thermoregulation as functions of the skin and hypothalamus temperature (Tanabe, et al. 2002). Although, there is no systematic evidence about the impact of specific medical conditions on the thermoregulation mechanisms of the human body, it has been established that differences exist in the impact of indoor thermal conditions between adults with and without disabilities. Individuals with disabilities, whose thermoregulatory system was impaired by the disability or by the required medication used as a treatment for the disability, were more sensitive than their carers, to uncomfortable thermal conditions (Hill, et., al., 2000)[61]. Among the participants who acquired the disability after the age of eighteen, preferences for warmer and for cooler environments were expressed by 53.00% and 13.00% of the participants, respectively, whereas the thermal preferences of 11.00% of the participants remained unchanged (Parsons, 2003). 74.00% of these participants reported that thermal discomfort adversely affected their ability to perform everyday tasks with hospitals being voted as hot spaces by 35.00% of these participants (Parsons, 2003). In another

[61] For four years a thermal comfort study of people with and without disabilities (531 in total) was conducted by the "Human Thermal Environments" Laboratory, Loughborough University, UK (Parsons, 2003). The participants received questionnaires by post (Parsons, 2003). Exposure temperatures ranged from 18.50 to 29.00 in the care centres participating in the study (Parsons, 2003). The participants suffered from the following medical conditions: multiple sclerosis, stroke, rheumatoid arthritis, osteoarthritis, spina bifida, polio, paraplegia, muscular dystrophy, and spinal injury (Parsons, 2003).

climate-controlled study in the same research laboratory, it was found that comfortable temperatures for disabled participants were equal to a vote of “slightly warm” or “warm” by a healthy adult (Parsons, 2003).

However, thermal comfort sensation and acceptability votes were not affected by the fitness levels among healthy participants in thermal comfort surveys conducted in air-conditioned offices (Haghighat and Donnini, 1999; Melikov, et al, 2005). One project examined the impact of the menstruation cycle, only to find a statistically insignificant impact (Haghighat and Donnini, 1999). In air-conditioned multi-patient wards in Malaysia, normal or good fitness levels were reported by 81% of the participants including 305 patients, while only 19% of the sample described their fitness levels as poor or very poor (Khalid, et al, 2019). By contrast, 45% of the patients, who were interviewed, in mechanically conditioned medical and surgical wards in a hospital in Taiwan, characterised their physical strength as weak (Hwang, et al, 2007). Verheyen, et al 2011, found an association (coefficient: 0.066) between P.M.Vs. and reported health status, with the effect of health status on P.M.Vs. varying among patients depending on their medical conditions.

4.4.6.3 The Impact of Clothing Insulation and Activity Levels[62]

Among the thermal comfort surveys in hospitals, fixed values were used for the clothing insulation of the participants with patients having the highest values (0.49-1.84clo)[63], especially in the studies that included the insulation of the bed mattress and the extra sheets (1.36-1.84clo), whereas significantly lower were the values for the clothing insulation among nurses and visitors that stood at 0.43clo for visitors and from 0.80 to 0.88clo for nurses (Yau and Chew, 2009; 2014; Khalid, et al., 2019; De Giuli, et., 2013)[64]. Regarding the activity levels among hospital occupants who participated

[62] Mean values of clothing insulation values and metabolic rates among the participants in the published thermal comfort surveys in hospital spaces across diverse climate zones are presented in Table 4.2 in Appendix 3.1.

[63] Among the samples of the study by Ferraro, et al. (2015), nine patients had clothing insulations higher than the values prescribed by ISO 7730 (2005) for its applicability.

[64] A body of research exists regarding heat-stress among hospital workers and protective clothing. The type of personal protection equipment (PPE) for the protection from EVD infection blocked the process of sweat evaporation which formed the only way of heat loss and protection from heat stress (Potter, et al., 2015, p.2). Simulation of the temperature inside the clothing indicated the value of 45oC (Brearley, et al., 2013).

in thermal comfort surveys in hospitals, Verheyen, et al. (2011) observed that in the mechanically conditioned wards in Belgium patients tended to spend most of their time in the reclining or sleeping position was the most dominant among patients with very few patients spending their time sitting. In the modelling of the P.M.Vs., patients' metabolic rates were taken as a fixed value of 65W/m^2 by Pourshaghaghy, et al. (2012). De Giuli, et al. (2013) applied a mean value of 1.00met for patients, while for nurses a higher mean value of 1.2met was applied with different values being assigned for different activities that were performed in the different spaces of the ward: 85 W/m2 in the break room, 110 W/m2 in the corridor and 115 in the bedded areas.

4.4.7 Adaptive Behaviours Among Occupants in Hospital Spaces and Non-Domestic Buildings

Under climate-controlled laboratory conditions, eight male and eight female participants were observed and their adaptive behaviour with regards to changes that they made in their clothing was recorded (Parsons, 2002). Parsons (2002) found that adjustments to clothing was indeed a prominent behaviour among the participant for the restoration of thermal comfort, with adaptation to cold conditions being easier than adaptation to warm conditions. Field surveys in offices across four continents have shown that the ability to adapt clothing insulation reflected established hierarchies in the working environment, with workers in the lowest rankings having the highest freedom in adapting their clothing insulations (Fountain, et al., 1996). Small diurnal and seasonal differences in indoor temperatures did not cause significant changes in the clothing insulation (Wijewardane and Jayasinghe, 2008). Karyono (2000) observed that participants reported changing clothes when they felt cold by adding extra layers, whereas an adaptation in their clothing insulation was not reported when they felt hot. In naturally ventilated buildings across diverse climate zones, the average increase in occupants' clothing insulation was found to be 0.1clo per 2K rise in the outdoor temperature (de Dear and Brager, 1998).[65]

Indraganti, et al. (2015) have noted that seasonal variations did not contribute to adjustments of the adaptive behaviours among the office workers, while having cold drinks and spending time in a place with high air velocities was reported as one of the common occupants' adaptive action across seasons. Having cold showers was a prevalent adaptive behaviour for the restoration of thermal comfort only in domestic spaces (Rijal, et al., 2010). Kumar, et al. (2019) reported that in naturally

[65] Nematchoua et al (2014) reported the following correlations: a) between metabolic rates and operative temperaturey=-0.012x+1. 38 b) between clothing insulation and outdoor temperature: y=0.044x+2.049 (R2=0.74).

ventilated hostels in India, most preferred adaptive behaviours consisted in switching on fans and opening windows and doors. Indraganti, et al. (2015) observed that in offices in India women changed the positions of the window openings more often than men, however, no differences between men and women were observed regarding the operation of fans. Higher levels of willingness among occupants to restore thermal comfort through interaction with environmental controls have been liked with higher satisfaction levels in both domestic and non-domestic building across diverse climate zones (Boerstra, et al., 2013). The level of personal control affected thermal sensations of office workers with identical clothing insulation and metabolic rates over both summer and winter in naturally ventilated offices with officers' satisfaction to be higher in mixed-mode buildings (Brager, et al 2004).

The adaptive capacity of both patients and staff is limited due to safety and occupational requirements (Lomas and Ji, 2009). Therefore, limited evidence exists that hospital occupants perform adaptive actions. Only Yau and Chew (2014) recorded the participants' adaptive capacity finding weak correlations between occupants' clothing insulation values and operative temperatures and between occupants' metabolic rates and operative temperatures and attributed these findings to the limited opportunities that hospital workers had to adjust their clothes and activity levels. De Giuli, et al. (2013), Verheyen, et al. (2011) and Pourshaghaghy, et al. (2012) collected responses about participant satisfaction regarding the existing thermal conditions and interior design with patients expressing the highest percentages of satisfaction (De Giuli, et al., 2013; Del Ferraro, et al., 2015, Verheyen, et al., 2011). De Giuli, et al. 2013, observed hospital workers with high levels of depression and anxiety gave more negative answers.

Part B: Methods of Data Collection and Analysis

4.5.1 Overview of the Collected Sample of Participants in the T.C.Is. and in Semi-Structured Interviews

4.5.1.1 Overview of the Collected Sample of Participants in the T.C.Is.

During the Thermal Comfort Interviews (T.C.Is.) at Connaught Hospital, a tolar sample of 750 participants was collected, representing a 100% response rate that by far exceeded the requirements of the ASHRAE 55 standard (2013) (Figure 4.5). In the collected sample, 33.33% (250/750) and 66.66% (500/750) of the T.C.Is. were performed in Sep.2016 and Mar.Apr.2017, respectively (Figures 4.1.b1-3). This is the second-highest sample of a thermal comfort survey conducted in hospital spaces located in the equatorial zone, as it is only surpassed by 178 participants of the sample collected by Sattayakorn, et al. (2017) (Table 4.1). A broadly accepted definition of randomly selected study samples is that every person of the population of interest has an equal chance of being selected as a participant in the study (Webb and Bain, 2011). According to this definition, it is highly likely that the selected sample of participants at Connaught Hospital was not statistically representative of the population of interest that was comprised of adult hospital occupants in government-run inpatient facilities in Sierra Leone. The compilation of a statistically representative sample of participants would require the random selection of participants by applying established algorithms in digitised datasets of personal data that could guarantee the balanced distribution of critical confounding factors between different groups (Webb and Bain, 2011). Implementing these approaches was impossible due to the lack of infrastructural capacity, not only at Connaught Hospital but across all government-run hospitals in Sierra Leone, regarding the maintenance of digital records of staff, patients, and visitors. Therefore, voluntary participation based on informed consent was the only achievable recruitment strategy. However, voluntary participation might have contributed to selection bias. Several epidemiological studies have shown that volunteers significantly differ from the general population and therefore should be excluded (Webb and Bain, 2011). However, crucial measures were taken to control the inevitable sampling error and the selection bias of this study.

Statistical models were applied for the estimation of the sample size that could reduce uncertainty levels. The recommended sample size stood at 384 participants (Figure 4.1a) (Lehmann, 2006). Larger samples are linked with more minor sampling errors (Webb and Bain, 2011). thus, the research team strived to spend as much time as possible in the case-study wards to recruit more participants. Aiming at higher levels of spontaneous participation and snowball effect, the research team avoid nudging in every possible way. Evidence suggests that sampling error can be reduced using restriction criteria at the data collection stage and applying the stratification techniques at the data analysis stage (Webb and Bain, 2011). In this study, the restriction criteria for participation and the stratification of the collected data were defined by physiological, psychological, and behavioural parameters, which drive critical differentiation in human thermal adaptability. Therefore, very sick patients such as the female patients at W9 and all type of occupants being present in the ward over less than fifteen minutes were not allowed to participate in the T.C.Is. Moreover, all T.C.Is., which were conducted with occupants close to a fan in operation in a distance equal to or lower than one-and-a-half metres were excluded from the analysis. Although the fan's impact on the ambient environment (as it is presented in the 4.7.1.1 section) was very small, its psychological impact could bias thermal comfort perception. In total, twenty participants were exposed to airflows coming from personal fans in the proximity of less than one-and-a-half metres (Figure 4.1.b4). As a result, the final sample size for analysis was reduced to 730 participants, including 370 nurses, 187 patients and 173 visitors (Figure 4.1.b5). This final sample displayed an unequal distribution, with nurses' participation prevailing across the four different building types during both seasons (Figure 4.1.b5). Overall, in Mar.Apr.2017, participation rates rose by 8.00% among patients and by 6.00% among visitors, with the Nightingale wards displaying the highest participation rates of patients both in Sep.2016 and Mar.Apr.2017 (Figure 4.2). However, visitors' participation rates were the lowest compared to those of nurses and patients both in Sep.2016 and Mar.Apr.2017 in all selected wards except for F.A. (Figure 4.2).

To guarantee complete understanding and honesty of responses, the T.C.Is. were conducted both in English and in Krio, which is the local language, and included a question about the education level of each participant and the number of previous participations In Sep.2016 all T.C.Is. were performed in Krio, while in Mar.Apr.2017 438 T.C.Is. were performed in Krio with the rest 48 T.C.Is. being performed in English. More specifically, the percentages of T.C.Is., which were communicated in English, stood at 16.10% among nurses, 3.65% among patients and 8.00% among visitors. Participation rates over multiple times were low to moderate among different occupant types in each selected ward, standing among nurses between 12.50% and 58.33% in Sep.2016 and between 8.00% and 66.67% in Mar.Apr.2017 with their percentages being exceeded by the percentages of patients only in Mar.Apr.2017 in W3 (43.33%) and in F.A. (40.00%) and by the percentages of visitors only in Sep.2016 in W6 (25.00%) (Figure 4.3). Illiterate participants were among the group of patients and visitors, with their percentages standing among patients at 3.85% (Sep.2016) and among visitors at 1.52% (Mar.Apr.2017) (Figure 4.4). Although tertiary education was the dominant education level among nurses and students, it represented the lowest percentages among patients, with these percentages standing at 7.69% in Sep.2016 and at 8.28% in Mar.Apr.2017, while secondary education was the dominant educational level among patients (53.85%) in Sep.2016 and among visitors both in Sep.2016 (62.75%) and Mar.Apr.2017 (42.42%) (Figure 4.4).

4.5.1.2 Overview of the Collected Sample of Participants in the Semi-Structured Interviews

The sample of the nine nurses who participated in the semi-structured interviews consisted only of ward sisters and head nurses, with seven of them being women (Table 4.7). The nurse station was the location where all the semi-structured interviews with nurses took place. Only two of the interviewed nurses gave permission for digital recording of their interviews; however, all the interviews had short durations, between three and eight minutes, with six of them being performed during the third week of the fieldwork in Sep.2016 (Table 4.7). In total, twelve doctors, with only two of them being women, agreed to be interviewed, with most of these interviews being realised during the second week (50.00%) and the third week (41.67%) of the fieldwork in Sep.2016 (Table 4.7). Due to doctors' limited availability, all the interviews were taken during breaks at their offices (41.67%), the cafeteria (33.33%), the duty house (8%), or the veranda at the Pavilion Building (8%) and the interviews had short durations that ranged from two to ten minutes, with only two of them being digitally recorded (Table 4.7).

4.5.2 Methods of Collection and Analysis of the Subjective and Environmental Data during the T.C.Is.

4.5.2.1 Overview of Data Collection Processes during the T.C.Is.

The data collection processes during the T.C.Is. in the selected wards of Freetown's Connaught Hospital were designed according to the guidelines published in ASHRAE Standard 55: 2013 regarding thermal comfort surveys in naturally ventilated spaces in existing buildings that combine subjective and environmental measurements. In addition to these guidelines, the data collection processes had to comply with established infection control protocols and context-specific codes of ethical research that involved human subjects while avoiding disruptions of operational routines for the provision of care. As illustrated in Figure 4.5 and are described with details in the following paragraphs, when context-specific challenges or limitation of financial resources impeded the application of the ASHRAE 55:2013 specifications, measures were taken to prevent the accuracy and validity of the data collection processes.

The collection of subjective and environmental data from each participant was conducted following a standardised procedure that consisted of four steps with a total duration of ten minutes. Each step was conducted by a predefined researcher within a specific amount of time. In the first step, the information letter was explained to the participants who were interviewed for the first time. In the second step, the consent form was described and then given to the interviewee for his or her signature. These two first steps were always performed by one of the trained researchers in Krio (local language) or English, or both languages, and had a maximum duration of two minutes. In the third step, the T.C.I. began with the research assistant reading the questions from the questionnaire in Krio and the author switching on the heat stress meter and beginning to complete the last section of the questionnaire following a visual inspection of the participant's location. The third step lasted between four and five minutes. In the fourth step, the author took the environmental measurements in three heights around the participant at a distance from thirty to fifty centimetres. That process lasted between three and five minutes. Nurses found it challenging to tolerate the research team's continuous presence in the ward for more than ninety minutes. Therefore, the maximum number of T.C.Is. conducted per day in one of the selected wards rarely exceeded the number of nine. At the end of each survey, first, the author disinfected the equipment and the pens (given to the interviewees to sign the consent form) with alcohol wipes that were later disposed in bins for medical waste in the ward. Before entering another ward for the performance of the next series of T.C.Is., each member of the team thoroughly washed his/her hands in the provided indoor or outdoor facilities according to WHO guidelines for hand hygiene.

4.5.2.2 Design of the Standardised Questionnaire for the Performance of the T.C.Is.

The final design and administration of the standardised questionnaire used for the performance of the T.C.Is. were informed by a two-phased pilot process during the first week of the fieldwork in Sep.2016 (from Monday 5/09/2016 to Sunday 11/09/2016) following opportunistic sampling. During this period, version one (Figure 4.6b) and version two (Figure 4.6c) were tested with twenty volunteers and feedback (Figure 4.6a) was kept in the form of handwritten notes during the interviews. However, physical measurements were not recorded during this pilot stage. Following the recommendations by Oppenheim (1993) and Krosnick and Presser (2010), the impact of the pilot study was maximised by the realisation of the pilot study in the selected wards (excluding Physio.), where the final versions of the T.C.Is. were performed. Throughout the pilot study, critical aspects of the format, the administration and the context of the questionnaire were tested in two different versions. In both versions, the main body consisted of questions about thermal comfort perceptions, recent metabolic rates and clothing insulation and satisfaction with the indoor thermal environment that covered the main topics specified by the ASHRAE 55: 2013 (Figure 4.5). Regarding the administration and the general format of the questionnaire, pilots of the first version of the questionnaire showed that the use of different questionnaires for each occupant type was very inconvenient for the researchers. Self-administration of the questionnaires created significant delays in completing both the subjective and physical measurements within a ten-minute timeframe restricting the maximum number of interviews that could be realised within the limited period when the researchers were allowed in the ward.

Best communication between the interviewer and the interviewees was achieved when the questionnaire was written and printed in the English language, while the interview was performed in the local language of Krio. Bilingual questionnaires (both in the country's official language (French) and in the local dialect (Malagasy) were used in another thermal comfort survey in hospital spaces in Madagascar (Nematchoua, et al., 2017). Furthermore, when the author took the T.C.Is., interviewees tended to give biased answers that indicated the most socially acceptable answers; thus, illustrating the impact of the so-called social desirability bias (Krosnick and Presser, 2010). Therefore, it was decided that the interviews had to be conducted only by the research assistants. During the piloting of the second version of the questionnaire, it became evident that the most efficient way of communicating the questionnaire's context while preventing loss of interest and concentration among the interviewees was by reading the questions to the interviewee while allowing him/her to see the questionnaire. The use of self-administered questionnaires during thermal comfort surveys in hospital spaces has been rare, with only Skoog (2006) and Yau and Chew (2014) permitting their participants, who were only hospital workers, to complete the questionnaires by themselves. Interestingly, Khodakarami and Knight (2007), in their thermal comfort survey in a hospital in Iran, combined both methods by interviewing the patients and allowing self-administration of the questionnaire among nurses. Finally, the interviewees experienced fewer distractions when environmental measurements and information about environmental and spatial conditions in the participants' locations were taken only by the author after the core part of the T.C.I. was complete. The apparent introduction of high heterogeneity in short-term acclimatisation and levels of metabolic rates between diverse types of health workers that could weaken the comparability of responses in a moderate sample lead to the decision to limit participation only between nurses, students, patients, and visitors.

Regarding the context of the questionnaire, two specific questions had to be added about the participant's short- and long-term acclimatisation experience. Repeated participation more than four times was associated with mechanical repetition of identical responses. Therefore, potential interviewees had to be asked about any previous participation in the study. Less fatigue among the participants was observed when the core body of the T.C.I. was composed by a mixture of questions about individual characteristics, thermal comfort votes and adaptive behaviours rather than starting with all the questions about individual characteristics, continuing with all the questions about thermal comfort and closing with questions about adaptive behaviours. Regarding the final ordinal scale and the exact phrasing of the questions consisting of categorical variable describing thermal comfort votes with respect to the levels of temperature, relative humidity, it was found that using a descending order to describe the votes of sensation, comfort, acceptance and preference was less confusing. Furthermore, whereas a seven-point scale was proved to be suitable for responses regarding thermal sensations and preferences in relation to the temperature and relative humidity levels, scales with fewer points were more suitable for responses regarding votes of comfort, acceptance, and satisfaction.

Applying a seven-point scale for the thermal sensation votes in relation to temperature and relative humidity levels is recommended by ASHRAE 55: 2013 (Figure 4.5), while applying response scales with fewer points for the acceptance and preference votes has been a common practice with all the thermal comfort surveys in hospital spaces across the equatorial zone (Azizpour, et al., 2013; Nematchoua, et al, 2017; Khalid, et al.; 2019, Sattayakorn, et al., 2017; Yau and Chew, 2014). To avoid culturally driven linguistic misunderstandings, a single question about acceptability prescribed by the ASHRAE 55: 2013 had to be changed to a question about comfort and another about preference. To avoid confusion among the participants regarding their perception of indoor humidity levels, the phrase “moisture in the air” replaced “air humidity’’. Participants were inclined to give negative responses when they were asked about their perceptions of indoor airflows and their satisfaction levels of existing building controls when they were given the option only of binary responses. Therefore, more categories were added in available responses to these questions. Lastly, modifications in the available options had to be made in the questions about clothing insulation, duration and type of activities, hospitalisation length, common adaptive behaviours, and preferred improvements in cooling options to comply with context-specific norms.

The final version of the questionnaire (Figure 4.6d) was organised around five thematic areas:

1. Characteristics of the T.C.I. (T.1)
2. Sensation, comfort, and preference votes in relation to the levels of indoor temperature, relative humidity, and air movement (T.2)
3. Personal characteristics of each participant (T.3)
4. Reported adaptive behaviours (T.4).
5. Environmental and spatial characteristics of the location of each participant (T.5).

Each thematic area consisted in the collection of information about several topics which were as follows:

T.1: a) continuous presence in the ward for the last fifteen minutes; b) date; c) season; d) location; e) start and end time of the interview; f) language; g) participant number; h) previous participation in the survey and number of previous participations in the survey.

T.2: a) Actual Temperature Sensation Vote (A.T.S.V.) (7 cat.); b) Actual Temperature Comfort Vote (A.T.C.V.) (6 cat.); c) Actual Temperature Preference Vote (A.T.P.V.) (7 cat.); d) Actual Relative Humidity Sensation Vote (A.R.H.S.V.) (7 cat.); e) Actual Relative Humidity Comfort Vote (A.R.H.C.V.) (6 cat.); f) Actual Relative Humidity Preference Vote (A.R.H.P.V.) (7 cat.); g) Actual Wind Speed Acceptance Vote (A.W.S.A.V.) (6 cat.); h) Actual Wind Speed Preference Vote (A.W.S.P.V.) (3 cat.).

T.3: a) type of hospital occupant; b) level of education; c) job position; d) field of studies (if the participant was a student); e) medical condition; f) gender; g) age; h) metabolic rate (type of activity ten minutes ago, between ten and thirty minutes ago, thirty minutes and one hour ago); i) clothing Insulation (right now, thirty minutes ago and between thirty minutes and one hour ago); j) health status; k) short-term acclimatisation (place of activity ten minutes ago, between ten and thirty minutes ago, thirty minutes and one hour ago, working hours of students and staff, duration of visitors' visit, duration of patients' hospitalisation); l) food intake (ten minutes ago, between ten and thirty minutes ago, thirty minutes and one hour ago); m) liquid intake (ten minutes ago, between ten and thirty minutes ago, thirty minutes and 1 hour ago); n) height; o) weight .

T.4: a) changes of clothes (over the last thirty minutes and between thirty minutes and one hour ago); b) opening windows and how often; c) opening external doors and how often; d) switch on fans , and how often; e) other type of adaptive behaviours; f) satisfaction of environmental control; g) further options of environmental controls; h) situations when restoration of thermal comfort was impossible.

T.5: a) weather conditions; b) temperature, relative humidity, and air velocity measurements; c) participant's location; d) proximity to a window, distance from the window and percentages of open apertures; e) proximity to a fan, type of fan, distance from the fan and state of the fan; f) proximity to an external door, distance from the door and percentage of door openings at "ajar" positions.

The author copied the handwritten data of the questionnaires in a Microsoft Excel 15.38 file. Each participant was assigned a unique identity code composed by the name of the ward, the date, the time of the start and the end of the interview. The three open questions about a) other types of adaptive action (T.4e/ Q13.1e), b) further options of environmental cooling (T4.g/ Q13.3), and c) situations when the restoration of thermal comfort was impossible, were copied in a separate excel file, with the last open question being excluded from the analysis of the data due to very low response rate of 1% (8/750).

4.5.2.3 Method of Collection of the Environmental and Spatial Data During the T.C.Is.

With a delay between three and five minutes after each participant's statement about his/her thermal comfort votes, all environmental data were recorded simultaneously and in digital format, every second throughout three minutes. This period of delay was necessary for the stabilisation of the sensors to mitigate any possible impact of the sensitivity of its bulb. Environmental and subjective data were collected simultaneously in the thermal comfort studies conducted by Azizpour, et al. (2013), Wang, et al. (2012), Nematchoua, et al. 2017, Derks, et al. 2018, Khalid, et al. (2019), Skoog (2006), and Ferraro, et al. (2015), while in the survey by Verheyen, et al. (2011) the interviews preceded the recording of the environmental data. At the location of each participant, wind speed data ($W.S._{(spot)}$) were recorded with a hot-wire anemometer (TROTEC TA 300) while a Thermal Stress Meter (PCE-WB 20SD) was monitoring the air temperature ($T.A._{(spot)}$), globe temperature (T_{globe})Wet Bulb Globe Temperature ($W.B.G.T._{(spot)}$) and relative humidity ($R.H._{(spot)}$) (Table 4.8). The application of climate analysers' compact devices was common only in thermal comfort surveys conducted in hospital spaces in high-income countries. Although the wetness of the skin is an essential indicator of discomfort, especially in hot-humid conditions (Givoni, 1969), neither the recording of actual measurements nor occupants' perceptions was feasible in Connaught Hospital's selected wards. Performing the thermal comfort survey only six months after the end of the 2014-2016 Ebola outbreak, put in place ethical and practical constraints on recording occupants' temperatures, as well as on talking about bodily fluids, which were the primary media of the Ebola virus.

In this project, following the guidance by ASHRAE 55: 2013, the recording of the environmental data was performed in three different heights in the area around the participant in a distance between thirty and fifty centimetres and over one minute in each height (Figure 4.5). In early studies of adaptive thermal comfort, Brager and De Dear (1998) stressed the importance of taking environmental measurements close to the subjects under non-experimental conditions while they performed daily tasks. When differences in the ambient temperatures are low between different heights, measurements can be taken at only one critical height. This practice was applied by Derks, et al. (2018), who took measurements at the height of 1.1m above the floor during their thermal comfort survey in a hospital in the Netherlands. During the T.C.Is. in the selected wards in Freetown's Connaught Hospital, environmental data were taken at the heights of 0.1m, 1.1m and 1.7m around standing participants and at the heights of 0.1m, 0.6m and 1.1m around seated participants and patients reclining in their beds. The process was timed while extra notes were taken in the relevant section of the questionnaire about the exact time when the recording began and ended. The digital files of environmental measurements were copied in a Microsoft Excel 16.00 file, where each participant was assigned a unique identification code composed of the time of the start and end of the recording. The validity of the environmental measurements was checked through descriptive statistics and plots (scatterplots and boxplots) with STATA 14.2 and it was found that all environmental measurements were valid.

In this final version of the database with the environmental data, each participant was paired with the mean value of the environmental measurements taken in the three different heights around him/her (in line with the guidance by ASHARE 55:2013) and the hourly $T.A._{(in)}$, $R.H._{(in)}$, $T.A._{ext.(S1)}$, $R.H._{ext.(S1)}$, $T.A._{ext.(Meteo)}$, $R.H._{ext.(Meteo)}$, corresponding to the relevant time interval. The exact location of the participant was marked in a copy of the ground plan of the ward, where the thermal comfort survey took place, while notes were taken based on visual inspection about the location, type and state of the fan, the ratio of open to close window-openings and door- openings. The participant's distances from the window area and the door were measured in a digital copy of the ward (from the exact location of each participant), when the handwritten data were copied from the author in a Microsoft Excel 16.00 file.

4.5.2.4 Methods of Analysis of the Collected Subjective and Environmental Data during the T.C.Is.

The T.C.Is.'s subjective and environmental data were stored in two separate Microsoft Excel 16.00 files. These files were linked based on each participant's identification code. Medical conditions among patients, who participated in the T.C.Is., were recoded according to the categories presented in Table 4.9. The categorical variables, which captured the votes of sensation, comfort, acceptability, and preferences corresponding to indoor temperature, relative humidity and wind speed values, the seasons and shifts, the spatial conditions, individual characteristics, adaptive behaviours, and satisfaction with existing environmental control, were reorganised in fewer categories (Figure 4.7). A participant's closeness to a window area was defined by a distance from 0 to 3.5m. According to the tables published at ASHRAE 55: 2013 (pp.6-7), final values of each participant's clothing insulation were calculated by adding the insulative values of each clothing layer that was recorded through visual inspection during the T.C.Is. (Table 4.10). For patients lying in beds, the extra insulation of the mattress and the bedding items were added to the clothing insulation provided by their clothes while taking into account the insulative impact of different percentages of coverage of their body based on the values provided by Lin and Deng (2008) (Table 4.10). A similar methodology for the estimation of the clothing insulation of patients was applied by Khalid, et al. (2019), but for the insulation of the mattress, the value of 1.45clo was applied. The metabolic rate was estimated for each participant in compliance with ASHRAE 55: 2013 (Table 4.11). The final metabolic rate corresponding to the activity levels of each participant over the last hour (before the T.C.I.) was calculated as a total time-weighted summary of the three metabolic rates of each type of activity (as each participant reported this during the T.C.I.) over fifteen minutes, between fifteen and thirty minutes and between thirty and sixty minutes before the T.C.I.

The environmental variables of operative temperature ($T_{op.(spot)}$) and mean radiant temperature ($T_{mrt(spot)}$) were calculated according to the equations shown in Table 4.12. The $T_{op.(spot)}$ representing the combined effect of radiant and convective heat exchange was used to estimate the neutral, comfortable and preferred temperatures. Wet Bulb Globe Temperature (WBGT) is recognised as the most suitable index to assess occupational heat stress (Kjellstrom et al., 2009). However, the recorded W.B.G.T.$_{(spot)}$ were not used to estimate the heat stress experienced by the hospital occupants because they corresponded only to sporadic measurements taken in different locations. Following the thermal comfort standards of ASHRAE 55:2013, the P.M.V.s were modelled using the online application created by Hoyt, et al. (2017) by inserting the required environmental and personal data separately for each participant. In line with the ASHRAE 55:2013, from the comparisons between the reported comfortable operative temperatures and the modelled comfortable operative temperatures were excluded the participants with the following characteristics: a) clothing insulation higher than1.5 clo b) participants whose body was fully covered with protective gear c) sleeping or awake participants who lied or reclined on beds d) participants with (time-weighted) metabolic rates below 1 met. and above 2.0 met (Figure 4.5).

Although the EN15121 standard is the only thermal comfort standard with applicability for people with physical disabilities (Parsons, 2003), it was not applied to estimate the PMV due to its suitability in contexts with temperate climates. Griffins' models were also applied for the modelling of comfortable temperatures according to the equations presented in Table 4.12. An overview of the statistical methods that were applied in the data analysis are illustrated in Figure 4.8. Non-parametric inferential statistics (Wilcoxon Rank Sum Test) were applied to investigate the impact of seasonal, temporal, and spatial conditions and personal factors on the variation of the physical measurements. Predictive correlations (Kendall's W test coefficients and Cramer's V effect size) were estimated between the thermal comfort votes and seasonal, temporal, and spatial conditions, personal factors, and adaptive behaviours and between different types of the thermal comfort votes in the separate samples of nurses, patients, and visitors. Simple bivariate linear regression was used to determine the links between the thermal comfort votes and physical measurements. The impact of indoor airflows on indoor temperature and relative humidity levels was explored through time-series regression. Investigation of the context-specific acceptable indoor thermal conditions was conducted through probit regression, while binary logistic regression was used to define the risk of higher thermal discomfort to rising temperatures and relative humidity levels.

4.5.3 Performance and Analysis of the Semi-Structured Interviews with Doctors and Nurses

Nurses and doctors were invited to participate voluntary and to determine the date, time, and location of the interview. An information letter and a consent form were distributed in advance, and the signed consent form was collected at the day of the interview. Special effort was made to take an interview from the head nurse in each one of the selected wards. The list of standardised questions was the following:

Principal Questions to Nurses

- Which is the character of this ward?
- Which are the most common cases
- Which is the most common treatment?
- Which is the average length of hospitalisation?
- How do you cope with extreme heat in the ward?
- What do you do for the patients when they feel very hot?
- Which are your aspirations in terms of a refurbished environment?

Principal Questions to Doctors and nurses

- How do you personally cope with extreme heat in hospital spaces?
- Which is your advice to the nurses about what to do for themselves and for the patients when they feel very hot?
- Which are your aspirations in terms of a refurbished environment?

For all the interviews notes were kept about the gender of the participant and the exact, date, location, and duration of the interviews (Table 4.7. The interview transcripts were analysed in a systematic way following the established standards of the Quantitative Content Analysis (Q.C.A.) to ensure reliability and validity of the research process along with the process of transcription of the verbal and written interviewees' narratives was executed according to a set of convections (Schreier, 2014), which were as follows:

- number lines
- ID for each participant
- body language and activity around [word]
- pause […], the number of dots indicate the duration of the pause
- interruption [-]
- emphasis indicated with capital letters

The transcripts were uploaded in NVivo 12, where the frequency of specific keywords being repeated in the narratives of the interviewees was calculated separately for nurses and doctors through the application of available functions.

Part C: Results and Conclusion

4.6 Results

4.6.1 Recorded Thermal Environmental Performance and its Associations with the Seasonal, Temporal and Spatial Variations and Occupants' Satisfaction Levels with Existing Environmental Controls

4.6.1.1 Key Statistics of Recorded Temperatures

In Sep.2016, the $T.A._{rm.ext.(S1)}$ had a mean value of 28.30°C with minimum and maximum values standing at 28.17°C and 28.42°C, respectively (Table 4.13). In Mar.Apr.2017 the mean value of the $T.A._{rm.ext.(S1)}$ was 28.41°C with minimum and maximum values standing at 28.36°C and 28.45°C respectively, while the mean value of the $T.A._{rm.ext.(Meteo)}$ was 26.77°C with a minimum value of

26.67^{o}C and a maximum value of 27.02^{o}C (Table 4.13). The mean value of R.H$_{.ext.(S1)}$ stood in Sep.2016 at 75.19% with a range of values from 63.26 to 92.34%, and in Mar.Apr.2017 at 59.36%, with a range of values between 39.48% and 72.79%, while R.H.$_{ext.(Meteo)}$ in Mar.Apr.2017 had a mean value of 76.27%, with a range of values between 52.00% and 90.90% (Table 4.13).

Both in Sep.2016 and in Mar.Apr.2017, mean values of $T_{op.(spot)}$ in all selected wards exceeded the mean values of both T.A.$_{(spot)}$ and T.A.$_{(in)}$ with differences between them staying below 1.5^{o}C, while mean W.B.G.T.$_{(spot)}$ values remained at the lowest levels (Figures 4.9a-b). In Sep.2016, W3 and W9 had the highest mean $T_{op.(spot)}$ values of 32.28^{o}C and 31.64^{o}C, respectively, while in Mar.Apr.2017 the highest $T_{op.(spot)}$ values of 31.64^{o}C and 32.28^{o}C were recorded in W6 and W9, respectively (Figures 4.9a-b). The minimum $T_{op.(spot)}$ values stood in the 27.50-29.07^{o}C in Sep.2016, , rising to the 27.63-30.46^{o}C in Mar.Apr.2017, while the maximum $T_{op.(spot)}$ values remained in the 29.86-32.75^{o}C range in Sep.2016 and in the 31.97-33.50^{o}C range in Mar.Apr.2017 (Figures 4.9a-b).

Around participants, who were close to an operating fan (during their T.C.Is.) the mean $T_{op.(spot)}$ values stood at 29.45^{o}C in Sep.2016, and varied from 30.83 to 33.46^{o}C in Mar.Apr.2017.[66] Both in Sep.2016 and Mar.Apr.2017, the widest range of $T_{op(spot)}$ values was recorded in W2, whereas Physio. and T.U. experienced the narrowest range (Figures 4.9a-b). In both Sep.2016 and Mar.Apr.2017, T.A.$_{.(spot)}$ values displayed higher variation than the T.A.$_{(in)}$ and $T_{op.(spot)}$ values in all selected wards except W3 in Sep.2016 and W6 and W9 in Mar.Apr.2017 (Figures 4.9a-b). T.A$_{.\ (spot)}$ measurements around patients and visitors had broader interquartile ranges, especially in Sep.2016 (Figures 4.10-12). Except for Physio. and W2, where differences in the mean T.A.$_{(spot)}$ values between nurses and patients and between nurses and visitors reached, respectively, approximately 1^{o}C, the differences in the mean T.A.$_{(spot)}$ values being recorded around nurses, patients and visitors in the rest of the selected wards remained below 0.5^{o}C in both Sep.2016 and Mar.Apr.2017 (Figures 4.10-12).

4.6.1.2 Key Statistics of Recorded Relative Humidity Values

Recorded mean R.H.$_{(in)}$ values in the selected wards, which stood in the 76.03-89.31% range in Sep.2016 and in the 58.09-69.75% range in Mar.Apr.2017, were slightly higher than the mean R.H.$_{(spot)}$ values, which varied from 73.36 to 87.63% in Sep.2016 and between 59.28 and 69.56% in

[66] Summary statistics (mean, standard deviation, minimum and maximum) of the recorded T.A.$_{(spot)}$, $T_{op.(spot)}$, W.B.G.T.$_{(spot)}$, R.H.$_{(spot)}$ and W.S.$_{(spot)}$ values in Sep.2016 and Mar.Apr.2017 around participants seated or standing next to an operating fan are presented in Table 4.3 in Appendix 3.1.

Mar.Apr.2017 (Figures 4.13a-b). Mean R.H.$_{(spot)}$ values being recorded around participants being close to an operating fan stood at 72.67% in Sep.2016, and in the 63.98 and 67.73% in Mar.Apr.2017. Although R.H.$_{(in)}$ and R.H.$_{(spot)}$ displayed a similar range of values, R.H.$_{(spot)}$ demonstrated higher levels of variation in all selected ward, except for W3 in Sep.2016 and W9 in Mar.Apr.2017 (Figures 4.13a-b). The minimum R.H.$_{(spot)}$ values remained in the 67.56-84.93% region in Sep.2016 and in the 37.56-56.30% region in Mar.Apr.2017 (Figures 4.13a-b). Regarding the maximum R.H.$_{(spot)}$ values, the range from 77.56 to 94.45% was recorded in Sep.2016, while in Mar.Apr.2017 it fell between 68.32 and 76.62% (Figures 4.13a-b). Although in Sep.2016 R.H.$_{(spot)}$ values remained lower than R.H.$_{(in)}$ values around nurses, patients and visitors, this pattern was not observed in Mar.Apr.2017, when visitors experienced a wider range of R.H.$_{(spot)}$ values (Figures 4.14-16). Although differences in the ranges of the R.H.$_{(spot)}$ values between nurses, patients and visitors were very low, differences in the variation of their exposure to the R.H.$_{(spot)}$ values remained higher (Figures 4.14-16). In Sep.2016, higher variation in the R.H.$_{(spot)}$ measurements was recorded around visitors in all selected wards, while patients in W2, W7 and F.A. and nurses in T.U. were exposed to more varied R.H.$_{(in)}$ values (Figures 4.14-16). In Mar.Apr.2017, nurses experienced more diverse R.H.$_{(spot)}$ values in W3, Physio., in T.U and in F.A., while higher variation in R.H.$_{(spot)}$ values was demonstrated around visitors in W2, W6 and W9 and around patients in W7 (Figures 4.14-16).

4.6.1.3 Key Statistics of Recorded Wind Speed Values

Whereas in Mar.Apr.2017 higher mean W.S.$_{(spot)}$ values were recorded in all selected wards, except for W3, W9 and T.U., all selected wards experienced less varied W.S.$_{(spot)}$ values with the Nightingale wards and W9 demonstrating the highest falls (Figure 4.17). The mean W.S.$_{(spot)}$ values stood between 0.34 and 0.52m/s in Sep.2016 and from 0.30 to 0.53m/s in Mar.Apr.2017, while around participants who were close to an operating fan the mean W.S.$_{(spot)}$ values stood at 0.55m/s in Sep.2016 and in the 0.13-1.00m/s region in Mar.Apr.2017. Minimum W.S.$_{(spot)}$ values stood in the 0.11-0.19m/s range in Sep.2016 and in the 0.10-0.18m/s in Mar.Apr.2017 (Figure 4.17). Patients in Mar.Apr.2017 experienced higher mean W.S.$_{(spot)}$ values in the Nightingale wards and Physio. that stood in the 0.39-0.48m/s region (Figures 4.18-20). However, mean W.S.$_{(spot)}$ values remained highest around nurses in all selected wards, except for T.U. and F.A., where in Sep.2016 patients experienced the highest mean W.S.$_{(spot)}$ values of 0.48m/s (T.U) and 0.50m/s (F.A.), and W3 in Mar.Apr.2017, where visitors experienced the highest mean W.S.$_{(spot)}$ value of 0.60m/s (Figures 4.18-20). When compared to the rest of the selected wards, T.U. had the narrowest range of W.S.$_{(spot)}$ values around nurses and visitors, but not around patients (Figures 4.18-20).

4.6.1.4 Overview of Temporal and Spatial Variations during the T.C.Is.

T.C.Is. were conducted both during the morning and the evening shifts in Sep.2016 and in Mar.Apr.2017 in all selected wards except T.U., where in Sep.2016 T.C.Is. were performed only during the morning shift (Figure 4.21). More T.C.Is. were taken over the evening shifts during both fieldwork periods in all selected wards except for W2 and T.U. in Sep.2016 and Physio. in Mar.Apr.2017 (Figure 4.21). Figures 4.22-25 show the exact location of each participant in each selected ward during his/her T.C.I. It becomes evident that higher percentages of participants, which varied from 60.53% to 100%, tended to be seated or to stand in a location that was in a distance from 0.00 to 3.50m from a window area in all selected wards except for T.U. (Figure 4.26). By contrast, between 50% and 100% of the participants stayed far away from the external doors in all selected wards, except for Physio. (Figure 4.26). Fans were scarce in the selected wards. Therefore, proximity to a fan was unusual with the percentages of participants being close to an operating fan standing at 37.04% in F.A, 5.26% in W6, 2.70% in W7, and 5.56% in Physio. in Sep.2016, and at 17.81% in F.A. in Mar.Apr.2017 (Figure 4.26).

Regarding the exact distance of the participants' location from the window, in Sep.2016, T.U. had the highest percentage (100%) of participants being interviewed in a location with the longest distance from the window area (between 2.5 and 3 meters), while in T.U., in Mar.Apr.2017, the highest percentage (91.33%) of participants was interviewed in a location with the shortest distance from the window (0.00-0.50m) (Figure 4.27). In Mar.Apr.2017, T.U. was followed by W9 with 65% of participants there being close to a window area (0.00-0.50m), while in Sep.2016 W9 had the highest percentage of 77.20% of participants being interviewed close to a window (Figure 4.27). During both the monitoring periods, the most prevalent location of the participants in the Nightingale wards ranged between 0.50 and 2 meters from the window area (Figure 4.27). In T.U., in Sep.2016, 100% of the windows located close to the participants were closed, whereas the rest of the selected wards displayed significantly different distributions in the percentages of open apertures located at window areas that were close to the participants' locations (Figure 4.28). The percentages of these windows varied in Sep.2016 from 6.06% to 68.57%, with W9 having the highest percentage, followed by Physio. with 33.00%, W6 with 30.43%, W2 with 26.92%, and W7 with 25.00%, while in Mar.Apr.2017, W9 had again the highest percentage of 87.50% followed by W7 with 39.47%, W6 with 37.78%, and W2 with 25.45% (Figure 4.28).

4.6.1.5 Associations between Recorded Environmental Measurements and Seasonal, Temporal and Spatial Conditions, and Occupants' Satisfaction Levels with Existing Environmental Controls

Visual inspection of possible correlations between the $T_{op.(spot)}$ and the $R.H._{(spot)}$ values with the $W.S._{(spot)}$ values showed that overall the impact of localised airflows on the reduction of temperature and relative humidity was weak or non-existent except for the $R.H._{(spot)}$ levels around patients in Sep.2016 and for the $T_{op.(spot)}$ levels around nurses in Mar.Apr.2017 while higher $W.S._{(spot)}$ values seemed to have contributed to higher $R.H._{(spot)}$ levels around patients in Mar.Apr.2017 (Figure 4.29a). Further investigation of these possible associations through statistical methods for time-series regression of stationary variables showed that only the $T_{op.(spot)}$ values around nurses in Mar.Apr.2017 and $R.H._{(spot)}$ values around patients in Mar.Apr.2017 displayed statistically significant associations with the recorded $W.S._{(spot)}$ values; however they both were autocorrelated with the $W.S._{(spot)}$ values (Figure 4.29b). Despite the observed differentiations on the cooling impact of the naturally induced indoor airflows, most of the interviewed occupants expressed their satisfaction with existing environmental controls, with percentages standing, in Sep.2016, at 71.60% among nurses, 48.39% among students, 34.61% among patients, and, in Mar.Apr.2017, at 81.46% among nurses, 84.21% among students, 72.92% among patients, and 59.85% among visitors (Figure 4.30).

The exploration of the impact of the variation of the seasonal, temporal, and spatial conditions and satisfaction levels on the variance of the exposure to diverse thermal conditions was performed through the application of the Wilcoxon rank-sum test in the total sample and the separate samples of each occupant type as they all had non-normal distributions (Figure 4.31a). Although seasonal and temporal variation affected the differentiation in exposure of all three occupant types to $T_{op.(spot)}$ and $R.H._{(spot)}$ (p-value<0.001), the $W.S._{(spot)}$ values only around patients displayed statistically significant differences (p-value<0.001) in their variance between the rainy and the dry seasons (Figure 4.31b). Differentiation of patients' exposure to thermal conditions ($T_{op.(spot)}$, $R.H._{(spot)}$ and $W.S._{(spot)}$)between the Pavilion building and the rest of the case-study buildings was not statistically significant (p-value>0.05) by comparison to the exposure experienced by nurses and visitors (p-value<0.01) (Figure 4.31b). Proximity to a window area and a window area with open apertures did not have any statistically significant (p-value>0.05) impact on the recorded $W.S._{(spot)}$ around all occupant types and on the recorded $T_{op.(spot)}$ and $R.H._{(spot)}$ values around patients (Figure 4.31b). Different satisfaction levels with environmental controls affected the equality of the variance among all occupant types only in terms of their exposure to $T_{op.(spot)}$ (p-value<0.001) (Figure 4.31b).Overall the differences in the median values of the recorded thermal conditions among the different groups with statistically significant variations remained at very low levels (Figure 4.31b).

4.6.1.6 Discussion about the Associations between the Recorded Environmental Measurements and Seasonal, Temporal and Spatial Conditions and Occupants' Satisfaction Levels with Existing Environmental Controls

Occupants in the case-study wards were forced to cope with higher indoor temperature levels. Although the range of indoor relative humidity did not significantly differ, indoor temperatures recorded in the case-study wards significantly exceeded the published evidence about indoor thermal conditions monitored during thermal comfort field surveys both in naturally ventilated and mechanically conditioned hospital spaces across the equatorial zone. Despite the recorded lack of significant heterogeneity in the exposure of nurses, patients and visitors to indoor temperatures ($T.A._{(spot}$ and $Top._{(spot)}$). high levels of variation were recorded in their exposure to indoor relative humidity levels ($R.H._{(spot)}$) and indoor airflow ($W.S._{(spot)}$). In naturally ventilated wards, where the frequency, strength, and dispersion of the naturally induced indoor airflows is significantly unstable, the need to secure protection from uncomfortable thermal conditions among the occupant types with restricted thermal adaptability becomes vital. As shown in the case-study wards, if exposure to the critical cooling force through natural ventilation is not adapted to indoor microclimate and occupant's capacity for thermal adaptability (both behavioural and physiological), thermal distress will probably differentiate disproportionally to thermal vulnerability among the occupant types. These differentiations need to be further ameliorated by considering the impact of seasonal, temporal, and spatial variation on thermal exposure (Wilcoxon rank-sum tests p-value<0.001). More specifically, in naturally ventilated healthcare buildings with limited resources in equatorial climates, interventions need to guarantee the strengthening of the cooling impact against elevated temperature during the dry season and high relative humidity levels during the rainy season while the climate responsiveness of historical healthcare buildings with a pavilion-plan typology that might contribute to the protection of occupant types with weak capacity for thermal adaptability cannot be guaranteed (Wilcoxon rank-sum tests p-value>0.05 in the sample of patients).

4.6.2 Reported Adaptive Behaviours

4.6.2.1 Adaptive Behaviours Reported during the Semi-Structured Interviews

Among the interviewed doctors' physiological adaptation due to lifelong exposure to the tropical heat was the leading heat-coping mechanism, followed by the adaptive behaviours of wiping off sweat (17%), taking a break, and moving around to cooler places either inside or outside the ward (14%) (Figure 4.32). The least prevalent adaptive actions among doctors consisted in the consumption of water (9%), changing clothes (9%) and self-fanning (6%), while 11% of them reported taking no action (Figure 4.32). Among the interviewed nurses, physiological adaptation and taking a break were the prime heat-coping mechanisms (29%), followed by water consumption (14%), clothing adaptation (14%), and moving around to cooler places (14%) (Figure 4.33). Providing water, fanning patients, changing patients' clothes and patients' bedding covers, and asking for a medical examination were reported by 44% of the nurses (Figure 4.34). 22% of the nurses reported removing patients to a bed at a different location in the ward while wiping patients' sweat or changing patients' posture or giving medication accounted for 11% of nurses' responses (Figure 4.34). The most prevalent doctors' recommendations were rehydration of patients (42%), followed by changing beds (32%), changing patients’ clothes and bedding covers (21%), putting powder (21%), fanning patients (16%), giving medication (16%), and asking for a medical examination (5%) (Figure 4.34). Doctors and nurses raised the following concerns:

1. Fever was perceived as a symptom of thermal discomfort.
2. Patients who sweated were more prone to dehydration and trying to keep sweating patients rehydrated increased nurses' workload.
3. Severely ill patients felt cold even in hot conditions.

4.6.2.2 Adaptive Behaviours Reported during the T.C.Is.

Whereas in Sep.2016, opening windows was a prevalent behaviour only among nurses and students, with 97.41% of nurses and 100% of students reporting this type of adaptive behaviour, in Mar.Apr.2017 all occupants, except students, admitted opening windows with their percentages standing at 93.66% among nurses, 60.42% among patients, and 50.76% among visitors (Figure 4.35). However, the percentages of occupants who reported opening the windows “often” prevailed only among nurses, students, and visitors in both Sep.2016 and Mar.Apr.2017, and among patients only in Mar.Apr.2017 (Figure 4.46). Opening doors was reported as a predominant adaptive behaviour collecting percentages higher than 50% among nurses (55.17%) and students (83.87%) in Sep.2016, and only among students (63.16%) in Mar.Apr.2017 (Figure 4.37). However, less than 40% of the nurses, students, and patients in Sep.2016 and Mar.Apr.2017 and of visitors in Sep.2016 reported opening doors frequently, whereas 58.82% of visitors in Mar.Apr.2017 reported opening the doors frequently (Figure 4.38). Switching on fans was a prevalent adaptive behaviour only among nurses, with their percentages standing at 49.14% in Sep.2016 and 42.93% in Mar.Apr.2017, whereas the percentages of students, patients and visitors reporting to switch on fans remained below 16% in both Sep.2016 and in Mar.Apr.2017 (Figure 4.39). In Sep.2016, 33.33% of nurses and students, 83.33% of patients and 50% of visitors reported their willingness to switch on fans frequently, while in Mar.Apr.2017, 78.41% of nurses and 100% of students reported their willingness to do so (Figure 4.40).

Asking for help accounted for the highest percentage among patients (54.55%) in Sep.2016, while it was reported in Sep.2016 only by 11.11% of visitors, and in Mar.Apr.2017 by 10% of patients and 12.57% of visitors (Figure 4.41). Fanning themselves scored the most votes among students (33.33%) and patients (36.38%) in Sep.2016, and among students (100%) and patients (60%) in Mar.Apr.2017, while it accounted for 14.29% of nurses' votes and 11.11% of visitors' votes in Sep.2016 (Figure 4.41). Going outside gained the most votes among visitors, standing at 44.44% in Sep.2016 and 50% in Mar.Apr.2017, while accounting for 28.57% of nurses' votes in Sep.2016 and 10% of patients' votes in Mar.Apr.2017. Moving to a cooler room was reported in Sep.2016 by 21.43% of nurses and in Mar.Apr.2017 by 20% of nurses and 25% of visitors (Figure 4.41). However, being outdoors between fifteen and thirty minutes before the T.C.I. accounted for 21.55% of nurses and 29.41% of visitors in Sep.2016 and for 2.08% of patients and 6.06% of visitors in Mar.Apr.2017 (Figure 4.42).

In Sep.2016 54.90% of visitors reported being outside the ward between thirty and sixty minutes before the T.C.I, while very low percentages of nurses, students, and patients, which stood in the 1.72-7.69% range in Sep.2016 and in the 2.78-9.09% region in Mar.Apr.2017 (Figure 4.42). Only nurses and students reported drinking water and pouring water in their bodies, with percentages standing in Sep.2016 at 21.43% among nurses and 33.33% among students and in Mar.Apr.2017 at 40% among nurses (Figures 4.41). Taking a break was reported only in Sep.2016 by nurses and students, with their percentages standing at 7.14% among nurses and 22.22% among students (Figure 4.41). Only patients and visitors reported changing clothes, with their percentages standing in Sep.2016 at 9.09% among patients and 11.11% among visitors and in Mar.Apr.2017 at 20% among patients (Figure 4.41). However, none of the participants reported changing clothes between ten and thirty and between thirty and sixty minutes before the T.C.I. in Sep.2016 and Mar.Apr.2017.Only students reported switching on fans, with their percentages standing at 11.11% in Sep.2016, while only nurses and patients reported moving close to a window or a fan (in operation), with their percentages standing in Sep.2016 at 7.14% among nurses and 21.22% among visitors, and in Mar.Apr.2017 at 20% among nurses and 17.50% among visitors (Figure 4.41).

Water or a soft drink between thirty and sixty minutes before the T.C.I. was consumed by most nurses (53.17%) only in Sep.2016 (Figure 4.43a). Most students tended to have consumed water or a soft drink only between ten and thirty minutes before the T.C.Is. in both Sep.2016 and Mar.Apr.2017 with their percentages standing at 54.84% in Sep.2016 and at 57.89% in Mar.Apr.2017 (Figure 4.43a). In both Sep.2016 and Mar.Apr.2017, more than 60% of patients reported the consumption of water or soft drinks between ten and thirty minutes and between thirty and sixty minutes before the T.C.Is. (Figure 4.43a). By contrast, most visitors reported not having consumed water or soft drinks between ten and thirty minutes and between thirty and sixty minutes before the T.C.Is. in Mar.Apr.2017, while in Sep.2016 most of them tended to have consumed water or a soft drink only between thirty and sixty minutes before the T.C.Is. (Figure 4.43a). Consumption of food between ten and thirty minutes and between thirty and sixty minutes before the T.C.Is. was avoided by most nurses, patients, and visitors in both Sep.2016 and in Mar.Apr.2017. Most students (84.12%) tended to consume food between ten and thirty minutes before the T.C.Is. in Mar.Apr.2017, and before thirty and sixty minutes in Sep.2016 (Figure 4.43b). Although nurses displayed higher levels of adaptive capacity at a personal level and in relation to their interaction with existing environmental controls, variance in exposure to indoor thermal conditions between the nurses and the rest of the interviewed occupant types in two separate subsamples consisting of the participants who expressed satisfaction with the environmental controls and those who were close to a window with open apertures (Figure 4.44).

Regarding the suggestions for the improvements for the cooling of the hospital environment and strengthening of occupants' adaptive capacity, in the T.C.Is.' responses in Sep.2016, provision of fans prevailed among all types of occupants, with their percentages standing at 40% among nurses, 35.29% among students, 23.08% among patients and 44.44% among visitors (Figure 4.45). In Mar.Apr.2017, percentages among students, patients and visitors recommending fans increased significantly, reaching 85.71% among students, 83.33% among patients and 56.25% among visitors while standing at 35.48% among nurses (Figure 4.45). By contrast, in Sep.2016, the installation of air-conditions represented 26.67% of nurses' votes, 29.41% of students' votes, 15.38% of patients' votes, and 11.11% of visitors' votes (Figure 4.45). The combination of fans and air-conditions was recommended in Sep.2016 by 13.33% of the nurses and 17.65% of the students, while in Mar.Apr.2017, it accounted for 19.35% of nurses' votes, 14.29% of students' votes, 8.33% of patients' votes, and 25% of visitors' votes (Figure 4.45). The combination of air-conditions and fridges was recommended only in Mar.Apr.2017, by 3.23% of the nurses (Figure 4.45). Showers were recommended in Sep.2016 by 10% of the nurses and 14.29% of the students (Figure 4.45). Cold drinks were recommended by 4.17% of the patients in Mar.Apr.2017 (Figure 4.45). Air conditions and fans represented most of the responses from both nurses and doctors during the semi-structured interviews, with installation of air-conditions accounting for 47.37% of doctors' answers and 44.44% of nurses' answers, while the provision of fans accounted for 57.89% of doctors' responses and 33.33% of nurses' responses (Figure 4.46). Interestingly, doctors reported by 10.53% changes in the building's thermal mass, by 21.05% passive cooling techniques and by 5.26% no changes (Figure 4.46).

4.6.2.3 Discussion about the Reported Adaptive Behaviours

Through comparisons of the controversies and synergies between the reported adaptive behaviours, which were reported during the semi-structured interviews and the T.C.Is., and the realised adaptive actions, which were indicated by participants' responses during the T.C.Is. or were monitored by the photographic recording of the position of the window opening at the facades of interest at the selected wards, it becomes evident that the high levels of awareness for adaptive behaviours among all occupant types, were not reflected in their realised adaptive actions. Yau and Chew (2014) showed that limited opportunities for adjustments of clothes and activity levels weakened occupants' responsiveness to changes in thermal conditions. Similar to adaptive behaviours being observed among office workers across the equatorial zone, the most common adaptive behaviour among doctors and nurses who participated in the semi-structured interviews was to take a break, while moving around (to cooler places) was most popular only among doctors. In contrast to nurses' statements during the semi-structured interviews regarding their habits to take a break when they experienced thermal discomfort, very low percentages of nurses and students reported during the T.C.Is. the adaptive behaviour of taking a break both in Sep.2016 and in Mar.Apr.2017. However, nurses' statement during semi-structured interviews that they tended to not move around to cooler places was also confirmed by their responses during the T.C.Is. regarding their heat-coping acclimatisation and their presence in outdoor places sixty minutes before the T.C.I.

Similarly, the adaptive behaviour to move to cooler places, which accounted for most visitors' responses during the T.C.Is. in both Sep.2016 and Mar.Apr.2017 was matched, only in Sep.2016, by their reported presence outdoors sixty minutes before the T.C.I. Likewise, patients' responses regarding their significantly limited presence in outdoor places sixty minutes before the T.C.I. confirmed their responses that they avoided moving around to cooler places. Although changing clothes and water consumption was the second most prevalent adaptive behaviour among nurses participating in semi-structured interviews, these adaptive actions were the least popular among interviewed doctors. As reported in semi-structured interviews, nurses' tendencies to consume water were confirmed by their responses during the T.C.Is. regarding both adaptive actions and the actual water consumption (ten and thirty minutes and/ or thirty and sixty minutes before the T.C.I.). However, nurses' narratives during semi-structured interviews about changing clothes as a heat-copying behaviour contradicted the answers given during the T.C.Is., which revealed that none of the participants among nurses, patients and visitors had changed clothes over the last hour before the T.C.I., both in Sep.2016 and in Mar.Apr.2017. It becomes evident that contrary to published evidence about changing clothes as an adaptive behaviour (Parsons, 2002; Wijewardane and Jayasinghe, 2008; de Dear and Brager, 1998), the interviewed occupants in Connaught Hospital's selected wards tended not to change their clothing layers. Similar observations were reported by Yau and Chew (2014). Nurses' responses revealed that actions for the restoration of patients' thermal comfort were an integral part of nursing care and in line with doctors' advice and patients' needs.

In Mar.Apr.2017, during the T.C.Is., most nurses, patients, and visitors reported strong willingness to open windows often, while in Sep.2016, this type of adaptive behaviour was common only among nurses and students. Despite the reported proximity to a window area among most of all type of occupants indicated by their location in the ward during the T.C.I., only low percentages of them reported the adaptive behaviour of moving close to a window area. However, opening doors was reported as a habitual action for the restoration of thermal comfort among nurses and students in Sep.2016, and only among students in Mar.Apr.2017. Whereas only nurses both in Sep.2016 and in Mar.Apr.2017 admitted in their majority to be willing to switch on fan when they felt thermal discomfort; all occupant types were keen on using the fans often. Similar attitudes were observed by Kumar, et al. (2019) in naturally ventilated hostels in India. Although only a few students in Sep.2016 reported the adaptive action of switching on fans and few nurses and patients admitted moving close to a fan as a heat-copying mechanism, recommendations for the provision of fans were made by most of all occupant types in Sep.2016 and by students, patients, and visitors in Mar.Apr.2017. Both doctors and nurses frequently mentioned the provision of fans during semi-structured interviews, with statements about the installation of air-conditioning exceeding the statements about fans only among nurses. There stronger preferences for air-conditions were also repeated in the answers given by nurses and students during the T.C.Is., which exceeded patients' and visitors' percentages in both Sep.2016 and Mar.Apr.2017.

The need for engineering interventions to strengthen the cooling capacity of natural ventilation in clinical spaces similar to the case-study wards at Connaught Hospital is stressed by the significantly low differences in thermal exposure between the nurses, who directed the operation of the existing building controls, and the rest of the interviewed occupant types. This indicates an incomplete and irresponsive realisation of the higher adaptive capacity among nurses and the limitations of the environmental change that these "soft" interventions could have in a significantly overheated humid indoor environment. Climate-responsive operation of the building controls can become part of nurses' training in naturally ventilated hospital wards with restrained resources. This can be supplemented by the real-time provision of visual evidence about the outdoor and indoor environmental changes, while posters and other visual aids can guide window operation to patients and visitors. The provision of cool water and accessibility to cool outdoor places with the appropriate microclimate can strengthen adaptive capacity at a personal level among all occupant types. Informal nursing practices for the amelioration of thermal discomfort can be integrated with established care and infection control protocols.

4.6.3 Thermal Comfort Votes and their Associations with Seasonal, Temporal and Spatial Conditions, Personal Factors and Adaptive Behaviours

4.6.3.1 Overview of the Thermal Comfort Votes during the T.C.Is.

Overall participants perceived the ambient thermal conditions as warm during both seasons (0<=median A.T.S.Vs.<=1, 1.28<=SD<=1.58), as humid during the rainy season (1<=median A.R.H.S.Vs. (Sep.2016) <=2, 1.28<=SD<=1.53), as neither dry or humid during the dry season (median A.R.H.S.Vs.(Mar.Apr.2017)=0.00, 1.23<=SD<=1.31) and with both acceptable and unacceptable indoor airflows during both seasons (-2.00<=median A.W.S.A.Vs.<=1.00, 1.90<=SD<=2.07) (Figures 4.47a-c). Votes of comfort showed general discontent with the levels of indoor temperature (-1<=median A.T.C.Vs.<=1, 1.17<=SD<=1.37) and indoor relative humidity (-1<= median A.R.H.C.Vs.<=1, 1.08<=SD<1.31) (Figures 4.47a-c).Predominantly unacceptability of the thermal conditions was indicated in the preference votes that indicated participants' preferences for lower indoor temperatures during both seasons (0<=median A.T.P.Vs.<=-1, 0.93<=SD<=1.62), for less humid indoor environments during the rainy season (median A.R.H.P.Vs.=-2, 1.21<=SD<=1.60) and more humid indoor environments during the dry season (0<=median A.R.H.P.Vs.<=1, 1.29<=SD<=1.34) while preferences for higher indoor airflows expressed during both seasons (A.W.S.P.Vs.=1, 0.44<=SD<=0.51 (Figures 4.47a-c).

The fact that votes of thermal neutrality were not paired with votes of comfort and acceptability was more clearly reflected in the percentages of votes for each response scale among the three occupant types (Figures 4.48a-b). Although in Sep.2016 60.00% (146/244) of the A.T.S.Vs. represented votes classified as slightly cool (-1), neutral (0) and slightly warm (1), which are considered to illustrate thermal comfort, especially in naturally ventilated spaces with hot-humid conditions where occupants are expected to be more tolerant to higher temperatures, only 18% (45/244) expressed their content with the indoor thermal conditions with 31.15% (76/244) voting for "no changes" (0) (Figure 4.48a). Similarly, in Mar.Apr.2017 whereas votes classified as slightly cool (-1), neutral (0) and slightly warm (1) accounted for 58.64% (285/486) of the A.T.S.Vs., majority was gained by A.T.C.Vs. classified as "extremely uncomfortable" (-3), "very uncomfortable" (-2) and "uncomfortable" (-1) (52.26%, 264/486) and A.T.P.Vs. classified as "much cooler" (-3), "cooler" (-2) and "slightly cooler" (-1) (63.37%, 308/486) (Figure 4.48b).

Both in Sep.2016 and in Mar.Apr.2017, more consistency between perception, comfort, and acceptability was illustrated in the votes regarding indoor relative humidity levels. In Sep.2016, A.R.H.S.Vs. classified as "high" (2) and "very high" (3) comprised 49.18% (120/244) of the reported votes, while votes classified as extremely uncomfortable (-3), very uncomfortable (-2) and uncomfortable (-1) composed 80.33% (196/244) of the A.R.H.C.Vs. and votes classified as "much less humid" (-3), "less humid" (-2) and "slightly less humid" (-1) accounted for 67.62% (165/244) of the A.R.H.P.Vs. (Figure 4.48a). In Mar.Apr.2017, 72.63% (353/486) of the A.R.H.S.Vs. comprised from votes classified as "very low" (-3), "low" (-2) and "slightly low" (-1) while prevalence was gained by A.R.H.C.Vs. classified as "extremely uncomfortable" (-3), "very uncomfortable" (-2) and "uncomfortable" (-1) (54.32%, 264/486) and A.R.H.P.Vs. classified as "slightly more humid" (1), "more humid" (2) and "much humid" (3) (52.06%, 253/486) (Figure 4.48b). Inconsistency between the reported acceptability of indoor airflows and preferences for change was evident. Although high levels of content with indoor airflows were reflected in the A.W.S.A.Vs. with votes classified as "slightly acceptable" (1), "acceptable" (2) and "very acceptable" (3) prevailing both in Sep.2016 (55.33%, 135/244) and in Mar.Apr.2017 (64.61%, 314/486), votes of preference for higher indoor airflow levels gained the majority both in Sep.2016 (77.05%, 188/244) and Mar.Apr.2017 (74.46%, 362/486) (Figures 4.48a-b).

The lack of evident patterns becomes obvious in assessing the distribution of the thermal comfort votes between the three occupant types across the four building typologies (Figures 4.49.1a-2c). Overall, in all four building typologies, votes of discomfort prevailed in relation to the indoor relative humidity in Sep.2016 (Figure 4.49.1b).and with respect to the indoor temperature in Mar.Apr.2017 (Figure 4.49.2a) with patients displaying the lowest tolerance levels of thermal discomfort. However, the following exceptions from this observation were recorded. Half of the nurses and patients in the Annex and the visitors in the A & E, who were interviewed in Sep.2016, expressed relative-humidity-related votes of comfort (Figure 4.49.1b). More than half of the nurses in the Pavilion building and in the Annex and half of the visitors in the A & E, who were interviewed in Mar.Apr.2017, expressed comfort in relation to the indoor temperature (Figure 4.49.2b). The distribution of thermal comfort votes between the occupant types does not indicate that the Pavilion building provided a significantly more thermally comfortable indoor environment (Figures 4.49.1a-2c). However, in the Pavilion building content with the indoor airflows was expressed by most of the nurses both in Sep.2016 and in Mar.Apr.2017 and by most of the patients and visitors in Mar.Apr.2017 (Figure 4.49.1c; Figure 4.49.2c). The distribution of the votes of preferences for changes in the indoor thermal conditions displayed minor differences between the occupant types across all four building typologies, with patients expressing the most unexpected votes (Figures 4.49.1a-2c). In Sep.2016, all the interviewed patients in the A &E expressed their preference for “no changes” in the levels of indoor temperature and humidity (Figures 4.49.1a-b), and 93% of the interviewed patients in the Pavilion building expressed their preference for lower indoor airflows (Figure 4.49.1c).

4.6.3.2 Associations between the Thermal Comfort Votes

The evaluation of the impact on the variation of the temperature-related votes (A.T.S.Vs., A.T.C.Vs. and A.T.P.Vs.) from differentiations in the relative humidity related votes (A.R.H.S.Vs., A.R.H.C.Vs. and A.R.H.P.Vs.) and wind speed related votes (A.W.S.A.Vs. and A.W.S.P.Vs.) showed that strong correlation did not exist between the temperature-related votes and the relative humidity related votes ($0.24 =< $Cramers V effect size$ <= 0.49$, p-value$<0.001$) (Figure 4.50a) , while only among patients the wind speed related votes displayed a strong effect size on the variation of the A.T.C.Vs. (Cramer’s V effect size: 0.55, p-value<0.001) with temperature-related discomfort being associated with A.W.S.S.Vs. expressing unacceptability of the indoor airflows (Figures 4.50a-b). In the sample of nurses, A.T.S.Vs. indicating warm sensation were linked with A.T.P.Vs. for lower temperatures displaying strong correlations (Cramer’s V effect size: 0.54-0.60, p-value<0.001) (Figures 4.50a-b). A.T.C.Vs. reported by nurses, patients, and visitors had strong links (Cramer’s V effect size: 0.51-0.54, p-value<0.001) with A.T.P.Vs. both for warmer and for cooler thermal conditions (Figures 4.50a-b). In the sample of visitors, A.T.S.Vs. expressing warm and cooler sensations was strongly correlated (Cramer's V effect size: 0.51, p-value<0.001) with A.T.C.Vs. showing discomfort (Figures 4.50a-b).

4.6.3.3 Impact of the Variation on the Seasonal, Temporal and Spatial Conditions, Personal Factors and Adaptive Behaviours on the Thermal Comfort Votes

4.6.3.3.1 Distribution of Personal Factors

In both Sep.2016 and Mar.Apr.2017, most nurses and students were women, with the percentages of female nurses standing at 75.86% in Sep.2016 and at 80.39% in Mar.Apr.2017, while female students accounted for 90.32% and 78.95% of the student sample in Sep.2016 and in Mar.Apr.2017, respectively (Figure 4.51). By contrast, men prevailed in the patients' sample, representing 69.23% and 68.97% of the interviewed number of patients in Sep.2016 and in Mar.Apr.2017, respectively (Figure 4.51). However, male participants dominated the visitors' sample only in Mar.Apr.2017 with their percentages standing at 56.06%, while in Sep.2016 female visitors had the highest participation (76.47%) (Figure 4.51). In both Sep.2016 and Mar.Apr.2017, nurses and students had the highest participation rates in the age groups from eighteen to twenty-nine and from thirty to thirty-nine years (Figure 4.52). Participation rates in the age group from eighteen to twenty-nine years old accounted for 31.90% among nurses and 96.77% among students in Sep.2016, and for 36.76% among nurses and 73.68% among students in Mar.Apr.2017 (Figure 4.52). In the 30-39 age group, participation rates stood in Sep.2016 at 46.55% among nurses, and in Mar.Apr.2017 at 43.63% among nurses and 26.32% among students (Figure 4.52). Patients had the highest participation rates in the 40-49 and 50-59 age groups, with the participation percentages of patients in the 40-49 age group standing at 28.85% in Sep.2016 and at 33.79% in Mar.Apr.2017, while patients in the 50-59 age group participated in the T.C.Is. by 42.31% in Sep.2016 and by 21.38% in Mar.Apr.2017 (Figure 4.52). Furthermore, participation percentages among elderly patients (>60 years) stood at 13.46% in Sep.2016 and at 2.76% in Mar.Apr.2017 (Figure 4.52). Visitors' participation rates spread across all age groups, with the highest percentages being recorded in the 18-49 age groups in both Sep.2016 and Mar.Apr.2017 (Figure 4.52). In Sep.2016, among interviewed patients, the most prevalent medical conditions were haematological diseases, followed by amputations, diseases of the reproductive system, and lung diseases, while in Mar.Apr.2017, trauma and orthopaedic injuries prevailed, followed by hypertension and cardiovascular diseases, cancer, and the abdominal system's diseases (Figure 4.53).

Most nurses, students and visitors described their health statuses as “fit” and “very fit” in both Sep.2016 and in Mar.Apr.2017 (Figure 4.54). By contrast, only 3.85% of patients in Sep.2016, and 22.07% of patients in Mar.Apr.2017 felt “fit”, while 38.46% in Sep.2016 and 9.66% in Mar.Apr.2017 described their health status as “very weak” (Figure 4.54). Furthermore, among patients, the health status’s category of “weak” accounted for 34.62% and 46.90% of the responses in Sep.2016 and in Mar.Apr.2017, respectively (Figure 4.54). Healthy levels of the BMI. index (20.89-31.27) was prevalent among nurses, students, patients, and visitors in both Sep.2016 and in Mar.Apr.2017 (Figure 4.55). However, both students and visitors in Sep.2016 and both students and patients in Mar.Apr.2017 had high percentages of participants with BMI in the lowest categories (15.44-20.76) (Figure 4.55). Most nurses had consumed water or a soft drink between ten and thirty minutes before the T.C.Is. in both Sep.2016 and Mar.Apr.2017, with their percentages standing at 72.17% and 54.78%, respectively. Patients had the lowest mean metabolic rates, which varied from 0.73 to 1.35met. in Sep.2016 and from 0.80 to 1.00met. in Mar.Apr.2017, while nurses’ and students’ mean metabolic rates were the highest ranging between 1.00 and 2.50met. in Sep.2016 and between 1.00 and 1.70met. in Mar.Apr.2017; these were followed by the mean metabolic rates among visitors (Figure 4.56). In Sep.2016, the clothing insulation values among patients, ranging from 0.45 to 2.40clo, by far exceeded the clothing insulation values among nurse and students, which varied between 0.38 and 0.48clo, and the clothing insulation values among visitors, which ranged from 0.35 to 0.56clo (Figure 4.57). In Mar.Apr.2017 mean clothing insulation values among patients, which kept their wide dispersion standing in the 0.29-1.62clo range, fell significantly to 0.54clo, displaying low differences with the mean clothing values among nurses (0.45clo), students (0.42clo) and visitors (0.47clo) (Figure 4.57). Whereas most prevalent periods of occupancy in the ward in both Sep.2016 and Mar.Apr.2017 among nurses and students were from one to three hours and between three to six hours and among visitors were from one to three hours, among patients’ hospitalisation periods from twelve hours to one day and between one and seven days prevailed with 1.92% (Sep.2016) and 0.69% (Mar.Apr.2017) reporting hospitalisation periods over more than a month (Figure 4.58).

4.6.3.3.2 Associations between the Thermal Comfort Votes and the Seasonal, Temporal and Spatial Conditions, Personal Factors and Adaptive Behaviours

Seasonal differentiation accounted for approximately 45% of the variations in the A.R.H.S.Vs. and A.R.H.P.Vs. (Cramer’s V effect size: 0.50-0.65, p-value<0.001) in the total sample and the separate samples of nurses while they moderately affected the A.T.P.Vs. (Cramer's V effect size: 0.31-0.39, p-value<0.001) across all examined samples (Figure 4.59a). Differentiation between the morning and the evening shifts had a strong impact on the distribution only on the A.R.H.P.Vs. in Mar.Apr.2017 and the A.W.S.S.Vs. in Sep.2016 (Cramer's V effect size: 0.50, p-value<0.001) reported by visitors (Figure 4.59a). Variability between the Pavilion-plan typology and the rest of the case-study building typologies had a strong impact only on the variation of both the sensation (A.T.S.Vs. and A.R.H.S.Vs.) and preference (A.R.H.P.Vs. and A.W.S.P.Vs.) votes reported by patients in Sep.2016 (Cramer's V effect size: 0.50-0.66, p-value) (Figure 4.59a). The patients in the Pavilion building, who were interviewed in Sep.2016, tended to perceive their ambient environment as cooler and drier than the rest of the interviewed participants (Figure 4.59b). However, the significantly unequal distributions between these two groups of patients are likely to have driven this strong differentiated impact on thermal comfort. Experienced thermal comfort was influenced both by the building and ward typology (Cramer's V effect size: 0.20-0.46, p-value<0.05 and p-value<0.001) with patients' preference votes (A.R.H.P.Vs. and A.W.S.P.Vs.) reported in Sep.2016 demonstrating the strongest effect size (Cramer's V effect size: 0.50-0.56, p-value<0.001) (Figure 4.59a). A.W.S.S.Vs. reported by patients in Sep.2016 displayed significant variation between the participants being interviewed far away and close to a window area (Cramer's V effect size: 0.51, p-value<0.01) with the latter expressing less discontent with the indoor airflows (Figures 4.59a-b). Similarly, patients interviewed in Mar.Apr.2017 close to a window area with open windows tended to express higher levels of acceptability of the indoor airflows (Cramer's V effect size: 0.56, p-value<0.001) (Figures 4.59a-b). Although proximity to a window area with open windows strongly correlated with the A.T.P.Vs. reported by patients in Mar.Apr.2017 (Cramer's V effect size: 0.53, p-value<0.05), it had minor influence on their preferences for cooler thermal conditions (Figures 4.59a-b).

Regarding the influence of personal factors on the variance of the reported thermal comfort votes, only gender and age had a strong effect size. More specifically, A.R.H.S.Vs., A.R.H.P.Vs. and A.W.S.S.Vs. reported by patients in Sep.2016 had a strong correlation with gender (Cramer's V effect size:0.53-0.58, p-value<0.001) with male participants tending to be feeling higher levels of moisture in the air and being more dissatisfied with the indoor airflows (Figures 4.59a-b). Age-related variability had a strong effect size on the A.R.H.P.Vs. reported by patients in Sep.2016 (Cramer's V effect size: 0.59, p-value<0.001) and on the A.W.S.S.Vs. reported by visitors in Sep.2016 (Cramer's V effect size: 0.53, p-value<0.001) without evident differences in the distribution of the votes of patients, but with younger visitors expressing higher levels of unacceptability of the indoor airflows (Figures 4.59a-b). Although characteristics of the small sample size and its significantly skewed distribution affected the correlation between the reported thermal votes and patients' medical conditions, resulting in the lack of statistically significant results, it is well documented that medical conditions and medication influence the critical thermoregulatory physiological function of the human body (Figures 4.60a-b). The investigation of the impact of the medical conditions between male, female, and elderly (above sixty-five years old) showed that trauma and orthopaedic injuries could contribute both to colder and warmer temperature-related sensation votes. In comparison, diseases of the reproductive system, hypertension and lung diseases can contribute to warmer temperature-related sensation votes (Figures 4.60a-b).

Regarding the correlations between the reported thermal comfort votes and occupant adaptive behaviours, strong effect size was found with the operation of windows, doors and fans, water and food consumption and satisfaction levels with existing environmental controls (Figure 4.59a). Window operation contributed with very strong (Cramer's V effect size: 0.71, p-value<0.001) and strong (Cramer's V effect size: 0.54, p-value<0.001) effect sizes in the variance of the A.R.H.P.Vs. and A.W.S.S.Vs. that were reported by patients in Sep.2016, with those admitting to actively change the state of the window openings, reporting higher levels of acceptability of the indoor airflows (Figures 4.59a-b). A.T.P.Vs. reported by nurses Sep.2016 had strong correlation with door-opening behaviours (Cramer's V effect size: 0.51, p-value<0.001) with nurses opening the doors in the wards tending to prefer no changes in the thermal conditions (Figures 4.59a-b). Among patients in Sep.2016, strong links were found between A.R.H.S.Vs. and water consumption (Cramer's V effect size: 0.52, p-value<0.01) and between A.T.S.Vs., A.R.H.S.Vs. and A.R.H.P.Vs. and food consumption (Cramer's V effect size: 0.50-0.66, p-value<0.01) but with minor impact on the tolerance of more or less extreme thermal conditions (Figures 4.59a-b). Overall moderate effect sizes (0.30<Cramer's V effect size<0.49, p-value<0.05) were found in the separate samples of nurses and visitors between the reported thermal comfort votes and age, gender, health status, operation of windows, doors and fans and proximity to a window area with or without open apertures. The reported thermal comfort votes had statistically non-significant correlations with BMI-index, metabolic rates, and clothing insulation.

4.6.3.4. Discussion of the Thermal Comfort Votes and their Associations with Seasonal, Temporal and Spatial Conditions, Personal Factors, and Adaptive Behaviours

In naturally ventilated multibed wards with hot-humid settings and limited resources, the reported thermal sensation votes might not be a good indicator of perceived thermal comfort and acceptability of thermal conditions. More specifically, sensation votes within the range from -1.00 to 1.00, which are widely accepted as signs of comfort and acceptability, might not be a robust indicator for content with the indoor thermal conditions among occupants. Therefore, sensation votes need to be paired with comfort votes and preference votes (reported by the same participant). In this way, an even better understanding of thermal comfort is achieved by avoiding wrong interpretations of the response scales that is driven by context-specific sociocultural driven linguistics, which were probably missed by the research team when they piloted the questionnaires. Although in the analysed sample, A.T.P.Vs. were strong indicators of the A.T.S.Vs. and the A.T.C.Vs. (Cramer's V effect size: 0.51-0.60, p-value<0.001), the direction of their effect was different among nurses, patients, and visitors. In naturally ventilated hospital wards similar to naturally ventilated spaces of other building types, thermal comfort votes regarding sensation, comfort and acceptance are interlinked not only in relation to the same environmental variables but between diverse environmental variables. In the case-study wards, although the reported thermal comfort votes with respect to indoor relative humidity levels did not have a strong impact on the variation of the temperature-related votes, A.T.C.Vs. reported by patients was strongly affected by their variation in A.W.S.S.Vs.

Overall, in the case study, wards reported thermal discomfort was driven by perceptions of high indoor relative humidity levels in Sep.2016, by elevated indoor temperature in Mar.Apr.2017 and low levels of indoor airflows during both seasons. High levels of acclimatisation among the interviewed occupants at Connaught Hospital were demonstrated at the reported A.T.S.Vs. Compared to the mean A.T.S.V. (-0.90) among patients, who were not hospitalised but just waiting for a medical examination, published by Khalid, et al. (2019), patients in the case-study wards reported higher mean A.T.S.Vs., while their mean A.T.S.Vs. were lower than those reported by patients in hospital wards across the temperate zone. In the case-study wards, mean metabolic rates among nurses and students displayed a similar range of values with those calculated by Yau and Chew (2009) and De Giuli, et al. (2013), whereas patients' metabolic rates were lower than those estimated by De Giuli, et al. (2013). At the same time, mean clothing insulation values among nurses and students, who participated in the T.C.Is., were lower than those estimated by Khodakarami and Knight (2007) for hospital spaces in Iran, while for patients covered with blankets, the values were close to those estimated by Khodakarami & Knight (2007) and Khalid, et al. (2019). Furthermore, it seems that although the reported working hours of nurses at Connaught Hospital's selected wards were slightly lower than those presented by Khodakarami and Knight (2007) for hospitals in Iran, prevalent hospitalisation periods of patients were higher than all those reported in published thermal comfort surveys in in-patient facilities.

The group of spatial attributes, which were defined by diverse building and ward typologies and proximity to existing environmental controls, of personal factors, which were determined by gender, and of adaptive behaviours, which were described by the operation of the existing environmental controls and by behaviours that changed thermoregulation at an individual level, had the strongest effect size (Cramer's V effect size: 0.50-0.69, p-value<0.001) only among interviewed patients. This indicates that in hospital wards with hot-humid conditions and limited resources, which restrain the optimal continuous operation of mechanical ventilation and cooling, patients' limited thermal adaptability can be significantly improved if the above-mentioned spatial personal and behavioural parameters are considered in ward allocation. Therefore, through the integration of critical aspects of thermal adaptability that extend the criteria for ward allocation beyond clinical outcomes, the healing potential of the ward's indoor environment, whose attributes are exploited towards a personalised type of health care, can be strengthened. Experienced thermal discomfort was associated with building typology (Cramer's V effect size: 0.20-0.46, p-value<0.05 and p-value<0.001), displaying a strong effect size on the preferences about indoor humidity and airflows among patients (Cramer's V effect size: 0.50-0.56, p-value<0.001). Allocation of patients in buildings with architectural and engineering characteristics like the case-study Nightingale typology can have a strong alleviating impact of thermal comfort during the rainy season (Cramer's V effect size: 0.50-0.66, p-value) while acceptability of the indoor airflows among patients might increase if they can control window operation (Cramer's V effect size: 0.54, p-value<0.001).

Interventions that consider seasonal variability are expected to have a strong impact on the amelioration of thermal discomfort caused by indoor relative humidity (Cramer’s V effect size: 0.50-0.65, p-value<0.001), whereas temporal variability between the morning and the evening shift might not influence the most vulnerable occupant types, namely the nurses and the patients (chi2 p-value>0.05). The impact of door-operation on ventilation cannot be ignored, particularly for the restoration of thermal discomfort among nurses (Cramer’s V effect size: 0.51, p-value<0.001). Similar to published evidence regarding the impact of gender, age, and health status on thermal sensation, in the case-study wards, reported votes in relation to indoor relative humidity and indoor airflows had strong and moderate correlations with gender, age and health status. Despite the published evidence about the influence of BMI-index, clothing insulation and metabolic rates, the collected thermal comfort votes had statistically insignificant associations with these personal factors.

4.6.4 Range of Comfortable Thermal Conditions

4.6.4.1 Reported Range of Comfortable Thermal Conditions

4.6.4.1.1 Reported Comfortable Thermal Conditions Defined by Descriptive Statistics

Overall, most sensation votes of neutrality were not paired with votes of comfort and acceptability of the thermal conditions, while many votes of warm, cool, humid, or dry sensations were not matched with votes of discomfort and unacceptability of the thermal conditions. Therefore, the range of comfortable thermal conditions was investigated among the sensation votes classified as “slightly cool” (-1), “neutral” (0) and “slightly warm” (1), “slightly low” (-1), “neither high or low” (0) and “slightly high” (1), “slightly acceptable” (1), “acceptable” (2) and “very acceptable” (3), the comfort votes classified as “comfortable” (1), “very comfortable” (2) and “extremely comfortable” (3) and the preference votes classified as “without change” (0) and their combinations. As it is illustrated in Figures 4.61a-c, votes of both comfort and content, which represented very low percentages (2.46-23.56%) of votes, corresponded to median $T_{op.(spot)}$ values from 29.04 to 29.59 ^{o}C in Sep.2016 and between 30.57 and 30.92 ^{o}C in Mar.Apr.2017, to median $R.H._{(spot)}$ values from 75.69 to 76.10% in Sep.2016 and between 65.17 and 66.16% in Mar.Apr.2017 and to median $W.S._{(spot)}$ values from 0.41 to 0.55 m/s in Sep.2016 and between 0.42 and 0.57 m/s in Mar.Apr.2017. Patients expressed the lowest tolerance levels both in Sep.2016 and in Mar.Apr.2017 with respect to indoor temperature and airflow levels (Figures 4.61a-c). Votes of comfort and content cover a wide range of thermal conditions, with their percentages peaking at different levels despite the low heterogeneity of the indoor thermal environments (Figures 4.62a-c). Results are showing that only in Mar.Apr.2017 at the 30.00-30.99^{o}C rank of the $T_{op.(spot)}$ values and the 61.00-70.00% rank of the $R.H._{(spot)}$ values, the highest percentages of content with thermal conditions were matched with the highest percentages of acceptability of the indoor airflows across all three occupant types (Figures 4.62a-c). This indicates the differentiation between nurses, patients, and visitors in their needs of exposure to diverse levels of indoor airflows at different levels of indoor temperature and relative humidity. Nurses were more likely to be exposed more frequently both to comfortable thermal conditions and acceptable indoor airflows with indoor airflows around them demonstrating the highest consistency with their thermal comfort needs at different ranks of $T_{op.(spot)}$ and $R.H._{(spot)}$ values (Figures 4.62a-b).

The interviewees (0.07%, 48/730), who reported thermal comfort votes corresponding to thermal conditions that were outliers, were not excluded from the final dataset's analysis following the confirmation that these interviewees have not misunderstood the relevant questions (Figures 4.63a-c). No evident patterns were found in their personal characteristics and their locations' spatial attributes (Figure 4.63d). In Sep.2016, median $T_{op.(spot)(com)}$(^oC) reported by patients with trauma and orthopaedic injuries, with hypertension and cardiovascular diseases and cancers were higher by 1.5^{o}C, while median $T_{op.(spot)(com)}$(^oC) reported by patients with amputations were lower by 1.0^{o}C (Figure 4.64a). However, no significant differences were evident regarding comfortable relative humidity values between patients with diverse medical conditions (Figure 4.64a). Median $W.S._{op.(spot)(com)}$(m/s) lower by 0.2 m/s were reported by patients with lung diseases in Sep.2016, and higher by 0.2 m/s were reported by patients with skin infections in Mar.Apr.2017 (Figure 4.64a). Exploring the range of the median values of the comfortable thermal conditions among groups of participants whose votes displayed very strong, strong, and moderate correlations with spatial and temporal conditions, personal factors and adaptive behaviours, no significant deviations were found (Figure 4.64b).

4.6.4.1.2 Reported Comfortable Thermal Conditions Defined by Regression

According to the intersection points between the two probit curves of the A.T.P.Vs. for warmer and for cooler temperatures, acceptable $Top._{(spot)}$ values in Sep.2016 stood at 30.38^{o}C corresponding to 57.50% of the nurses' A.T.P.Vs., 29.12^{o}C corresponding to 27.50% of the patients' A.T.P.Vs., and 29.13^{o}C corresponding to 15.00% of the visitors' A.T.P.Vs. (Figure 4.65.1a). Proportions as high as 80% of A.T.P.Vs. for warmer temperatures corresponded to $Top._{(spot)}$ values that stood at 29.35^{o}C among nurses and 27.38^{o}C among patients, while 80% of A.T.P.Vs. for cooler temperatures stood at 31.15^{o}C among nurses, 30.63^{o}C among patients and at 32.35^{o}C among visitors (Figure 4.65.1a). In Mar.Apr.2017, acceptable $Top._{(spot)}$ values, which represented the intersection points between the two probit curves of the A.T.P.Vs. for warmer and for cooler temperatures, stood at 29.38^{o}C (10.45% of their A.T.P.Vs.) among nurses, at 29.00^{o}C (24.50% of their A.T.P.Vs.) among patients, and at 28.20^{o}C (11.20% f their A.T.P.Vs.) among visitors (Figure 4.65.1b). Proportions as high as 80% of A.T.P.Vs. for cooler temperatures stood at 31.63^{o}C among nurses, 31.88^{o}C among patients, and 32.00^{o}C among visitors (Figure 4.65.1b). According to the results of probit regression models, in Sep.2016, acceptable $R.H._{(spot)}$ values stood at 66.25% among nurses representing 41.00% of their A.R.H.P.Vs., 69.75% among patients representing 35.60% of their A.R.H.P.Vs., and 67.50% among visitors representing 32.00% of their A.R.H.P.Vs. (Figure 4.65.2a). In Mar.Apr.2017, acceptable

R.H.$_{(spot)}$ values stood at 71.25% among nurses accounting for 21.25% of their A.R.H.P.Vs., at 71.45% among patients accounting for 29.50% of their A.R.H.P.Vs., and at 71.50% among visitors accounting for 29.50% of their A.R.H.P.Vs. (Figure 4.65.2b). The wind speed value of 0.9m/s corresponded to A.W.S.P.Vs. for "more air" linked with A.W.S.A.Vs. expressing acceptability among 77.00% of nurses and 100% of visitors and 50.00% of patients (Figure 4.65.3).

A.T.P.Vs. for cooler temperatures paired with A.T.S.Vs. in the categories of "warm" and "hot" was linked with $T_{op.(spot)}$ values of 31.13^{o}C representing 41.00% of nurses and with $T_{op.(spot)}$ values of 30.00^{o}C representing 26.00% of visitors (Figure 4.66.1). Overall 80% of participants reported A.T.P.Vs. for cooler temperatures that were paired with A.T.S.Vs. in the categories of "neutral" and "slightly warm" at 28.90^{o}C among nurses, 27.60^{o}C among patients, and 28.10^{o}C among visitors, while A.T.P.Vs. for cooler temperatures representing 80% of the participants and being linked with A.T.S.Vs. in the categories of "slightly warm", "warm" and "hot" corresponded to $T_{op.(spot)}$ values of 32.38^{o}C among nurses, 31.85^{o}C among patients, and 32.72^{o}C among visitors (Figure 4.66.1). According to the results of probit regression, A.R.H.C.Vs. expressing discomfort paired with A.R.H.S.Vs. in the categories of "neutral" and "slightly high" corresponded to the R.H.$_{(spot)}$ value of 68.75% representing 42.50% of the nurses, the R.H.$_{(spot)}$ value of 66.25% representing 43.00% of the patients and the R.H.$_{(spot)}$ value of 66.25% representing 43.00% of the visitors. Furthermore, 43% of nurses, patients and visitors reported A.R.H.C.Vs. expressing discomfort linked with A.R.H.S.Vs. in the categories of "slightly high", "high", and "very high" at the R.H.$_{(spot)}$ values that stood at 73.75% among nurses and patients and at 74.90% among visitors (Figure 4.66.2).

The investigation of the impact of indoor and outdoor environmental conditions, which were grouped into bins, on temperature-related thermal comfort votes through simple linear regression showed the following. Only A.T.P.Vs. had statistically significant but weak and moderate associations with outdoor environmental conditions, with nurses expressing preferences for cooler indoor temperatures with rising T.A.$_{ext.(S1)}$ values (coefficient=0.12, R^2=0.29, p-value<0.01) and with patients expressing preferences for warmer indoor temperatures with rising R.H.$_{ext.(S1)}$ values (coefficient=0.14, R^2=0.49, p-value<0.01) (Figures 4.67a-b). R.H.$_{(spot)}$ values had stronger influence on the change of A.T.S.Vs., than the $T_{op.(spot)}$ values, with the most severe impact being recorded around nurses (coefficient=0.68, R^2=0.97, p-value<0.001)(Figures 4.67a-b). Furthermore, although $T_{op.(spot)}$ values did not affect the change of the A.T.P.Vs., R.H.$_{(spot)}$ values were predictors of the A.T.P.Vs.. with the A.T.P.Vs. reported by nurses displaying the strongest and steepest linear relationship with

$R.H._{(spot)}$ values (coefficient=0.41, R^2=0.83, p-value=0.001) (Figures 4.67a-b). A.T.C.Vs. had statistically significant linear correlations with the $T_{op.(spot)}$ values across all types of occupants and with the $W.S._{(spot)}$ values only among patients with comfort votes being linked with lower $T_{op.(spot)}$ values and higher $W.S._{(spot)}$ values (coefficient=0.29, R^2=0.66, p-value<0.001) (Figures 4.67a-b). Diagnostics of linear regression between the examined pairs of variables showed the absence of multicollinearity among all of them, however linear association was not the best fit for all the examined models (Figure 4.67c).

The multiple logistic regression analysis was conducted to estimate the probability of reporting a vote of discomfort due to ”warm” (2) and “hot” (3) sensation votes followed by a preference vote for much cooler (-3), cooler (-2) and slightly cooler (-1) thermal conditions (A.Discom.Warm.Sen.) or a vote of discomfort due to sensation votes of “high” (2) and “very high” levels of moisture in the air followed by a preference vote for much less humid (-3) and less humid (1) (A.Discom.Humid.Sen. in relation to the $Top._{(spot)}$, the $R.H._{(spot)}$ and the $W.S._{(spot)}$ values that were applied as first predictors in the multi-predictor models consisting of the spatial and temporal conditions, the personal factors and the adaptive behaviours that had very strong and strong effect sizes in the reported thermal comfort votes in the separate samples of nurses, patients and visitors. Multicollinearity was not detected between the independent categorical variables that comprised the multi-predictor logistic models (Figure 4.68a). Figure 4.68b presents the logit coefficients, the standard errors, and the odds ratios for the two-predictor model (Model 1) and for the full model (Model 4). Only in the sample of nurses indoor airflows had a statistically significant protective effect to thermal discomfort caused by both higher $T_{op.(spot)}$ values (odds ratio=0.23, p-value=0.01) and $R.H._{(spot)}$ values (0.05, p-value=0.001) (Figure 4.68b). The higher level of sensitivity to temperature-related discomfort with rising $T_{op.(spot)}$ values among patients is reflected in the odds ratio (7.02, p-value<0.001) that is approximately 1.3 times higher than that reported by nurses (5.49, p-value<0.001) and two times higher than that reported by visitors (3.95, p-value<0.001). Significantly lower differences were found in the odds ratios of discomfort with higher indoor relative humidity levels between nurses (1.37, p<0.001), patients (1.26, p-value<0.01) and visitors (1.19, p-value<0.001).

The mitigative impact of $R.H._{(spot)}$ values to rising temperature-related discomfort was low (odds ratio 0.91-0.92, p-value<0.001) and statistically significant only in the separate samples of nurses and visitors. By contrast, the mitigative impact of $T_{op.(spot)}$ values to relative-humidity-related discomfort was also higher (odds ratio=0.57, p-value=0.001) but statistically significant only in the sample of nurses (Figure 4.68b). The inclusion of spatial and temporal conditions in the two-predictor model with the $R.H._{(spot)}$ values as an independent variable had a significant improvement in the in the sample of nurses with dependent variable the temperature-related discomfort (Cragg-Uhler/Nagelkerke R^2 rose from 0.14 to 0.21) and in the sample of patients with dependent variable the relative-humidity discomfort (Cragg-Uhler/ Nagelkerke R2 rose from 0.19 to 0.31) with the odds ratio among patients increasing by 6 times. Furthermore, in the sample of patients, the inclusion of adaptive behaviours with the relative humidity-related discomfort as the dependent variable and the $R.H._{(spot)}$ values as the first predictor had a significantly better fit Cragg-Uhler/Nagelkerke R^2 increasing from 0.19 in the two-predictor model to 0.63 in the final full model (Figure 4.68b). The adaptive behaviours of rehydration, eating and operation of doors and windows had a slight mitigative impact (Figure 4.68b).

4.6.4.2 Modelled Range of Comfortable Thermal Conditions

4.6.4.2.1 Modelled Range of Comfortable Thermal Conditions Defined by the ASHRAE 55:2013 Thermal Comfort Indexes and the Griffins Models

In Sep.2016, percentages of occupants with clothing insulation values higher than 1.50clo, which is the applicability limit for the ASHRAE 55:2013 standard, stood among patients at 12.50% in W2, 12.50% in W3, and 26.67% in W6 (Figure 4.69.1). Whereas the metabolic rates among nurses and visitors exceeding the applicability thresholds for the ASHRAE 55:2013 standard stood at 8.70% in W2 (among nurses) and at 6.25% in W9 (among visitors), percentages of patients with metabolic rates lower than the 1.00 met threshold remained high varying from 62.50% to 100% (Figure 4.69.2). Similarly, in Mar.Apr.2017, percentages of patients with metabolic rates lower than 1.00met ranged between 58.62% and 100% in W2, W3, W6, W7, W9, T.U. and F.A. (Figure 4.69.2). Overall, in Sep.2016, the percentages of questionnaires that complied with the applicability thresholds of the ASHRAE 55:2013 standard varied from 2.63% to 33.33% in all selected wards, except W7, which had no valid questionnaire while in Mar.Apr.2017, only 9.64% of the T.C.Is. in W2 and 4.55% of the T.C.Is. in W3 complied with the applicability principles for the ASHRAE 55: 2013 standard (Figure 4.69.3).

During both Sep.2016 and Mar.Apr.2017 adaptation among all occupant types to higher indoor temperatures was underrated while intolerance to lower temperatures was overlooked with the median $T_{op.(spot)}$ values corresponding to PMV (ASHRAE 55: 2013) values from -1 to 1 being found lower by approximately 0.5^{o}C than the reported $T_{op.(spot)(com)}$(^{o}C) (Figure 4.70a). However, their range was similar to the $T_{op.(spot)(com)}$(^{o}C) (Figure 4.70a). Comparing the distributions of the reported and the modelled comfortable $T_{op.(spot)}$ values, it is evident that the greatest deviations occurred in the sample of patients in Sep.2016 (Figure 4.70b). Exploring the associations between the mean A.T.S.Vs. per 0.2^{o}C interval and the $T_{op.(spot)}$ values and the links between the mean PMVs (ASHRAE 55:2013) per 0.2^{o}C interval and the $T_{op.(spot)}$ values in linear regression models, as it is illustrated in the steepness of the fitted lines, the rate of change in the reported sensation votes per unit rise in the indoor operative temperatures was significantly underestimated in the PMVs models by approximately three times in Sep.2016 and two times in Mar.Apr.2017 (Figures 4.70.c1-2). Comfortable $T_{op.(spot)}$ values ($T_{op.(spot)(Grif.0.25)}$, $T_{op.(spot)(Grif.0.33)}$ and $T_{op.(spot)(Grif.0.50)}$) calculated according to Griffins models, which were developed as a function of the temperature-related sensation votes reported by occupants, displayed wider range and dispersion with more extreme minimum and maximum values and higher median values by comparison to the $T_{op.(spot)(com)}$ values (Figures 4.71.a1-2). The relationships between the reported and modelled comfort votes (calculated according to Griffins models) grouped per 1^{o}C intervals with the $T_{op.(spot)}$ values were better represented with models of quadratic regression displaying R^2 values higher than 0.50. Although these models captured the discomfort caused by temperatures at the lower and at the higher ranks, they underestimated the responsiveness of experienced thermal distress illustrating more gradual changes in the perception of discomfort per unit change in the $T_{op.(spot)}$ values (Figures 4.71.b1-2).

4.6.4.3 Discussion about the Reported and the Modelled Range of Comfortable Thermal Conditions

As it was illustrated in the inconsistencies between votes of sensation, comfort and acceptability reported by the same participant, the range of thermal conditions that do not cause discomfort can be better represented through the matching of recorded physical measurements with a variable that combines the relevant categories of sensation, comfort and preference votes in one variable. This range of comfortable and acceptable thermal conditions at the case-study wards at Connaught Hospital was defined by median $T_{op.(spot)}$ values between 29.00 and 31.00 ^{o}C, median $R.H._{(spot)}$ values from 65.00 to 76.00% and median $W.S._{(spot)}$ values between 0.41 and 0.55 m/s. Higher sensitivity in thermal discomfort was found during seasons with more extreme thermal conditions in hospital spaces in the Netherlands (Derks, et al., 2018) and in hospital spaces in Iran (Pourshaghaghy, et al., 2012). As several studies have shown, tolerance to higher temperatures increases at lower humidity levels and higher airflows (Cândido, et al., 2011). Higher tolerance to higher $T_{op.(spot}$ values during the rainy season was indicated by the acceptable $T_{op.(spot)}$ values, which were found as the intersection points between the two probit curves of the A.T.P.Vs. expressing preferences for warmer and for cooler $T_{op.(spot)}$ values in the separate samples of nurses, patients and visitors, with nurses expressing the lowest sensitivity to higher $T_{op.(spot)}$ values in both Sep.2016 and Mar.Apr.2017. Acceptable $T_{op.(spot}$ values stood between 29.12 and 30.38^oC in Sep.2016 and from 28.20 to 29.38 ^oC corresponding to percentages of votes that stood below 50%. As regards the acceptable $R.H._{(spot)}$ values being taken as an intersection point between the two probit curves for A.R.H.P.Vs. for higher and for lower $R.H._{(spot)}$ values, lower levels of tolerance in higher $R.H._{(spot)}$ values were found in Sep.2016 than in Mar.Apr.2017, with nurses expressing the highest sensitivity and visitors expressing the highest tolerance. Acceptable $R.H._{(spot)}$ values stood in the 66.25-69.25% range in Sep.2016 and in the region between 71.25 and 71.50% in Mar.Apr.2017 corresponding to A.R.H.P.Vs. representing percentages lower than 41.00%.

Although adaptive thermal comfort in naturally ventilated spaces is considered a function of outdoor temperatures, in highly overheated and humid naturally ventilated clinical spaces, outdoor temperatures might be a weak predictor of the experienced thermal discomfort as it is indicated by the linear regression models between the reported temperature-related votes and the recorded $T.A._{ext.(S1)}$ and $R.H._{ext.(S1)}$ values. Context-specific thermal comfort models can estimate with greater accuracy the expected thermal discomfort, especially in hot-humid clinical settings. Comparisons between reported thermal comfort and modelled thermal comfort (PMVs estimated according to ASHRAE 55:2013 and Griffins models), although thermal discomfort was overestimated, the sensitivity of thermal distress to rinsing indoor temperatures was underestimated. The calculated PMVs (ASHRAE 55:2013) displayed the most significant deviations from the reported sensation votes during the rainy season, indicating its limited applicability in very humid indoor environments while PMVs modelled according to ASHRAE 55:2013 and Griffins models displayed the highest deviations from reported thermal comfort among patients.

The wind speed value of 0.9m/s corresponded to A.W.S.P.Vs. for “more air” linked with A.W.S.A.Vs. expressing acceptability across all occupant types. However, reported acceptability of indoor airflows at different levels of indoor temperature and relative humidity differed between nurses, visitors and patients, with nurses being most consistently exposed to airflows that matched their needs across diverse levels of both $T_{op.(spot)}$ and $R.H._{(spot)}$ values. The influence of different physical variables of the indoor environment on temperature-related comfort might vary between occupant types. In the case-study wards, whereas temperature-related comfort votes were linked in linear regression models with $T_{op.(spot)}$ values among all occupant types ($0.44<R^2<0.72$, p-value<0.001), the impact of indoor airflows found to be more critical only around patients (R^2= 0.66, p-value=0.001). In contrast indoor relative humidity levels might be a more critical modifier of temperature-related preference votes than indoor temperature levels across all occupants. These are indications that temperature-related discomfort can be more drastically improved through interventions that can increase indoor airflows while reducing indoor levels of moisture in the air, thus achieving a synergetic impact on thermal comfort and airborne infection control.

This intervention might be of vital importance for improving patients' thermal comfort in hot and humid hospital wards without ventilation systems that are tailored to occupant needs. In the case-study wards only in the sample of patients, the $W.S._{(spot)}$ values were a statistically insignificant predictor of reported thermal comfort in logistic regression models. This is an indication that ambient airflows had no impact on the amelioration of thermal discomfort around patients. At the same time, patients were more sensitive to rising indoor temperatures by 1.3 times more than nurses and by two times more than visitors. However, in these logistic regression models, differences between occupant types regarding their sensitivity to thermal discomfort caused by rising relative humidity values were minor. Therefore, interventions that prioritise the differentiation between occupant types with respect to their exposure to indoor temperatures, relative humidity and airflows is very critical. Furthermore, attention needs to be paid to the removal of localised sources of excess moisture around patients. Moreover, the allocation of patients far away from window areas with operable windows that are left open over long periods, especially in modern wards, which lack the climate-responsive characteristics of the tropical Nightingale ward, can reduce thermal discomfort caused by high indoor relative humidity levels by six times.

4.6.5 Conclusions

Overall, in hot-humid clinical spaces like the case-study wards at Connaught Hospital is essential to mitigate thermal discomfort to rising indoor temperatures during the dry season and to rising indoor relative humidity levels during the rainy season and low levels of indoor airflows during both seasons. Differentiations in the thermal performance between diverse building typologies, especially regarding patients' exposure to indoor airflows, might be critical. The expected climate responsiveness of historical healthcare buildings with a pavilion-plan typology might fail to perform the required thermal performance; thus, failing to protect from both thermal distress and airborne infection risks their most vulnerable occupant types, namely the patients. Reported thermal comfort is likely to be defined by lower tolerance levels to elevated temperatures during the warm season and higher relative humidity levels during the rainy season with varying sensitivity levels between occupant types. In the case-study wards, thermal comfort was defined by median $T_{op.(spot)}$ values between 29.00 and 31.00 ^{o}C, by median R.H.$_{(spot)}$ values from 65.00 to 76.00%, and by median W.S.$_{(spot)}$ values between 0.41 and 0.55 m/s with acceptable thermal conditions, which were defined through ordinal probit regression, standing between 28.20 and 29.38^{o}C in Mar.Apr.2017, from 66.25 to 67.50% in Sep.2016 and at 0.90 m/s during both seasons. The application of PMV (ASHRAE 55:2013) and Griffins model might result in lower comfortable temperatures while underestimating occupants' sensitivity to rising temperatures and completely overlooking different tolerance thresholds between nurses, patients, and visitors.

"Tailored" interventions that become more critical in naturally ventilated wards where instability characterises the dispersion of the indoor thermal conditions resulting in a higher risk of thermal distress experiences, which might disproportionately affect the occupant types with the highest levels of vulnerability to thermal discomfort. Sensation votes need to be paired with comfort votes and with preference votes (reported by the same participant) to validate the comfort and acceptability of the thermal conditions. This might also help to avoid any unexpected sociocultural-driven linguistic wrong interpretations of the thermal comfort response scales. It is important to include questions about sensation, comfort, and preference votes. Although they might be interlinked, the strength and direction of their associations between diverse occupant types might differ. As the findings indicate, high levels of acclimatisation demonstrated in the sensation votes might not reflect the actual levels of experienced discomfort and aspired changes.

These "tailored" interventions need to be informed by context-specific understandings of human thermal adaptability beyond the quantitative determination of the range of comfortable thermal conditions to include socio-culturally driven behavioural aspects. It is likely that in hot-humid clinical spaces with limited resources, occupants are aware of possible adaptive actions to restore thermal comfort. However, reported awareness of adaptive behaviours needs to be validated through empirical evidence and modelling to determine the most realistic adaptive actions and design occupant-centric interventions to extend adaptive capacity in ways that respond to occupants' aspirations. In the case-study wards, nurses, patients, and visitors expressed great willingness to adapt their exposure, thermoregulation mechanisms and interact with the existing environmental controls. However, comparisons between reported and observed individual adaptive behaviours showed that nurses drank water, visitors moved to cooler places, and asked for help while actions to restore patients' thermal comfort were an integral part of nursing care. Although opportunities for interaction with existing controls in close distance occurred to all occupant types, only nurses directed the operation of building controls. This evidence suggests that occupant adaptive capacity in thermal environments like Connaught Hospital can be significantly strengthened by training climate-responsive behaviours supported by real-time environmental monitoring, integration of adaptive behaviours with nursing practices, the provision of cool water and accessibility to cool outdoor places. More specifically, patients' content with thermal conditions can double through ward allocation, water and food provision and operation of building controls at an individual level.

In hospital wards, where thermal comfort needs among occupants significantly differ while their physiological and behavioural capacity for thermal adaptability is determined by their health status and their role in a strictly regulated clinical environment, extreme thermal comfort responses can be expected by all types of occupants; hence thermal comfort responses classified as outliers cannot be overlooked. These extreme responses are an indication that thermal comfort needs can very often deviate from permitted opportunities for the restoration of thermal comfort in environments where restricted thermal adaptability comprise a core element for the safe operation of these environments. Consequently, in these settings, extending the adaptive capacity in different ways between each occupant types while maximising these interventions' synergetic impact for optimal thermal comfort and infection controls is of vital importance. The finding from the field survey at Connaught Hospital shows that temperature-related discomfort can be more drastically improved through interventions that can increase indoor airflows while reducing indoor moisture levels in the air. This can be achieved through the removal of localised sources of excess moisture around patients and the allocation of patients far away from window areas with operable windows that are left open over long periods especially in modern wards, which lack the climate responsive characteristics of the tropical Nightingale ward, and the integration of the control of doors in climate-responsive schedules for the operation of the components in systems of natural ventilation.

Chapter 5

Conclusion

5.1 Drivers and Expectations

In Sierra Leone, no legislative framework exists that defines the acceptable environmental conditions in domestic and non-domestic buildings, including hospitals. Furthermore, recommendations about the thermal conditions in naturally ventilated inpatient hospital facilities in hot-humid settings have been overlooked by all existing international standards, while overheating criteria for naturally ventilated hospital spaces exist only for those located across the temperate zones. Moreover, existing acceptable ventilation rates for naturally ventilated hospital wards do not integrate the dynamics links between the risk of infection and changes in environmental variants, occupancy frequencies and occupant activities. The assessment of the thermal environmental performance in naturally ventilated inpatient facilities in hot-humid settings becomes more challenging by the lack of any previous overheating assessment of naturally ventilated and occupied inpatients facilities in both new and historical buildings, where on-site environmental monitoring was applied. Hospitalised patients have been excluded from all thermal comfort surveys, which combine both physical and subjective measurements, in naturally ventilated hospital spaces across the equatorial zone, while thermal comfort surveys in hospital spaces across the equatorial zone lack functional diversity of both inpatient and outpatient facilities.

Drawing on a case-study and mixed-methods approach conducted just six months after the end of the 2014-16 Ebola epidemic, in the course of nine weeks of fieldwork at Freetown's Connaught Hospital in Sierra Leone, this project explored for the first time, in eight operational and naturally ventilated multi-patient wards in a hot-humid setting with limited resources, the impact of occupancy and operational schedules, adaptive actions, personal factors and the building's envelope thermal performance on indoor thermal conditions, the thermal comfort, and occupant adaptive behaviours. Special attention was paid to the selection of the case-study, the design of the mixed-methods approach and the sampling strategies to extend the applicability of the findings, which are integrated in set of recommendations for the extension of the cooling capacity of natural ventilation, to other hospital spaces in hot-humid settings with limited resources. Freetown's Connaught Hospital was a critical case study because it is the largest tertiary government hospital that provides healthcare indiscriminately to a very high number of patients per year in the country.

Furthermore, Connaught Hospital is in a historic site and consists in a complex of buildings built consecutively between the 1920s and the 2000s, including a pavilion-plan building, which is composed of eight Nightingale wards. The cohort of the eight case-study wards was a critical sample representing differing levels of climate modification through passive engineering designs at wards of diverse ages, layouts, orientations and locations, functions, operational schedules, and occupancies with four of them located at the pavilion-plan building. A standardised protocol, which determined the mixed-method data collection processes, was co-designed with the head nurses and doctors. In this way potential conflicts between scientifically approved recording procedures of environmental and behavioural parameters and infection control and nursing schedules were eliminated. Participation in the semi-structured and thermal comfort interviews (T.C.Is.) was voluntary and was limited only to people aged 18 and over with the capacity to give consent. At the same time, diverse biases caused by the presence of the author (such as, social desirability bias) were identified during the pilot processes and controlled with the help of the research assistants.

5.2 Recommendations

This set of recommendations can help architects, engineers and clinicians interested in extending the cooling capacity of natural ventilation in multi-patient wards in hot-humid settings with limited resources. Design, operational and behavioural interventions and advice about thermodynamic modelling and design of thermal comfort surveys comprise the following set of recommendations.

Design interventions

- In hospital spaces with hot-humid setting and restrained resources, occupant-centric design interventions for the mitigation of thermal discomfort need to be driven by resolving the expected experienced discontent with high levels of indoor relative humidity during the rainy season, elevated indoor temperature during the dry season and low levels of indoor airflows during both seasons. Interventions that consider seasonal variability are expected to have a substantial impact on the amelioration of thermal discomfort caused by indoor relative humidity (Cramer's V effect size: 0.50-0.65, p-value<0.001), whereas temporal variability between the morning and the evening shift might not influence the most vulnerable occupant types, namely the nurses and the patients (chi2 p-value>0.05).
- Priority should be given to interventions that can reduce temperature-related discomfort among patients. In this way, the highest level of sensitivity to temperature-related discomfort with rising $T_{op. (spot)}$ values among patients can be addressed. In the case-study wards, this sensitivity was reflected in the odds ratio (7.02, p-value<0.001) that was

approximately 1.3 times higher than that reported by nurses (5.49, p-value<0.001) and two times higher than that reported by visitors (3.95, p-value<0.001). In particular, the rise of indoor airflows around patients can increase temperature-related comfort. Temperature-related comfort votes (A.T.C.Vs.) reported by patients were strongly affected by the variation of their wind-speed related sensation votes (A.W.S.S.Vs.) (Cramer's V effect size: 0.55, p-value<0.001). Furthermore, in the case-study wards, whereas temperature-related comfort votes were linked in linear regression models with lower $T_{op.\ (spot)}$ values among nurses and visitors ($0.44<R^2<0.72$, p-value<0.001), the impact of indoor airflows was found to be more critical only around patients ($R^2= 0.66$, p-value=0.001), with higher levels of temperature related comfort being correlated with higher indoor airflows

- Strengthening indoor airflows around patients can be achieved by providing personal fans. Permitting patients to use these fans might reduce experienced thermal discomfort by a half (Cramer's V effect size: 0.50-0.69, p-value<0.001). The addition of fans will extend indoor airflows' impact on indoor temperatures and indoor relative humidity levels during both the dry and the rainy seasons. In the case-study wards, through statistical methods for time-series regression of stationary variables, only the $T_{op\ (spot)}$ values around nurses in Mar.Apr.2017 and the $R.H._{(spot)}$ values around patients in Mar.Apr.2017 displayed statistically significant associations with the recorded $W.S._{(spot)}$ values; however, they both were autocorrelated with the $W.S._{(spot)}$ values. Furthermore, differentiation of patients' exposure to thermal conditions ($T_{op.(spot)}$, $R.H._{(spot)}$ and $W.S._{(spot)}$) between buildings of diverse typologies and levels of climate-responsiveness can be eliminated. In the collected sample, variation in patients' exposure to indoor airflows between the Pavilion building and the rest of the case-study buildings was not statistically significant (Wilcoxon rank-sum tests p-value>0.05) by comparison to the exposure experienced by nurses and visitors (Wilcoxon rank-sum tests p-value<0.01).
- Installation of environmental monitoring equipment for the real-time provision of visual evidence about the outdoor and indoor environmental changes can transform the high levels of awareness of behavioural thermal adaptability to actions for the restoration of thermal comfort. In case of financial constraints, priority should be given to the installation of indoor monitoring equipment. In the case-study wards, despite the statistically insignificant correlation with outdoor temperature and relative humidity levels, occupant-controlled widow operation displayed during the rainy season weak correlations with rising indoor temperature (0.13<Spearman coefficient<0.19, p-value<0.01) and falling indoor relative humidity values (Spearman coefficient=-0.14, p-value<0.01).

- Obstructions in the operation of windows need to be identified. Contemporary needs for health and safety and vector control that enforce railings and mosquito nets diminish occupants' ability to control the position of the window openings. Insect screen meshes should be operable in directions opposite to the directions of the window apertures.
- In hospital wards with facades lacking appropriate shading, bedded areas should be allocated far away from the facades. In this way, experienced indoor overheating can be reduced by almost a half during the critical period of night-time over the dry season. In the case-study ward, typologies that lacked optimal design for natural ventilation and protection of the nurse station and the bedded area from extensive direct solar radiation deeper plans were protective against overheating during night-time over the dry season (Spearman coefficient=-0.63, p-value<0.001). In these wards, the allocation of patients far away from window areas with operable windows that are left open over long periods can reduce thermal discomfort caused by high indoor relative humidity levels by six times.
- Providing facilities for cool water and accessibility to cool outdoor places can strengthen adaptive capacity at a personal level among all occupant types.

Operational interventions

- Characteristics of the operational schedules that contribute to indoor overheating need to be identified and changed without harming relationships and activities driven by critical socio-cultural norms. Despite the widely accepted view that in equatorial-monsoonal climates seasonal and diurnal fluctuations are low, in naturally ventilated inpatient spaces in these climates, the responsiveness of the building's envelope and the operation of the environmental controls by the hospital occupants as well as the schedules of the clinical activities and the visiting hours need to be adapted to diverse environmental conditions across seasons and between daytime and night-time. In the case-study wards, the busiest time of the day (11:00 to 14:00), when doctors' and nurses' rounds were scheduled, coincided with high levels of solar exposure (being extended until 16:00) and intense visitors' activities that were affective and had practical significance for the care of patients. In the thermodynamic model of a representative Nightingale ward with an improved environmental performance, the doctors' rounds were transferred earlier during the morning shift (9.00-11:00) and later during the evening shift (18:00-20:00), while visitors' presence was restricted only at the peripheral areas, which were thermally separated from the bedded areas, and without any patient-beds.

- Seriously ill patients, who will require more intense care and are more sensitive to thermal distress, is advisable to be allocated at the wards in existing historical buildings that might display stronger climate-responsive characteristics. In 1864, the British Commission for the Improvement of Barracks and Hospitals (B.H.I.C.), building on Florence Nightingale's extensive work, published a best practice framework for barrack hospitals' design in British India. Although thermal comfort was not Nightingale's primary focus, by conceptualising the ward as an instrument for efficient infection control through natural ventilation, she created a spatial system to maximise climate sensitivity, airflow rates, and nurses' control over the indoor thermal conditions. Patients allocated at tropical Nightingale wards might be expected to be two times more content with indoor humidity and airflows (Cramer's V effect size: 0.50-0.56, $p\text{-value}<0.001$), especially during the rainy season (Cramer's V effect size: 0.50-0.66, p-value). Furthermore, even if the window-opening behaviours among occupants are not responsive to indoor or outdoor changes, in the Nightingale wards, where the capacity for the exploitation of natural ventilation is higher, and the nurse station and the bedded area are better protected from extensive direct solar radiation, higher openable window coverage can reduce 24-hour overheating during the rainy season (Kendall's W test coefficient=-0.60, $p\text{-value}<0.001$) and night-time overheating over the rainy season (Spearman coefficient=-0.34, $p\text{-value}<0.001$).
- General distinctive features of the tropical Nightingale wards are expected to be the allocation of the clinical areas and the nurse station in the central bedded area and the administrative and auxiliary uses in the front wings, and the back wings, along with extensive openable window coverage in the facades towards the prevailing wind directions and the complete protection of the bedded area from direct solar exposure. The case-study Nightingale wards displayed the most optimal combination of spatial attributes for maximization of the natural ventilation performance by comparison to the rest of the case-study wards. In these case-study Nightingale wards, cross-ventilation was further advanced by low width-to-length and width-to-floor-to-ceiling height ratios coupled with high coverages of openable windows.

Behavioural interventions

- Informal nursing practices for the amelioration of thermal discomfort among patients need to be integrated with established guidelines of nursing care and infection control. Timely provision of water and food to patients can decrease patients' thermal discomfort by two times (Cramer's V effect size: 0.50-0.69, p-value<0.001). Furthermore, more attention needs to be paid to the required adaptation of patients' clothing insulation, which is exceptionally high due to the additional insulative impact of the bed-mattress, and to training to improve nurses' ability to make distinctions of fever a symptom of infection and a symptom of heat stress.

- Training regarding climate-responsive operation of windows need to be provided in the nurses of every hospital ward regardless of ward layout and existing building controls. In the case-study wards, window-opening behaviours had weak correlations (Spearman coefficient: -0.24-0.24, p-value<0.001) with the spatial attributes for ventilative cooling that became strong (Spearman coefficient: -0.42, p-value<0.001) only over the dry season when lower percentages of open aperture were linked with higher width-to-floor-to-ceiling height ratios and with higher coverages of openable windows indicating the slightly more responsive window-opening behaviours at the Nightingale wards. Training patients to control windows' operation might increase by two times their acceptability of indoor airflows (Cramer's V effect size: 0.54, p-value<0.001) in diverse ward typologies. Considering the link between higher ventilation rates and more efficient dilution of pollutants, it might be best to leave the windows open even if warm air comes inside. It is suggested that higher humidity levels are associated with higher survival rates of different viruses. It might be best to keep the windows closed or partly open during periods of high outdoor humidity levels.
- Guidance through posters and other types of visual aids regarding actions for the restoration of thermal comfort at an individual level and interaction with building controls need to be provided to the occupants in the wards to exploit potential awareness of adaptive behaviours. Although nurses directed the operation of the existing environmental controls in the case-study wards, opportunities for interaction with existing controls in close distance occurred to all occupant types. This is an indication that the combination of a ward layout that facilitates the operation of building controls equitably among diverse hospital occupants and the education of hospital occupants regarding climate-responsive operation of the building controls is required.

Thermodynamic modelling

- Widely accepted assumptions regarding the occupancy schedules and occupants' activities might contradict context-specific aspects of healthcare delivery. As it was illustrated in the case-study wards, the deduction of the expected intensity and diversity of activities from the number of patient beds might result in the underestimation of the impact of nursing and other activities on internal heat gains and, more importantly, on the potential of natural ventilation to protect against airborne infection through the control of the directions and dispersions of viral air contaminants.

- Door-opening behaviours should be integrated with the operation schedules of the components of natural ventilation systems in hospital wards with hot-humid conditions. Responsive door-opening behaviours can double the acceptability of the indoor thermal conditions among nurses (Cramer's V effect size: 0.51, p-value<0.001).
- Indoor overheating in existing hospital wards, which were not designed according to climate-responsive and passive cooling principles, with hot-humid conditions need to be estimated in relation to outdoor and indoor temperatures. To avoid overestimation of overheating and thus an overestimation of the required cooling load, the low limit of the ASHRAE 55: 2013 model is more suitable only for night-time overheating when required high sleep quality for patients sets the thermal comfort expectations at very high levels. However, models for indoor overheating that integrate the impact of indoor humidity might be a better predictor of experienced heat stress. Although both seasonal variation and differences between daytime and night-time might affect indoor temperature (Wilcoxon Rank Sum Test p-value<0.001), only seasonal variation might introduce statistically significant variation in indoor relative humidity (Wilcoxon Rank Sum Test p-value<0.001).
- Existing historical hospital buildings (built before the 1940s) might require the restoration of their lost embodied capacity for climate-sensitivity and responsiveness due to incomplete realisation of the original ideas and contemporary operational requirements. The case-study Nightingale wards displayed significant deviations from the original ideas as these were reflected in the ward prototype for British India stations and the ward for Europeans at the Singapore General Hospital. These deviations consisted of omitting an open-air veranda around the central bedded area, the insufficient shading of the building envelope, the disconnection between the ceiling and the ventilated roof, the extended airflow distance for cross-ventilation and significantly lower indoor volumetric spaces. During contemporary operation, environmental performance drivers were similar between the selected Nightingale wards and the rest of the case-study wards. All case-study wards lacked adequate shading devices and double-glazed windows, while internal window curtains trapped solar radiation and, by convection, induced higher adjacent air temperatures. At the same time, heat gains by conduction through the heavyweight external and internal walls and by convection through the uninsulated ceilings and floors reduced the potential of nocturnal cooling, contributing to higher night-time overheating. In a representative case-

study Nightingale typology, the geometry of the building's envelope was modified according to the following actions: a) the central bedded area was separated from the peripheral zones with the addition of doors and windows; b) windows were added to the roof perimeter c) the roofs of the peripheral zones were separated from the roof covering the central bedded area; d) roof lights were added in the new roofs of the peripheral area. A set of interventions in the thermal mass, the ventilation and shading design and the operational schedule were applied in a thermodynamic model to reduce the accumulation of internal heat gains through the reduction of the rate and range of heat exchanges between the internal and external surfaces of the fabric, the addition of shading and responsive operation of all openings (doors and windows). Although overheating, which was calculated according to the static threshold of 28°C and the low limit of the ASHRAE 55:2013, was reduced, it was not eliminated.

- Estimation of expected overheated in naturally ventilated wards with hot-humid conditions similar to the case-study wards can be simulated according to the following environmental metrics. According to probit regression of the preference votes, the range of acceptable indoor thermal conditions might be determined by operative temperatures varying between 29.00 and 30.00°C during the rainy season and between 28.00 and 29.00 °C during the dry season, relative humidity levels from 66.00 to 69.00% during the rainy season and around 71.00% during the dry season while acceptable airflows stand at 0.9m/s during both seasons.
- The application of the thermal comfort indexes of the PMVs (ASHRAE 55:2013) and the Griffins models for the estimation of thermal comfort might result in the underestimation to tolerance to higher indoor temperatures and sensitivity to the rise of indoor temperatures, with the impact of these deviations to be higher among patients especially during the rainy season due to the omission of the impact of indoor humidity.

Thermal comfort surveys

- Context-specific qualities of thermal comfort need to be investigated and analysed. The reported thermal sensation votes might not be a good indicator of the perceived comfort and acceptability of the indoor thermal conditions. More specifically, sensation votes within the range from -1.00 to 1.00 that are widely accepted as signs of comfort and acceptability might not be a good indicator. Therefore, sensation votes need to be paired with comfort and preference votes reported by the same participant.

- Although associations might exist between sensation, comfort, and preference votes, deductions between the different types of thermal comfort votes should be avoided as they might result in negligence of critical differences between the occupant types. In the analysed sample, although temperature-related preference votes were strong indicators of the temperature-related sensation and comfort votes (Cramer's V effect size: 0.51-0.60, p-value<0.001), the direction of their effect was different among nurses, patients, and visitors.

5.3 Limitations and Further Research

The allocation of only one data logger per ward at or close to the nurse station and the recording of the occupancy frequencies, occupants' activities and the state of the windows' openings in a non-digital way and the recording of the indoor airflows ($W.S._{(in)}$)over shorter periods than the recording of the indoor temperatures ($T.A._{(in)}$) and indoor relative humidity values ($R.H._{(in)}$) limited the quantity and representativeness of the collected data. Further research can involve the identification of the links between occupancy frequencies and the intensity and diversity of the occupants' activities, especially in those settings where visitors' presence in the ward has an affective and practical significance for the care of patients. Understanding of occupant-control window operation in clinical settings can be advanced through the exploration of the socio-culturally driven dynamics that influence window-opening behaviours. Furthermore, causal associations and probabilistic risks between the thermal comfort votes and seasonal, temporal, spatial and environmental conditions, the participants' individual characteristics, adaptive behaviours and satisfaction levels with existing environmental controls can be further explored through the application of more advanced statistical non-parametric approaches.

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