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INDOOR AIR MOVEMENT ACCEPTABILITY AND THERMAL COMFORT IN HOT-HUMID CLIMATES

(ACEITABILIDADE DO MOVIMENTO DO AR E CONFORTO TÉRMICO EM CLIMAS QUENTES E ÚMIDOS)

Tese submetida à Universidade Federal de Santa Catarina como requisito parcial exigido pelo Programa de Pós-Graduação em Engenharia Civil – PPGEC, para a obtenção do Título de DOUTOR em Engenharia Civil.

CHRISTHINA MARIA CÂNDIDO

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Tese julgada adequada para a obtenção do Título de DOUTOR em Engenharia Civil e aprovada em sua forma final pelo Programa de Pós-Graduação em Engenharia Civil – PPGEC da Universidade Federal de Santa Catarina.

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To Leonardo Bittencourt, my mentor and dear friend, and all members of Geca/UFAL. I take what I’ve learned from you everywhere.

Resumo

Tradicionalmente, a velocidade do ar tem sido enquadrada em termos de limites máximos admissíveis, a fim de se evitar desconforto dos usuários por correntes de ar (i.e. *draft*). Inúmeros autores têm proposto valores para a velocidade do ar tida como aceitável, variando de 0,50 a 2,50 m/s, sendo 0,80m/s considerada como a máxima permitida pela ASHRAE 55-2004. Em climas quentes e úmidos, no entanto, é provável que valores mais elevados sejam preferidos pelos ocupantes. Este projeto visa compreender a relevância e a aplicabilidade dos limites máximos para a a velocidade do ar, focando no conforto térmico dos ocupantes em edifícios ventilados naturalmente em climas quentes e úmidos. A metodologia se baseia em experimentos de campo, com medições das variáveis microclimáticas realizadas simultaneamente ao preenchimento de questionários pelos usuários. Duas campanhas foram desenvolvidas em faculdades de arquitetura em Maceió, localizada no nordeste brasileiro, durante o ‘inverno’ (Ago/Set) e verão (Fev/Mar), resultando em 2.075 questionários. A velocidade do ar foi investigada focando em dois valores de aceitabilidade do movimento do ar: 80 e 90%. As velocidades do ar *mínimas* encontradas para tal aceitabilidade foram próximas ou acima dos 0,80m/s determinado pela ASHRAE 55-2004. Os usuários apresentaram diferenças significativas na preferência e aceitabilidade do movimento do ar dependendo do seu historico térmico de exposição à ar-condicionado. Os resultados também indicaram que o incremento do movimento do ar definitivamente assume grande importância, sendo a aceitabilidade térmica insuficiente para investigar a satisfação dos usuários. Combinar a aceitabilidade do movimento do ar e térmica se constitui em desafio a ser enfrentado em climas quentes e úmidos. Por fim, este projeto sugere um conjunto de orientações para futuras normas em edificações naturalmente ventiladas no Brasil, considerando o incremento do movimento do ar como bemvindo para o conforto térmicos dos usuários em climas quentes e úmidos.

Palavras-chave: aceitabilidade do movimento do ar, conforto térmico, modelo adaptativo, climas quentes e úmidos, historico térmico.

Abstract

Traditionally, air velocity has been framed in terms of *maximum* permissible limits in order to avoid occupants' complaints due to 'draft'. Numerous authors have proposed a variety of maximum acceptable indoor air velocity, ranging from 0.5 to 2.5m/s, and 0.8m/s has been deemed as maximum allowable air velocity by ASHRAE 55-2004. In hot humid climates, however, it is likely that higher air velocity values would be preferred by occupants. This project aims to understand the relevance and applicability of maximum air velocity limits, focusing on occupant's thermal comfort, preference and acceptability, within naturally ventilated buildings. The methodological approach focuses on field research design, based on the proximity, in time and space, of the indoor climate observations with corresponding comfort questionnaire responses from the occupants. The two field experiment campaigns took place in naturally ventilated buildings in Maceio, located at the north-east hot-humid zone of Brazil, during the cool (Aug/Sep) and also hot seasons (Feb/Mar), resulting in 2075 questionnaires. Air movement was investigated based on two goals for acceptability: 80 and 90%. Minimal air velocities values obtained based on this analysis were close to, or above 0.8m/s, which is currently mandated as the maximum air velocity for ASHRAE 55-2004. Findings also indicated significative differences in occupant's air movement preferences and acceptability based on their thermal history (air-conditioning exposure). Findings also indicated that air movement definitely assumes a major significance in terms of preference and acceptance of the indoor thermal environment. Thermal acceptability alone was not enough to satisfy occupants. Combining thermal and air movement acceptability is the key challenge that must be faced in hot-humid climates. Finally, this project suggested a set of guidelines for future Brazilian standard for naturally ventilated buildings, considering air movement enhancement as a welcome breeze in hot-humid climates.

Keywords: air movement acceptability, thermal comfort, adaptive model, hot-humid climates, thermal history.

Declaration

I certify that the work in this thesis entitled “Indoor air movement acceptability and thermal comfort in hot-humid climates” has not previously been submitted for a degree in this or any other University. This project was developed under joint co-tutelle agreement signed between Macquarie University (Department of Environment and Geography) and Federal University of Santa Catarina (Department of Civil Engineering) and, as such, will be submitted as part of requirements for a degree in both institutions. The two Institutions undertake, based on their respective procedures pertaining to the submitted thesis, to award the degree of Doctor of Philosophy of Macquarie University and the Doctoral degree of Civil Engineering of Federal University of Santa Catarina subject to the satisfactory completion of all award requirements by the candidate. A decision to award the degree by either University is not binding upon the other.

I also certify that the thesis is an original piece of research and it has been written by me. Any help and assistance that I have received in my research work and the preparation of the thesis itself have been appropriately acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

The research presented in this thesis was approved by Macquarie University Ethics Review Committee, reference number: HE23FEB2007-R05007.

Christhina Maria Cândido

Statement of Contribution

The thesis follows the structure of *thesis by publication*. The thesis contains peer-reviewed journal papers that constitute the 'Results and Discussion' chapter. The candidate's individual contribution with respect to the other co-authors is stated in the overview section preceding each paper.

Research Thesis by Publication (s): a preferred Macquarie University model

"…Theses may include relevant papers (including conference presentations) published, accepted, submitted or prepared for publication during the period of candidature, together with a comprehensive and critical introduction and an integrative conclusion. These papers should form a coherent and integrated body of work, which should be focused on a single project or set of related questions or propositions. These papers may be single author or co-author – for co-authored papers the candidate must specify his/her specific contribution. The contribution of others to the preparation of thesis or to individual parts of the thesis should be specified in the thesis Acknowledgements and/or in relevant footnotes/endnotes. It is not necessary to reformat published works in a thesis". (Macquarie University, 2008)

Publications list and awards

This thesis is presented in accordance to Macquarie University's guidelines for a thesis by publication. Results from this thesis were published or accepted for publication on the following papers.

Peer-reviewed journal papers

Cândido, C. M., de Dear, R., Lamberts, R., Bittencourt, L. S. (2010) Air movement acceptability limits and thermal comfort in Brazil's hot-humid climate zone. *Building and Environment* **45** (1): 222-229. doi:10.1016/j.buildenv.2009.06.005

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Cândido, C. M., de Dear, R., Lamberts, R. (2011) Combined thermal acceptability and air movement assessments in a hot-humid climate. *Building and Environment Building and Environment* **46**: 379-385. doi:10.1016/j.buildenv.2009.11.005

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Cândido, C. M., Lamberts, R., de Dear, R., Bittencourt, L. S. (2011) Towards a Brazilian standard for naturally ventilated buildings: guidelines for thermal and air movement acceptability. *BRI.* (submitted). (paper invited from *2010 Windsor Conference).*

Peer-reviewed conference papers

Cândido, C. M., Lamberts, R., de Dear, R., Bittencourt, L. S. (2010) Toward a Brazilian standard for naturally ventilated buildings: guidelines for thermal and air movement acceptability. In: *2010 Windsor Conference - Adapting to Change: New Thinking on Comfort*, Cumberland Lodge, Windsor, UK.

Cândido, C. M., Lamberts, R., Bittencourt, L. S., de Dear, R. (2009) Aplicabilidade dos limites da velocidade do ar para efeito de conforto térmico em climas quentes e úmidos (Applicability of air velocity limits for thermal comfort in hot humid climates). In: *ENCAC 2009 X Encontro Nacional e VI Encontro Latino Americano de Conforto no Ambiente Construído*, Natal, Brazil.

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Book chapter

Cândido, C. M., de Dear, R., Lamberts, R., Bittencourt, L. S. (2010) Cooling exposure in hot-humid Climates: Are occupants 'addicted'? In: *Transforming markets in the Built Environment: Adapting to Climate Change*. 1ed. EarthScan. Sue Roaf (Ed), 140p. ISBN 9781849710886. (paper invited from *Architectural Science Review*).

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Introduction

I. Introduction

The last 100 years have witnessed major international research efforts directed towards quantifying the relationship between the quality of the indoor environment, as perceived by occupants on the one hand and the physical character and intensity of the various indoor environmental elements on the other [1]. The benefits of people spending more time inside artificial and controlled environments during their daily activities in order to keep “neutral” have been questioned. But if we agree that those thermal environments which are slightly warmer than preferred or “neutral”, can still be acceptable to building occupants, as the adaptive comfort model suggests [2,3,4], then the introduction of elevated air motion into such environments should be universally regarded as desirable because the effect will be to remove sensible and latent heat from the body, thereby restoring body temperatures to their comfort set-points [5,6,7,8,9].

A recent revival of natural ventilation, as a passive design strategy, has been widening the range of opportunities available in buildings to provide comfort for occupants, both in newly-built and retrofitted contexts. When designed carefully, naturally ventilated indoor environments do not compromise occupants’ comfort, well-being or productivity. Indeed some argue it is quite the opposite – that naturally ventilated buildings provide indoor environments far more stimulating and pleasurable compared to the static indoor climate achieved by centralised air-conditioning [10,11,12].

One of the challenges in optimizing natural ventilation is to define when air movement is desirable and when not. Based on the argument that elevated air speeds in indoor environments could be unwelcomed (draft), air velocity limits have been skewed downwards in the standards. However, a considerable number of laboratory studies and particularly field experiments in real buildings have been providing compelling evidence that occupants prefer the contrary. Indeed, occupants have been demanding ‘more air movement’ in numerous field studies. While in cold and temperate climates, air motion might cause unwanted ‘draft’, in hot-humid climates, air movement enhancement is, without doubt, one of the key factors in providing occupant thermal comfort.

So far, a variety of studies indicate that within indoor environments, indoor air speed should be set between 0.2 - 1.50 m/s, yet 0.2 m/s has been deemed in ASHRAE[1] Standard 55 [13] to be the upper limit allowable inside air-conditioned buildings where occupants have no direct control over their environment [13]. In discussing these design limitations, it is appropriate to remember that the 'end' product is not the air movement per se, but rarther the occupants' satisfaction within the indoor climate [11]. None of the previous researches in this area explicitly addressed air movement as 'acceptable', instead focusing mostly on overall thermal sensation and local discomfort. Therefore, it is important to develop more field experiments that consider different approaches for subjective air movement assessments.

Much of Brazil's territory is classified as having a hot-humid climate. In such climates, natural ventilation combined with solar protection, are the most effective building design strategies to achieve thermal comfort without resorting to mechanical cooling. However, the use of air-conditioning as the main cooling strategy inside buildings has been increasing. Governmental data suggests that buildings are responsible for about 30.7% of the energy end-use in Brazil (public and commercial sectors combined) [14]. The role of natural ventilation as an energy conservation strategy is a path towards more sustainable buildings. The weight of research evidence to date suggests that neither the "risk" of draft nor the possibility of negative indoor air quality posed by elevated enthalpy in buildings with natural or hybrid ventilation systems, are real enough to sacrifice the environmentally sustainable goals of bioclimatic design strategies.

1.1. Research objectives

The first objective of this project is to understand the relevance and applicability of maximum air speed limits, focusing on occupant's thermal comfort, preference and acceptability, within naturally ventilated buildings located in a hot humid climate. This scope seeks to understand how occupants perceive and classify air movement in their thermal indoor environments, with the specific aim of determining the minimal air velocity necessary to provide thermal comfort.

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[1] ASHRAE: American Society of Heating, Refrigerating and Air Conditioning Engineers.

The second objective of this project is to investigate the influence of prior exposure to air conditioned environments on thermal and air movement acceptability and preference, focusing if prior exposure to air-conditioning leads to building occupants actually preferring air-conditioning over natural ventilation.

The third objective is to investigate the limitations, if any, of thermal acceptability predictions in order to thoroughly assess occupants' comfort in naturally ventilated indoor environments. The scope of this analysis extends to a critical assessment of thermal acceptability within the predictions of the ASHRAE 55 [13] adaptive model.

The fourth, and final objective, is to propose guidelines for a Brazilian comfort standard focusing on naturally ventilated indoor environments, fully considering thermal comfort and air movement acceptability issues. This proposal aims to summarize guidelines for naturally ventilated environments in which specifications for thermal and air movement acceptability goals must be achieved for the majority of occupants within the building.

1.2. Thesis structure

Chapter I introduced the broad contet of this project and instated the key objectives pursued during the development of this thesis. Chapter II focuses on the current literature related to the research questions in this thesis. The first part focuses on the revival of natural ventilation in relation to energy conservation challenges within the building sector and, in particular, the Brazilian context, energy efficiency initiatives and thermal comfort studies. The second part revisits thermal comfort studies from both the “static” and “adaptive” approaches and their respective influences on international comfort standards. The third section discusses how air movement has been studied in the thermal comfort field with reference to comfort standards and the role of occupant control. Finally, the fourth part focuses on the emergent research topic of thermal alliesthesia, whereby physiological mechanisms can be used to explain the pleasure associated with natural ventilation.

Chapter III describes the methodological design applied to assess occupant thermal comfort in naturally ventilated buildings. This chapter focuses on the fundamental feature of this field research design, namely the proximity, in time and space, of the indoor climate measurements with corresponding comfort questionnaire responses from the occupants. The two field experiment campaigns that took place in Maceio, during the cool (August - September) and also hot seasons (February - March) are presented, along with detailed descriptions of the buildings and their occupants, as well as the questionnaires, instruments, and measurement protocols.

Chapter IV presents the results and discussion and, as a thesis by publication, comprises the research papers that have been published in, or submitted to peer-reviewed journals, during the course of this project. Four topics of analysis are presented, based on the corresponding peer-reviewed journal paper: *Topic I: Air movement acceptability in hot humid climates; Topic II: Cooling exposure and air movement preferences in hot humid climates; Topic III: Applicability of thermal and air movement acceptability limits in hot humid climates, and Topic IV: Towards a Brazilian standard for naturally ventilated indoor environments: guidelines for thermal and air movement acceptability in hot humid climates.* Complementary publications that have been published in peer-reviewed journals and conference proceedings are presented in Appendix A to F.

Chapter V is dedicated to the final remarks about this project's results and it presents specific areas in which further research is necessary.

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Background

II. Background

This chapter presents the state of the art related to this project. Firstly, the revival of natural ventilation related to the energy conservation challenges within the building sector and, particularly within the Brazilian context. Secondly, thermal comfort studies are presented, focusing on ‘static’ and ‘adaptive’ approaches. Thirdly, air movement studies are discussed along with their relation to thermal comfort field. Finally, the emergent topic of *alliesthesia* is presented as a thermophysiological hypothesis that accounts for thermal comfort observations in natural ventilation.

2.1. Energy conservation and buildings: The revival of natural ventilation

In its Fourth Assessment Report in 2007, the IPCC[2] Working Group III [1] identified the building sector as possessing the greatest potential for deep cuts in CO_2 emissions. Figure 1 presents 2030 greenhouse gas emission mitigation potential for three separate valuations per tonne of carbon. In 2004, emissions from the building sector attributable to electricity use were about 8.6 $GtCO_2$, equivalent to a quarter of the global total. Furthermore, the IPCC Working Group III [1] estimated the global potential to reduce projected baseline emissions in the built environment through cost-effective engineering measures as 29% by 2020.

With buildings accounting for up to 40% of energy end-use in developed economies, regulatory and economic pressures are mounting to reduce the sector’s greenhouse gas emissions [2]. One of the key lessons from the oil crises of the 1970s is that the ultimate success or failure of a building project – in terms of its long-term viability, energy use and occupant satisfaction, depends heavily upon the quality of the indoor environment delivered to the building occupants. Therefore for significant CO_2 abatement potentials to be realised, it is imperative that sustainable buildings (both newly-built and retrofitted projects) meet the

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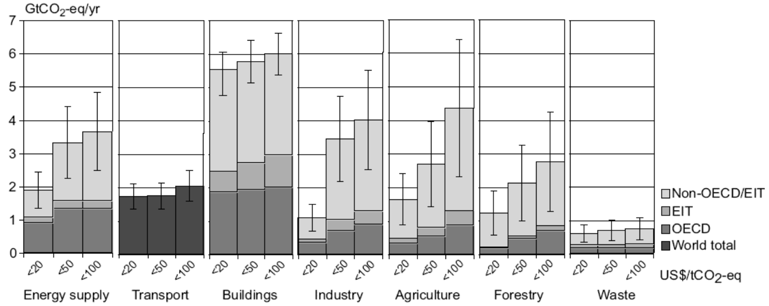
[2] IPCC: Intergovernmental Panel on Climate Change.

occupants' expectations. It has been established that behavioural change in buildings can undoubtedly deliver fast and zero-cost improvements in energy efficiency and greenhouse gas emission reductions.



(potential at <US\$100/ tCO$_2$-eq: 2.4 - 4.7 Gt CO$_2$-eq/yr)	*(potential at <US\$100/ tCO$_2$-eq: 1.6 - 2.5 Gt CO$_2$-eq/yr)*	*(potential at <US\$100/ tCO$_2$-eq: 5.3 -6.7 Gt CO$_2$-eq/yr)*	*(potential at <US\$100/ tCO$_2$-eq: 2.5 - 5.5 Gt CO$_2$-eq/yr)*	*(potential at <US\$100/ tCO$_2$-eq: 2.3 -6.4 Gt CO$_2$-eq/yr)*	*(potential at <US\$100/ tCO$_2$-eq: 1.3 - 4.2 Gt CO$_2$-eq/yr)*	*(potential at <US\$100/ tCO$_2$-eq: 0.4 - 1 Gt CO$_2$-eq/yr)*

Figure 1 - Assessment of 2030 greenhouse gas emission mitigation potential for three costs per tonne of carbon (<US\$20, 50 and 100). EIT refers to Economies in Transition [4].

Since HVAC[3] is the single largest energy end-use in the built environment, it is inevitable that we should look critically at our dependence on mechanically cooled indoor climates. Cooling energy in buildings can be reduced by: 1) reducing the cooling load on the building; 2) exploiting passive design principles to meet some, or the entire load and 3) improving the efficiency of cooling equipment and thermal distribution systems. Natural ventilation reduces the need for mechanical cooling by; a) directly removing hot air when the incoming air is cooler than the outgoing air, b) reducing the perceived temperature due to the cooling effect of air motion, c) providing night-time cooling for exposed thermal mass inside the building and d) increasing the acceptable range of temperatures through psychological adaptation where occupants have direct control of operable windows [3]. Even where these technical solutions are feasible to implement, they are also

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[3] HVAC: Heating, Ventilating, and Air Conditioning.

limited to the building’s performance, without any consideration of the occupants.

After the 1970s oil crises, many countries started to look for ways of improving building energy efficiency and different initiatives were implemented. Energy certification schemes for buildings emerged in the early 1990s as a regulatory initiative for improving energy efficiency and enabling greater transparency in the market with regards to the use of energy in buildings. An overall objective of energy policy in buildings is to save energy consumption without compromising occupant comfort, health and productivity levels. In other words, being more energy efficient is consuming less energy while providing equal or improved building services [5].

Regulatory bodies such as energy agencies, local authorities, etc., have three broad strategic instruments available for driving savings and maximising energy efficiency in buildings: regulations, auditing and certification. Building energy regulations, also referred to as building energy codes, establish minimum requirements to achieve energy efficient designs in new buildings. In Europe, the building sector accounts for about 40% of primary energy consumption [2]. Energy certification of buildings has emerged as one of the core measures. Europe enacted early building envelope performance regulations in the late 1970s aimed at reducing heat transfer through envelope elements and reducing vapour diffusion and air infiltration. This was followed by regulations or best-practice recommendations in relation to design, calculation and maintenance of building thermal services. Eventually, HVAC equipment was, for the first time, subject minimum performance requirements for energy efficiency. More recently, the European Parliament’s 2003 Energy Performance Buildings Directive (EPBD) specifically tackles energy dependency via actions aimed at reducing consumption and therefore directly reducing energy demand.

An analysis of the response of EPBD reveals how diverse the situation is in Europe, with energy certification in each country being different in terms of implementation and scope of application [2]. Andaloro et al. [2] pointed out that some European countries have adopted either their own system for the selection and qualification of certificate advisors; some of them, like the Netherlands and the United Kingdom, impose particularly rigorous standards requiring two tiers of qualification accreditation (company/personnel). In other countries requirements are still left up to local or regional authorities to decide, as in Italy, or in the case of Germany, a deliberate wide range of authorities are admitted, including parties only marginally linked to planning and design of buildings.

Despite the fact US Federal Government in the avoided signing the Kyoto protocol, approximately half of the states have embarked on state-level carbon restriction laws. California has taken perhaps the most aggressive approach of all the states, aiming for deeper cuts in CO_2 emissions. Its legislation establishes a comprehensive program of regulatory and market mechanisms aiming to achieve cost-effective and quantifiable greenhouse emission reductions. Pursuant to the California Global Warming Solutions Act of 2006, the state is required to reduce its aggregate emissions to 1990 levels by 2020 [6].

Australia, a major producer and user of coal, has the highest greenhouse gas emissions per capita in the industrialized world [7]. The first white paper concerning energy conservation in buildings was instigated in 1997 after the Kyoto Earth Summit. In the view of the Sustainable Energy Building and Construction Taskforce Report [8], the targets that Australia committed under the Kyoto Protocol were widely perceived as ‘soft’, particularly, to those developed nations who made commitments to reduce emissions to 5 per cent below 1990 levels by 2010. In 1990, the Australian building sector was responsible for 21% of the total greenhouse emissions and 28% of the energy related emissions; the residential sector contributed 60% of the total building sector while the non-residential sector contributed the other 40% (9). Most recent Australian reports show the increasing importance of buildings and in 2010, Australian houses were pointed-out as the biggest users of electricity in the world, overtaking the US [6].

Japan’s target of reducing greenhouse emissions by 6% from 1990 levels by 2012 was one of the most onerous undertakings in the Kyoto Protol. By 2003, emissions were 8% higher than those of the base year. In a concerted effort to meet its Kyoto commitments, Japan implemented the ‘*Cool Biz’* campaing in which office buildings should set thermostats at 28°C indoors thereby encouraging the relaxation of office dress codes. By removing jacket and neck tie (*circa* 0.2*clo* units) the perceived comfort was estimated to be equivalent to a 2°C reduction in temperature, so that 28°C would feel like 26°C.

In developed nations, energy conservation strategies present enormous scope for improvement, but in developing countries, this discussion shifts to another dimension. It relates to the very intricate balance between economic considerations and social development. Energy is generally assumed to be the basis for economic grow and investments in energy resources and end-use management are therefore integral to this agenda. Wasting energy is, in other words, a waste of precious investments and must be minimized by all means necessary in countries such as Brazil, Russia, India and China.

Overtaking the US as the world's largest carbon emitter has put China in the spotlight, at a time when the world community is negotiating a post-Kyoto climate regime [10]. In China, construction is the third largest industry and the total floor area of built buildings is about 40 billion m^2, estimated increase to 70 billion m^2 in 2020 [11]. The country’s building sector is responsible for 46.7% of China’s total energy consumption and heating and air-conditioning systems alone contribute 65% to the sector’s total energy consumption [11].

In India, the implications on a large scale move to fully air conditioned buildings become also profound. Data from India’s Construction Industry Development Council [12] shows that the construction sector has seen an increase of about 40.8 million m^2 in 2004-05, which is about 1% of the annual average constructed floor area around the world, with trends showing a sustained growth of 10% per annum over the coming years. According to Thomas et al. [13] “...by following the high-carbon development pathways of warm/hot climate cities such as Singapore and Dubai, the rapid expansion of Grade A, air-conditioned office buildings are a key contributor to India’s soaring demand for electricity over coming years”.

By the late 20th century it became extremely rare for commercial and educational buildings to rely on anything other than compressor-based cooling to create comfort indoors. Occupant expectations of the indoor environment have changed ever since the advent of air-conditioning in the early 20th century. Ackerman [14] argues that “...there is fairly persuasive evidence that ice-cold air transported working and middle class customers to movie palaces, department stores, hotels, and railroad cars as part of the total entertainment experience. Air-conditioned environments offer an escape from a drab and hot workaday life and, at the same time, it became increasingly associated with *luxury, comfort, and modernity*. The marketing of these newly air-conditioned spaces appealed to ‘Mr. Consumer’ as a *presumed desire for comfort*. In the US, air-conditioning became embedded in the perceptions and expectations of the emerging middle class after World War II and hence there is a well established “romance with air-conditioning” [14].

A central issue in the efficiency, and effectiveness, of buildings in providing occupant comfort is where “intelligence” is assumed – either implicitly or explicitly. Technological innovation led to shifting design responsibility in comfort provision from the architects to mechanical engineering consultants, and control responsibility from the *occupants to technology* [15]. The intelligence is now associated with systems and controlled indoor environments. Roaf et al. [16] say that “…in the plethora of studies so far on the subject of achieving emission reductions from buildings, much is said about mechanical and constructional strategies as well as renewable energy systems, but behavioral strategies are very seldom mentioned”.

A recent study re-analyzed data supplied by the New Buildings Institute and the US Green Buildings Council on measured energy use data from 100 LEED[4]-certified commercial and institutional buildings [17]. The results revealed that 28–35% of LEED buildings use more energy than their conventional counterparts “with no statistically significant relationship between the level of LEED certification and energy use intensity, or % energy saved vs. Baseline” [17]. The main reasons for this result, as pointed out by Newsham et al. [17] were that: (1) the occupancy hours differed from those in the initial design assumptions; (2) the final as-built building differed from the initial design; (3) experimental technologies did not perform as predicted and (4) a knowledge transfer gap existed between the design team and end users’’. So there is indeed a missing piece in this puzzle: occupant behaviour.

Behavioural change in buildings can undoubtedly deliver fast and zero-cost improvements in energy efficiency and greenhouse gas emission reductions. In order to provide such behavioural opportunities, or adaptive opportunities, buildings must be designed to re-engage ‘active’ occupants in the achiviement of comfort. Architects are (or at least should be) becoming aware that their lack of understanding of how

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[4] LEED: Leadership in Energy & Environmental Design.

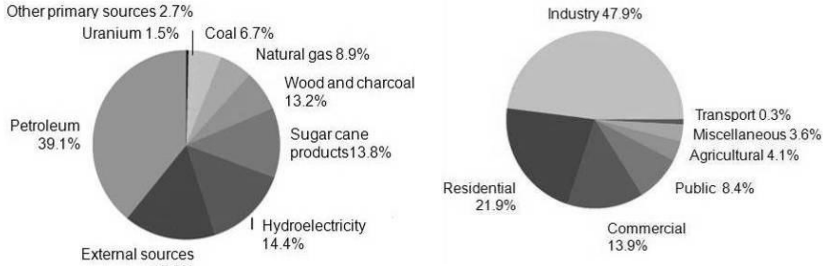
buildings perform and their lack of concern for, or knowledge of, how occupants respond, leads them to allow engineers to make the key decisions relating to comfort inside buildings [18]. It is now becoming clear that the idea of air-conditioning as a provider of higher degrees of ‘freedom’ for architects is unsustainable, if not to say, irresponsible.

Designing buildings totally disconnected from the outdoor climate and environment in which they are found is becoming completely out of date [18]. With this in mind, designers are beginning (rather slowly) to shift their attention to widening the range of opportunities available in a building to provide comfort for occupants, both in newly-built and retrofitted contexts. This in turn has re-awakened an interest in the role of natural ventilation, not only in the provision of comfort but also in terms of regulations and standards. When designed carefully, naturally ventilated indoor environments need not compromise occupants’ comfort, well-being or productivity. Indeed some argue it is quite the opposite – that naturally ventilated buildings provide indoor environments far more stimulating and pleasurable compared to the static indoor climate achieved by centralised air-conditioning [19, 20].

2.2. The Brazilian context: energy conservation initiatives and potential

In Brazil, power generation is heavily weighted towards hydroelectricity, accounting for approximately 91% of the total energy sources. Brazil’s total hydroelectric power potential is 260 GW, of which approximately 22% has already been implemented [21]. A large proportion of hydroelectric power potential is in the Amazon region (40%), where demand is low, while most of the potential for large developments in the Southeast have already been exploited [21].

Recently, due to the lack of investment in the supply side combined with constant growth of demand, energy efficiency investment has become essential. Energy used in buildings accounts for about 48.3% of the total electrical energy consumption in Brazil [22]. Figure 2 shows the energy source availability and electricity consumption per sector in Brazil.



a) b)

Figure 2 - Energy source availability (a) and electricity consumption per sector in Brazil (b) [22].

The main energy conservation initiatives that took place in Brazil were a direct consequence of the energy crisis in 2001. As a result under-investment, in terms of generation and especially distribution associated to climatic conditions, Brazilians have endured a harsh regimen of blackouts and electricity rationing. After this landmark event, the Federal Government released a "National Policy of Conservation and Rational Use of Energy" [23], establishing minimum levels for energy efficiency of appliances and equipments. According to Geller et al. [24] "...energy efficiency improvements in Brazil were inhibited by a series of market and imperfections:

- Many decades of economic instability and high inflation induced conditions which strongly discouraged life-cycle analysis and longer term investment;
- Immature energy efficiency delivered to infrastructure, again related to the recent introduction and limited adoption of many measurements;
- Subsidized electricity prices still paid by large industrial consumers as well as low income residential consumers;
- Electricity representing a relatively small portion of total costs for most business and consumers;
- Lack of capital or attractive financing for many consumers and businesses – interest rates are generally very high in private markets with borrowing discouraged by heavy bureaucracy, onerous warranty requirements, etc.;

- Lack of financial incentives for utilities to operate demand-side management which leads to significant electricity saving by costumers.”

This list of items has been reduced in recent years, especially in relation to energy management and distribution networks, as a result of increased financial stability and economic growth. Based on a comprehensive study, Geller et al. [24] concluded that “Brazil has demonstrated the ability to adopt and effectively implement innovative energy policies and technologies, as exemplified by the ethanol fuel program and efforts to increase the efficiency of electricity use. These efforts involved a long-term commitment from the government; a comprehensive set of policies to overcome technical, institutional and market barriers; and the active engagement of the private sector”. Similar strategies could be feasibly to successfully implement a set of policies related to the building sector as the building sector presents a major potential in terms of energy efficiency.

Despite the fact that Brazil is not amongst the world’s major energy consumers, electricity consumption has significantly increased in recent years [25]. Figure 3 shows the growth in electricity consumption in residential, commercial and public sectors in Brazil from 1965 to 2005. The residential sector accounts for 21.9% of energy consumption in Brazil, with the biggest end-uses being water heating, air-conditioning and lighting. Consumption in this sector is expected to grow with the development of the economy, mainly due to the poor thermal design of buildings being constructed - without any consideration of the climate in which they are located and making air-conditioning the only viable solution for the personal comfort of residents [25].

The importance of good building design reappears in the commercial and public sectors in terms of energy efficiency with the majority of electricity consumption attributed to lighting and air-conditioning systems. Brazil’s mild climate presents impressive potential for the application of passive technologies if considered during the early design stage. However, building designers have ignored this potential, preferring thermally underperforming ‘international architecture’ style. Building design in Brazil has not been pushed towards energy efficiency due to the loose regulatory framework and a lack of professionals trained in this interdisciplinary field. The only standards in building energy efficiency were, until recently, the NBR

6401 and NBR 5413, but they deal with the design of air-conditioning and lighting systems without any consideration for energy efficiency and the influence of building design. It should be noted that the air-conditioning standard is very outdated, encouraging oversized, inefficient systems [23].

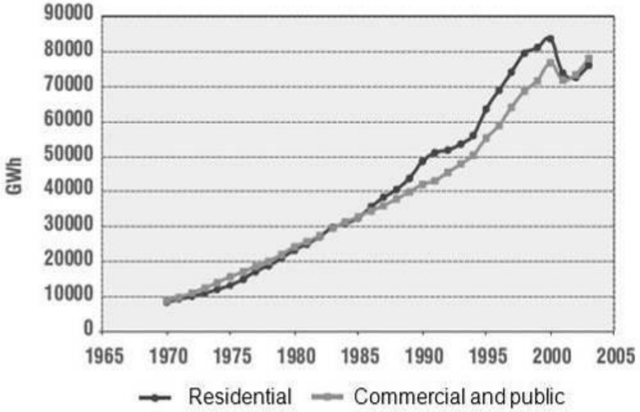


Figure 3 - Electricity consumption growth in residential, commercial and public sectors in Brazil from 1970 to 2005 [22].

The conclusion that much energy is wasted in buildings in Brazil identifies a clear path towards improvement. A comprehensive approach has to be adopted in order to transform the existing market. The main ingredients in this market transformation are expected to be standards and much has been done so far. However, standards will only set a cut-off point below which energy efficiency will not fall. The committee formed after the "National Policy of Conservation and Rational Use of Energy" was aware of this scenario as was the Technical Group for Energy Efficiency in Buildings. In 2004, the Action Plan for energy efficiency in buildings established the following actions, including: *bioclimatic architecture, benchmarking for buildings, building materials and appliances certification regulations and legislation, removing barriers to energy efficiency and education* [26]. Implicit to the PROCEL-Edifica Program and its actions was a demand for a more holistic approach for building design. The main focus was on stimulating projects that prioritize energy efficiency consideration during the early design stage *in lieu of post facto* technical solutions (i.e. 'green bleach').

2.3. Revisiting thermal comfort models and standards

Roaf et al. [27] says "...if one owns a machine that can produce air at a certain temperature in an otherwise uncomfortable climate, then one can simply adjust the machine until the environment is comfortable". However, "...the temperature that might suit a group of individuals will vary, and in establishing limits, a single temperature or range of temperatures that people prefer as being neither 'cooler nor warmer' becomes important. This became of great importance after the 1970s oil crisis, when comfort research abandoned the central optimum, and began to explore the edges of comfort, searching for how cold or warm it could get before getting uncomfortable" [28].

Fanger's climate chamber experiments produced a comprehensive comfort index - Predicted Mean Vote – PMV. Fanger's PMV started from the premise that it is possible to define a comfortable state of the *body* in physical terms which relate to the body rather than the environment [28]. His book proposed three necessary conditions for thermal comfort: steady-state heat balance; mean skin temperature should be at a level appropriate for the metabolic rate; and that sweating rate should be at a level appropriate for the metabolic rate. Based on these conditions, the final equation comprises variables related to the function of clothing (clothing insulation and ratio of clothed surface area to nude surface area); activity (metabolic heat production and work) and four environmental variables (air temperature, mean radiant temperature, relative air speed and vapour pressure of water vapour). According to Parsons [29] the resultant model should be "*universally applicable*, regardless of building type, climate zone or population".

The landmark research of Fanger [30] provided the framework necessary to determine a set of design temperatures for engineering mechanically controlled indoor environments. The PMV model can also be used to assess given room's climate, in terms of deviations from an optimal thermal comfort situation [28]. This model has been globally applied for almost 40 years across all building types, although Fanger was quite clear that his PMV model was originally intended for application by the heating, ventilation and air-conditioning (HVAC) industry in the creation of artificial climates in controlled spaces [31]. It is interesting that Sue Roaf says that "…important to realize that the air-conditioning industry is one of the most powerful industries in the world, dwarfed only by the Financial, Insurance and Motor industries, and its lobbying power is extremely effective [18]. The Predicted Mean

Vote – PMV and the Predicted Percentage of Dissatisfied – PPD encouraged not only the tight set-points necessary in order to keep people feeling “neutral” but also, indirectly, “…the wholesale commoditization of the building design process, taking power from architects to service engineers” [32]. The PMV and PPD were and still are broadly used in standards such as ASHRAE Standard 55 [33], CEN CR 1752 [34] and ISO 7730 [35], and its influence in thermal comfort field is widely recognized.

As with any theory, model or index, Fanger’s legacy has been both widely supported and widely criticized. In his dissertation, Fanger stated that the PMV model was derived in laboratory settings and should therefore be used with care for PMV values below -2 and above +2. Especially on the hot side, Fanger foresaw significant errors [31]. But probably the most important criticism is the concept of a universal “neutral” temperature. Regarding the inadequacies of PMV applications in naturally ventilated buildings de Dear and Brager commented that “…the cool, still air philosophy of thermal comfort, which requires significant energy consumption for mechanical cooling, appears to be over-restrictive and, as such, may not be appropriate criterion when decisions are being made whether or not to install HVAC systems” [36]. The widely accepted ‘adaptive comfort model’ shifted this paradigm.

The dialectic between conventional, or ‘static’, and the adaptive comfort theories can be seen in innumerable papers and goes back to the 1970s and 1980s [37, 38, 39, 40]. This discussion became more prominent, however, by the end of the 20th century with the realization of the (unsustainable) energy carbon required to air condition indoor environments. de Dear and Brager [36] noted that “…the basic tenet of the adaptive model is that building occupants are not simply passive recipients of their thermal environment, like climate chamber experimental subjects, but rather, they play an active role in creating their own thermal preferences. Contextual factors and past thermal history are believed to influence expectations and thermal preferences. Satisfaction with an indoor environment occurs through appropriate adaptation”.

Based on an analysis of over twenty thousand row set of indoor microclimatic and simultaneous occupant comfort data from buildings around the world, the ASHRAE RP-884 database found that indoor temperatures eliciting a minimum number of requests for warmer or cooler conditions were linked to the outdoor temperature at the time of the survey. Figure 4 shows this relationship for the naturally ventilated buildings, thermal acceptability was found for 80 and 90% by applying the 10 and 20% PPD criteria to the thermal sensation scale recorded in the building. Details about the analysis can be found in [3, 36 and 40].

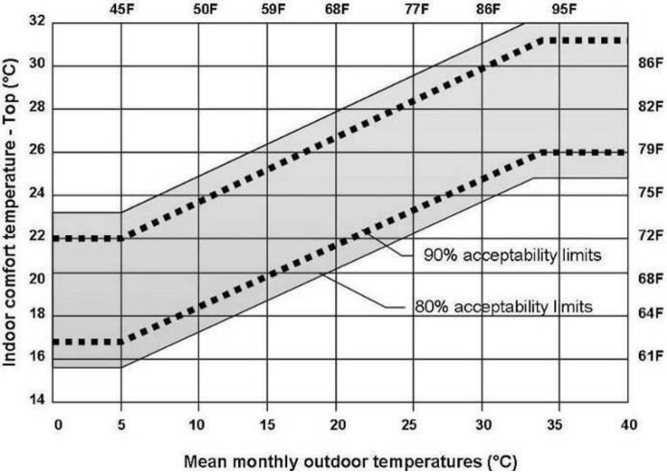


Figure 4 - The adaptive model of thermal comfort [40].

Buildings were separated into those that had centrally-controlled heating, ventilating, and air-conditioning systems (HVAC), and naturally ventilated buildings (NV). Since the ASHRAE RP-884 database comprised existing field experiments, the HVAC versus NV classification came largely from the original field researchers' descriptions of their buildings and their environmental control systems. The primary distinction between the building types was that NV buildings had no mechanical air-conditioning, and that natural ventilation occurred through operable windows that were directly controlled by the occupants. In contrast, occupants of the HVAC buildings had little or no control over their immediate thermal environment. Figure 5 shows the separate analysis for HVAC and NV buildings.

de Dear and Brager state that "…while the heat balance model is able to account for some degree of behavioural adaptation, such as changing one's clothing or adjusting local air velocity, it ignores the psychological dimension of adaptation, which may be particularly important in contexts where people's interactions with the environment (i.e. personal thermal control), or diverse thermal experiences, may alter their expectations, and thus, their thermal sensation and satisfaction. One context where these factors play a particularly important role is naturally ventilated buildings”. The adaptive model of thermal comfort advocates the shift from statically controlled indoor environments to active naturally ventilated buildings. The posterior implementation in ASHRAE 55 - 2004 [33] was, undoubtedly, a step forward towards mainstreaming naturally ventilated buildings [41, 42].

Based on the adaptive model, ASHRAE 55-2004 [33] offered a new approach towards naturally ventilated buildings. Examples of building designs focusing on naturally ventilated or mixed-mode indoor environments are increasing. For instance, the recently completed green flagship Federal Building in San Francisco deploys a number of innovative technologies, including an integrated custom window wall, thermal mass storage, and active sun shading devices to regulate internal thermal environmental conditions within the adaptive model’s seasonally adjusted comfort ranges [43]. In this building’s initial design stage, San Francisco’s Typical Mean Year (TMY) of meteorological data was used to calculate month-by-month ranges of acceptable indoor temperature using the ASHRAE 55-2004 adaptive model [43].

In response to the European Parliament’s 2003 EPBD, there are about 30 new European *standards* including one defining *“Criteria for the Indoor Environment”* [34]. The new European standard EN 15217 [41] is an attempt to describe methods for expressing energy efficiency and certification of buildings. Energy Performance Certificates are redefined within the development of a certification scheme [4]. The scope of the certification is therefore extended not only to the energy performance of the building but also to include a minimum requirement and a label or class that allows users to compare and assess prospective buildings. The certificate must contain, amongst other information, a classification of the building energy efficiency based on an energy label.

ISO standard 7730 [35] and CEN15251 [44] include three categories (also called ‘classes’) of environmental quality: A, B, C, with A requiring the tightest control of interior conditions. This schema is now being proposed for ASHRAE Standard 55 as well [33]. Class A will require tighter control than the existing Standard 55, whose specifications are now at the B level. The class categories apply to the variables *PMV, draught, vertical air temperature difference, floor temperature, and radiant temperature asymmetry*. The present classification approach suggests that buildings with tight, centralized temperature control (e.g. with summer temperatures between 23.5 and 25.5ºC) are perceived as more satisfying than buildings with less tight temperature control (e.g. with summer temperatures between 22 and 27ºC). Based on raw data analysis, the assumptions of significant differences in terms of thermal acceptability between the three classes were categorically dismissed by Arens et al. [45].

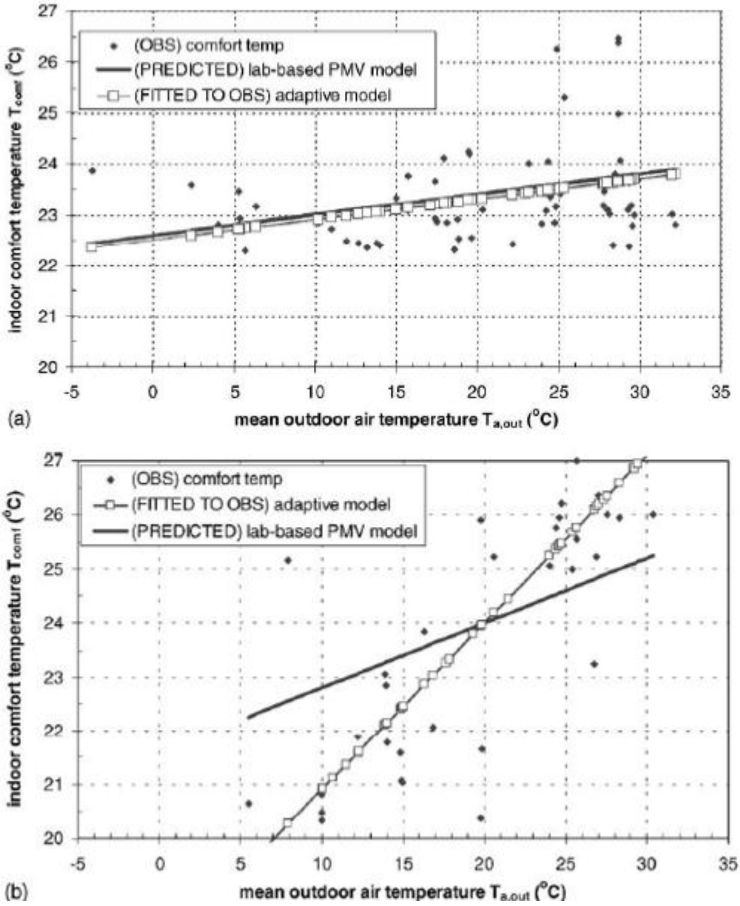


Figure 5 - (a) Observed (OBS) and predicted indoor comfort temperatures from RP-884 database, for HVAC buildings and (b) Observed (OBS) and predicted indoor comfort temperatures from RP-884 database, for naturally ventilated buildings [2].

In 2004, the Netherlands moved from a PMV/PPD approach to its comfort standard to adaptive temperature limits, based on ASHRAE's RP-884 adaptive model [36, 40). Figure 6 shows the maximum allowed operative temperature for a specific acceptability level as a function of outdoor temperature. The temperature limits for 90%, 80% and 65% acceptability bandwidths around $T_{comfort}$ and classify buildings into Alpha and Beta types (adaptive *v* conventional comfort guidelines respectively). In addition to data analysis from the exclusively "SCAT" comfort database, CEN has developed a standard for naturally ventilated (or free-running) buildings. This standard uses outdoor temperatures to predict thermal comfort for three different categories [41, 46].

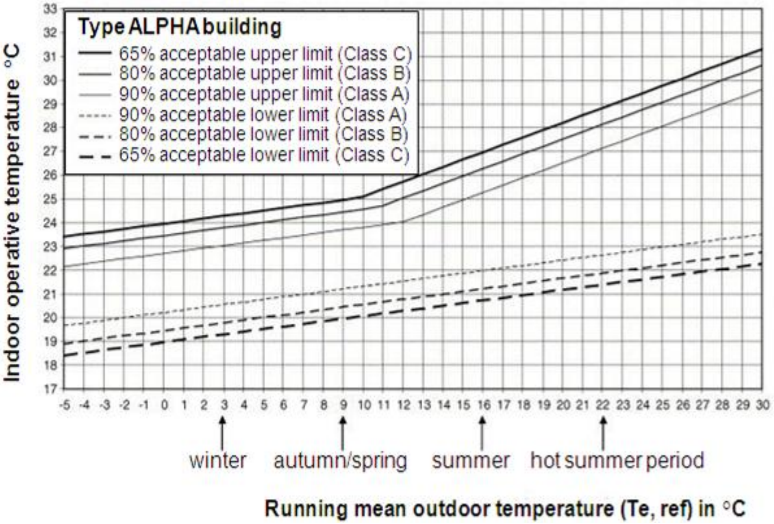


Figure 6 - Maximum allowed operative temperatures for a specific acceptability level, as a function of the outdoor temperature [41].

Energy efficiency requirements were introduced into the Building Code of Australia (BCA) in 2003 and Australia also has one of the first energy efficiency certifications, the Green Star rating system [47]. One of the difficulties is that building codes differ from each other as they are associated with characteristics of each city, region and country, such as climate, culture, technological level and others. For instance, in South Australia, there is no building envelope requirement while its counterpart in Victoria establishes a minimum rating of 2 or 3 for commercial and public buildings [48].

Figure 7 shows typical 1990's design temperatures in Japan in comparison to other parts of the world (US, Australia and Canada). In the 1990s, comfort zones for Japan [49] were different from other countries' standards and the adaptive model was later incorporated as a reference for acceptable indoor conditions by SHASE[5]-G 0001-1994; "Technical Guideline for Energy Conservation in Architecture and Building Services" [42]. Despite this, other parts of Asia have not followed Japan's lead in lifting HVAC set-points. For instance, Hong Kong bank premises are often running at 19°C in summer and there it has been explained by some *prestige* factor or *ostentation* if they can feel cold and make their guests feel cold in summer [50].

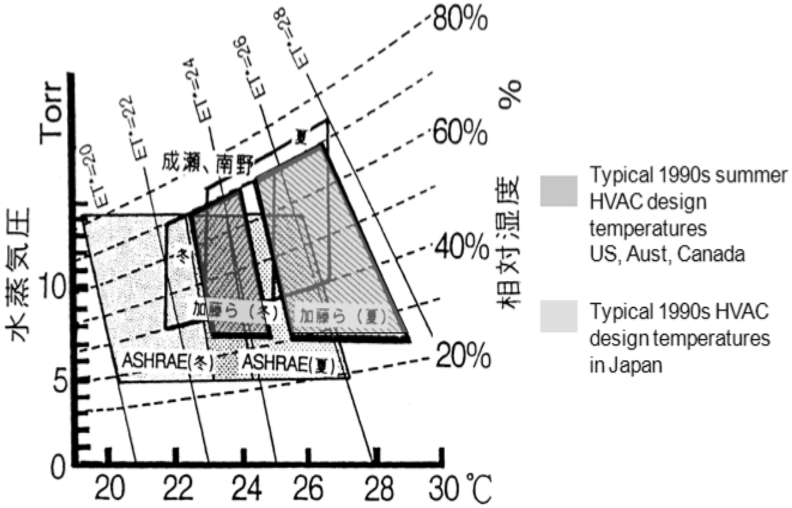


Figure 7 - Differences in typical 90's HVAC design temperatures in Japan and other parts of the world [42].

China, Brazil and India are moving towards standards [12, 13, 51, 52]. Recent developments toward a Chinese thermal comfort standard highlight the interest in incorporating the adaptive model for naturally ventilated buildings [51]. There is an ongoing research project aiming to establish a database of occupant's comfort, thermal performance and

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5SHASE: The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan.

energy consumption across commercial, office and public buildings in India [12, 13].

In the midst of all the action that has transpired in Brazil there are two regulations that must be highlighted: design guidelines for residential sector and the labelling system for commercial buildings. For the residential sector, the “Thermal performance in buildings – Brazilian Bioclimatic Zones and Building Guidelines for Low-Cost Houses” [53] provides requirements related to the thermal envelope, lighting and acoustics, along with minimum requirements for ventilation and opening areas. Eight zones were defined according to their climate characteristics from 330 cities across Brazil. Based upon this division, a set of specific bioclimatic design strategies was indicated focusing its application during the early design stage. Currently, energy efficiency labelling for residential buildings is in progress and will be made public towards the end of 2010.

For commercial and public buildings, there is the newly released “Federal Regulation for Voluntary Labelling of Energy Efficiency Levels in Commercial, Public and Service Buildings” [54]. This new regulation focuses on Brazil’s climate requirements for designers in general with specific items related to lighting systems, HVAC and building envelope. In a similar fashion to the residential sector, the eight bioclimatic zones and design strategies are intended as a reference point for designers and architects [55].

Considering that natural ventilation is indicated in seven of the eight bioclimatic zones in Brazil, a set of standards focusing on air movement enhancement combined with thermal comfort requirements is necessary. The current approach is related to technical aspects and it is frequently associated with airflow distribution in indoor environments, hence recommendations should relate to opening areas and ventilation pattern [53]. This is also the traditional reference for regional buildings’ codes all over Brazil. These requirements undoubtedly contribute to more energy conservation techniques in building’s design. However it is time this topic is taken beyond its minor technical approach and focused on a more holistic understanding of indoor environments. Thermal acceptance in general is not completely fulfilled in existing regulations and field experiments developed in Brazil offer more insight into this issue [56, 57, 58, 59].

Standards are tangible mechanisms for stimulating energy conservation initiatives in the built environment. There is an impetus for "radical new approaches to thermal comfort standards" in response to the energy consumption and environmental impacts intrinsically related to the tight control of indoor environments. Instead, standards that put thermal control into the hands of the buildings users would be more meaningful to, and usable by, architects and occupants alike; consequently, they are more likely to be well understood and therefore will be useful to reduce energy use.

2.4. Pleasant breeze or draft?

Many of the justifications for the shift from naturally ventilated indoor climates to HVAC during the late 20th century emphasised the risk of local discomfort, or draft, in situations where indoor air movement relies on natural processes instead of controllable mechanical ones [28, 60]. As a concept, draft means any unpleasant air movement and is related not only to air temperature and air speed but also other factors such as area, variability and the part of the body that is exposed [28]. Based on laboratory studies, an effect of turbulence intensity on draught discomfort was identified [60] and incorporated into a model that predicts the percentage of dissatisfied due to draught (DR) as a function of mean air velocity ($\bar{v}$), air temperature (t_a) and turbulence intensity (Tu) [60], (Equation 1). The air movement limits for occupants without personal control indicated in ASHRAE [33] and also ISO [35] standards are based on this model.

Equation 1

$$DR = (34 - t_a) \times (\bar{v} - 0.05)^{0.62} \times (0.37 \times \bar{v} \times Tu + 3.$$

Where:

$\bar{v}$: mean air velocity

t_a : air temperature

Tu : turbulence intensity

In current standards, the permissible air velocity values are limited to 0.8m/s as the upper limit of draft perception allowed where occupants have control over their environment [61]. The limits for air speed levels are based on the operative temperature and also the difference between the mean radiant temperature and air temperature [62]. When occupants do not have control over their environment, the limits revert back to Fanger's laboratory based limits for draft in which the air velocity value must not exceed 0.2m/s.

In moderate climates, draft is one of the main sources of complaint in regards to the workplace environment, concerning up to one third of office workers and at least two thirds of workers in moderately cold environments [65, 66]. No consistent influence of thermal sensation was found in these studies, although a cool thermal sensation seemed to increase draft complaints at low air velocities and decrease draft complaints at high air velocities. One reason for the large number of draft complaints among people working in cool or cold environments is simply because they are more sensitive to draft than people who feel thermally neutral [63]. In situations where people are more likely to feel warmer than neutral, the situation is qualitatively different.

The environmental variable *draught* has also been examined in recent field studies. The ASHRAE 55 [33] and ISO 7730 [35] predicted percent dissatisfied for draught risk (DR) were developed from climate chamber experiments of great specificity, but because there are many other types of air movement conditions present in occupied buildings (direction of draught, position of occupant, body parts affected, thermal status and activity of the occupants), field studies found tend to report actual preferences and levels of dissatisfaction expressed by building occupants bear no resemblance to the DR predictions whatsoever, especially when the temperature is above 'slightly cool' (~ 22.5ºC) [45]. In neutral-to-warm conditions, occupants happily accept (even prefer) substantially higher levels of air movement than predicted by the DR model.

Fountain [67] used laboratory methods to focus on air movement preferences when occupants had control over air movement. The outcome of that research was an index known as Predicted Percent Satisfied (PS), defined as the fraction of a sample of persons that prefer a certain level of air velocity or lower, at a particular air velocity and operative temperature. The PS model can be used to predict the percent of satisfied persons in an office environment where locally controlled air movement is available. The model was developed based on experiments carried out in and above the upper temperature range of the comfort zone (25.5°C to 28.5°C). A comparison of predictions made with the DR and the PS model is not valid because of the different assumptions concerning temperature and control of air movement [65].

Air movement preferences inside actual buildings have been examined by Toftum [65] based on the ASHRAE RP-884 database [36]. The results indicated as one might expect, that people who feel cold prefer ‘less air movement’, and those who feel hot prefer ‘more air movement’, with the dividing line being *circa* 22–23°C. Figure 8 and Table 1 show these results. Nevertheless, the distribution of air velocities measured during field studies was skewed towards rather low values. This is true even though occupants in the database buildings rarely had individual control over air movement. It is worth investigating other sources of data on air movement effects in actual buildings, with or without individual; personal control, because air movement limits imposed by current standard come with inherent energy penalties and may not be providing occupants with the indoor environments they prefer.

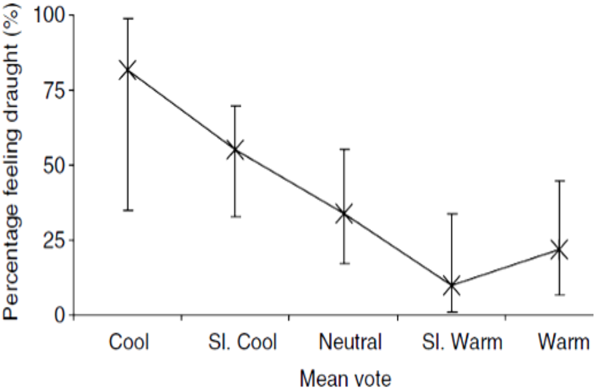


Figure 8 - Percentage of people feeling draft as a function of their mean thermal vote. Error bars show 95% upper and lower confidence limits [65].

Table 1 - Air movement preference as observed for ASHRAE field studies [65].

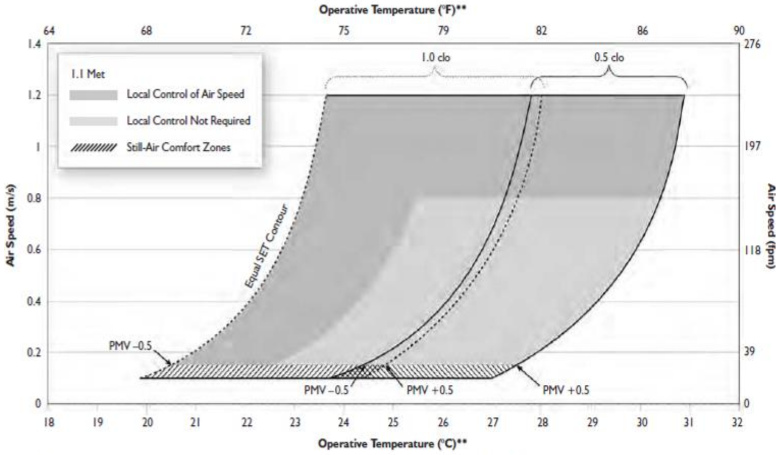
Thermal sensation	Air velocity (m/s)	Occupant’s air movement preference (%)		
		Less	no change	more
Slightly cool	0 - 0.15	13.6	46.3	40.1
	0.15 - 0.25	16.7	41.7	41.6
Neutral	0 - 0.15	2.0	46.0	52.0
	0.15 - 0.25	2.0	68.6	29.4
Slightly warm	0 - 0.15	2.7	21.6	75.4
	0.15 - 0.25	8.4	33.3	58.3

In hot-humid climates, natural ventilation plays an important role in controlling indoor air quality, indoor temperature, and also prevents the risk of occupants overheating [68]. Investigations indicate that inadequate ventilation is probably the most important reason for occupant discomfort in naturally ventilated buildings [68]. Based on this scenario and in order to define the *maximum* air velocity range acceptable for the occupants, many studies were carried out and it is possible to identify considerable differences between them.

A pioneer study by Rohles et al. [70], examining the effects of air flow provided by fans, indicates that for an air velocity of 1m/s, the effective temperature can be extended to 29°C. In a similar investigation [71] it was found that at least 80% of the occupants can be comfortable for a temperature limit of 28°C and air velocities of 1.02m/s. Other studies found that, for the same temperature and thermal acceptability, the air velocity values should be from 1.0 to 1.5m/s [72] and from 0.2 to 1.5m/s [73]. Higher values, up to 1.6m/s, were suggested to maintain the occupants’ thermal comfort for a temperature of 31°C [74, 75]. Melikov et al. [76] and Olesen and Nielsen [77] investigated human responses to local cooling with air jets in warm conditions and found that the air jet velocity preferred by the subjects was not the same as that corresponding to thermal neutrality, but the one decreasing the sensation of warmth without causing too much discomfort due to draft. These studies clearly indicate how higher air velocities in warmer indoor environments can influence on human thermal acceptability and comfort.

Focusing on occupants’ satisfaction, other experiments indicate that the draft limit proposed by ASHRAE and ISO standards should not be applied when people feel neutral or warmer [78, 79]. Even when people are slightly cool, the ASHRAE and ISO standards' prediction of draft discomfort overestimates the dissatisfaction percentage actually observed [79]. "Air movement too low", "air movement too high", "draft from windows", and "draft from vents" were recorded as main sources for dissatisfaction for a significant percentage of the occupants and all refer to air movement.

In a recent review by Arens et al. [20] of air movement preferences from the ASHRAE RP-884 database concluded that for thermal sensations from 0.7 to 1.5, air movement should be encouraged [20]. The air movement should not be made so great that it leaves people feeling cold, but a certain amount of it does answer a basic need found in the surveys, and can offset an increase in temperature in the space. Similar results have been found for a building in which occupants have personal or group control over window ventilation. Based on these findings, the authors proposed a two-step process in order to define comfort zones, considering temperature, radiant heat, humidity and air movement (see Figure 9).



** In determining operative temperature, use the lowest air temperature in the occupied zone. In this Figure, $t_r = t_a$

Figure 9 - Air speed limits proposed by Arens et al. [20].

This new procedure encourages elevated air speeds in combination with the standard effective temperature and occupant's control requirements. The authors add that "…these new provisions allow designers to use fans, stack effects, or window ventilation to offset mechanical cooling, or in some climates, supplement it entirely" [20]. This new provision is indeed a big step forward in encouraging air speed enhancement in indoor environments as well as occupant control.

When combined, all these studies suggest that relaxing the current draft limit for neutral-to-warm conditions (above 26°C) would open up opportunities for saving energy that, under current regulations and standards, is now restricted to personally controlled air movement devices. None of the previous research reviewed here has explicitly addressed air movement acceptability; the focus to date has been on overall thermal sensation and comfort. As a consequence, it is essential to conduct field experiments in real buildings with real occupants in order to start filling some of these gaps properly. It is of course desirable to give occupants personal control over air movement, but the practical ways of achieving this remain limited.

2.5. The role of occupant control

Control over air velocity is considered a form of behavioural adaptation when people are able to make the environmental adjustments themselves such as opening or closing a window, turning on a local fan, or adjusting an air diffuser. The adaptive model has long insisted that a given thermal environmental stimulus can elicit disparate thermal comfort responses, depending on the architectural context in which it is experienced [67]. It has been noted that thermal environmental conditions perceived as unacceptable by the occupants of centrally air-conditioned buildings can be regarded as perfectly acceptable, if not preferable, in a naturally ventilated building [40].

From a psychological perspective, studies reveal that offering personal control over the indoor environment seems to be very effective in minimizing negative effects, such as stress. [81]. Other studies demonstrated that control has a direct effect in the occupants and their satisfaction with their work environment in general, acting as "compensation" [82]. Data from the same authors showed that occupants tend to be more forgiving of daily malfunctions in their work environments, such as problems with equipments and systems, when they had greater degrees of freedom in adapting their immediate indoor conditions.

Relationships between occupants' control and sick building syndrome have also been found. A large field study conducted in 47 English office buildings revealed that occupants with limited control over their indoor environment were most likely to show symptoms such as dry eyes, dry throat, stuffy nose, itchy eyes and lethargy [83]. Results from similar field experiments in Germany corroborate these results. Indeed occupants with limited control generally showed more signs of sick building symptoms [84].

Focusing on thermal comfort, other researchers found that occupants with access to desk lighting, windows and adjustable HVAC set points are by far more satisfied with their work environments than those occupants without these opportunities [85]. Results from a large survey in the US provide further indications of the control – satisfaction relationship [86]. An extensive study carried-out in mixed-mode buildings in the US clearly show that the main reasons for dissatisfaction with the indoor environment were related to lack of control [87]. The main results are presented in Figure 10. Occupants reported complaints such as temperature (‘my area is hotter/colder than other areas’), control (‘thermostat is inaccessible’ or ‘adjusted by other people’), lack of air movement (‘air movement too low’), and speed of response (‘heating/cooling system does not respond’. The authors concluded that these “…occupants’ comments in the surveys, combined with findings from other research in the field, suggest that people value operable windows for a wide variety of reasons – personal control of their thermal environment, increased air movement, perceived fresh air, and connection to the outdoors” [87].

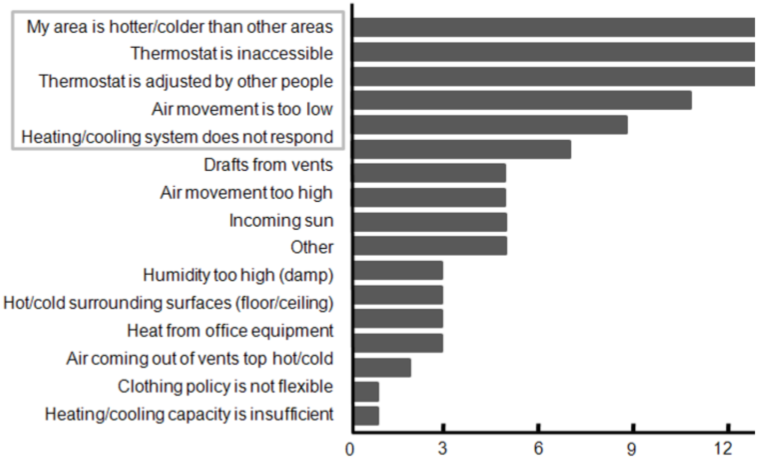


Figure 10 - Reasons for thermal dissatisfaction in mixed-mode buildings in the US [87].

More recent research "…confirms the importance of having some level of direct control over the environmental conditions in the workplace to occupant satisfaction" [15]. So is the challenge of new or reviewed standards to somehow include occupant control? As pointed-out in Zweers et al. [84] and reiterated by Boerstra [88], "...offering occupants control over their indoor climate results in fewer less sick building symptoms, higher comfort satisfaction rates and improved performance. People have expectations and, when they are not fulfilled, they will complain". But how certain are the occupants about what they really want from their thermal environment?

Commenting about occupant's behaviour and expectations, Leaman and Bordass [89], said that "…people usually strive to give their personal environment as much variety as they think is required to carry out their range of tasks comfortably - not too hot, not too cold, not too much space, not too little, and so on". If the necessary requirements cannot be met, people often become uncomfortable or dissatisfied. Tolerance ranges (sometimes termed "envelopes", as in "comfort envelope") differ from one person to the next, and vary with status, roles, tasks, goals and working situations". Therefore, the overall conclusion, as confirmed by many available studies, is that offering occupants control over their indoor climate results in fewer health symptoms, higher comfort satisfaction rates and improved performance of building occupants. It seems very logical to include the aspect of personal control over indoor climate in future (thermal) comfort standards.

2.6. For more pleasurable and stimulating indoor environments: a physiological approach

Kerslake said "…it is a matter of common experience that the air temperature alone is not an adequate indication of environmental warmth. Everyone recognizes the importance of wind, sunshine and humidity, and the notion that all these factors might be combined into a single figure indicating warmth is immediately *attractive*" [90]. "If we agree that thermal environments that are slightly warmer can still be acceptable to building occupants (as the adaptive comfort model suggests) [3], then the introduction of elevated air motion into such environments should be universally regarded as desirable because the effect will be to remove sensible latent heat from the body, thereby restoring body temperatures to their comfort set-points…". Such hypothesis can be explained by the principle of *alliesthesia* [91].

In a classic paper titled "The physiological role of pleasure" [91], Cabanac explains that "…in light of this theory, it is possible to reconsider the nature of the whole conscious experience. The existence of alliesthesia implies the presence of internal signals modifying the conscious sensations aroused from peripheral receptors". This conscious experience, as a result of a stimulus, can be pleasant or unpleasant, and it will be related to the subject's internal state. Cabanac coins the word 'alliesthesia' to describe this occurrence perceived by human senses. Alliesthesia is essential to regulatory negative feedback systems relying on behavioural interventions, such as: hunger, thirst and thermoregulation [92].

The emergent application of thermal alliesthesia to the thermal comfort as explored by de Dear [95] "…investigates situations in which a peripheral thermal sensation can assume either positive or negative hedonic tone, depending on the state of core temperature in relation to its thermo-neutral set-point. A slight breeze on the skin brings thermal pleasure ('breeze') when the core temperature is displaced slightly above neutral. Yet the same peripheral air movement is perceived as an unwanted 'draught' if the core temperature is below its set-point". The schematic Figure 11 shows these interrelations between the negative alliesthesia as result of *antagonism* between core and periphery and the positive alliesthesia as a result of the *complementary* relationship between core and periphery.

Zhang [93] says that "…when we perceive warmth or coolth, we do not actually sense the temperature of the room's air or surfaces directly, but rather our nerve endings, the thermoreceptors, which send signals to the hypothalamus at the base of the brain when stimulated. The thermoreceptors are sensors that signal the conditions of the space around us and permit us to feel those conditions as thermal sensations". Nakamura et al. [94] points out that it is generally assumed that inputs from the same warm or cold skin thermoreceptors are utilized for both temperature sensation and thermal comfort, although there is no direct experimental evidence for this supposition. Although it is difficult to quantitatively evaluate differences in the density of skin thermoreceptors in humans, the density of hot and cold spots would be expected to correlate positively with the density of warm and cold receptors.

de Dear [96] explains that skin thermoreceptors provide the *data from the environment* to compare against *deep body temperature* (the controlled variable). The rate of firing (i.e. frequency of neural output) of skin thermoreceptors has a *steady-state* component, and a *transient* component (i.e. firing frequency) Accelerations in air velocity on skin surface trigger dynamic discharges from the skin’s cold thermoreceptors. So, in the warm adaptive comfort zone these turbulence-induced dynamic discharges from exposed skin’s cold thermoreceptors elicit small bursts of positive alliesthesia. When the core temperature is *warmer* than the core set-point, any peripheral stimulation of *cutaneous cold receptors* will trigger positive alliesthesia. In light of this theory, the fluctuations in temperature and air movement in naturally ventilated buildings would be regarded as thermal pleasure by the occupants.

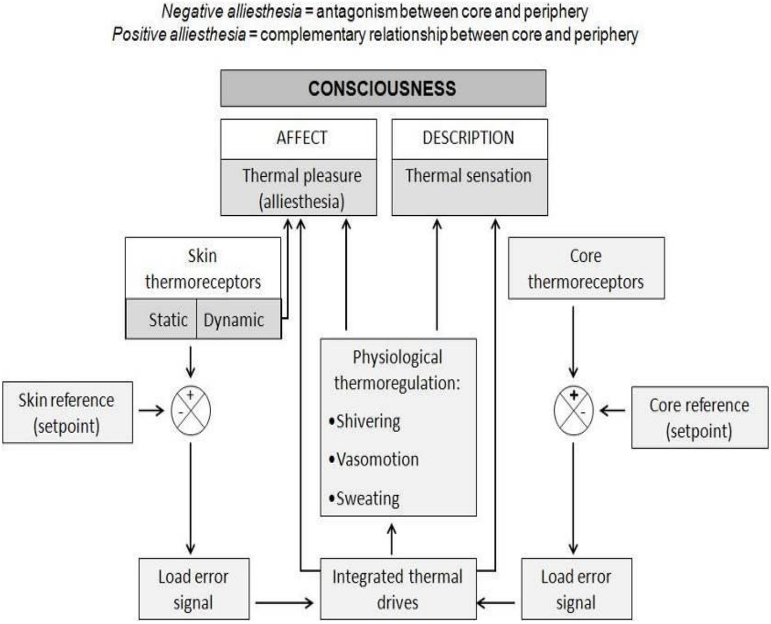


Figure 11 - Negative and positive alliesthesia [93].

The thermal pleasure or ‘thermal delight’ explored by Herchong [98] indeed aligns with the adaptive model and it provides more evidence why naturally ventilated indoor environments would provide more satisfied occupants. Researching the interaction of peripheral and core thermal states as they relate to thermal pleasure and displeasure holds considerable promise for the design of energy-efficient indoor environments. However, such research requires control over internal and peripheral thermal states, suggesting an experimental method based on controlled climatic conditions rather than uncontrolled studies in field settings [95].

2.7. Background summary

This chapter dicussed the state of the art within air movement and thermal comfort research field. In summary:

- The dialectic between conventional and the adaptive comfort theories can be seen in innumerable papers and it became more prominent by the end of the 20th century with the realization of the (unsustainable) energy carbon required to air conditioned indoor environments. The adaptive comfort showed that occupants play an active role in creating their own thermal preferences, and satisfaction with an indoor environment occurs through appropriate adaptation. The ASHRAE 55 adaptive model offered a new approach towards naturally ventilated buildings and its broadly influence is recognized within the thermal comfort research field. However, there are questions remaining regarding the upper and also lower limits applied for thermal acceptability, especially when higher air velocities values than those experienced by occupants during the RP-884 comfort database are provided. More research seems to be necessary, particularly in hot-humid climates. There are also other factors, such as thermal history, that can provide more information about limitations of thermal acceptabililty in naturally ventilated indoor environments and it should be more explored by thermal comfort research.

- The revival of natural ventilation as a research topic corroborates the importance of this design strategy in providing stimulating indoor environments. Naturally ventilated buildings indeed provide indoor environments with higher percentages of occupants overall satisfaction and it presents enourmous potential in contributing to energy conservation challenges faced by the building sector. There are important questions remaining related to allowable air velocity values (maximum) and occupants control within the occupied zone that should be investigated in more depth. Much has been done focusing when air movement is ‘unwelcome’ (i.e. draft) but there is an enormous potential in research considering air movement enhacement in buildings as a ‘welcome breeze’. Especially in hot-humid climates, this research topic is pivotal in providing thermally acceptable indoor environments and occupants’ satisfaction.

- In Brazil, energy efficiency became an emergent topic after the energy crisis in 2001. Thermal comfort research has improved in providing insight about thermal acceptance across the vast Brazilian territory. The weight of research done so far focuses on thermal sensation, preference and acceptability in buildings where occupants wear uniforms and adaptive oportunities are limited or nonexistent (high school classrooms, army headquarters, etc.). Air movement still remains as a research topic without much attention from Brazilian researchers and individual air velocity measurements are often not taken in field experiments. Interestingly, natural ventilation is indicated as one of the main bioclimatic design strategies in Brazil and, as such, should be studied in more detail within the thermal comfort research field. More field studies combining thermal comfort and air movement issues are therefore necessary.

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Method

III. Method

The fundamental feature of this field research design is the proximity, in time and space, of the indoor climate observations with corresponding comfort questionnaire responses from the occupants of naturally ventilated buildings. Two field experiments took place in Maceio, during the cool (August - September) and also hot seasons (February - March). This chapter presents detailed information about the methodological design applied in order to develop this thesis and all publications related to this project were based on the same method presented here.

3.1 Regional context: Maceio’s climatic environment

Brazil is the largest country in South America and its dimension cover almost half of the subcontinent’s land area. Brazil’s surface area is 8,574 km^2 making it the fifth largest country in the world, measuring 4,345 km from its most northerly point to the its southern tip, and 4,330 km from east to west [1]. Maceio city is located on the north-east sea coast of Brazil (9º31' S, 35º42' W). The low latitude combined with high solar radiation intensity, as well as proximity to large warm water surfaces – ocean and lagoons – elevates the humidity level. Hence the climate is classified as hot and humid (Aw) according to Köppen’s classification.

Approximately 92% of Brazil’s land mass lies between the tropics, together with its relatively low topography, account for the predominantly hot climate, with annual average temperatures above 20° C. The climate varies due to geographical and topographical factors, the continental dimensions of the country and the dynamics of air movement, which directly influence temperatures and rainfall [1]. Maceio’s climate is very equable, which is typical of the north-east coast of Brazil. Seasons are divided into winter and summer, although the “winter” remains warmer than many mid-latitude climate zones’ summers. Because of this, summer can be classified as a “hot season” and the winter as a “cool season” (these descriptions will be applied for this thesis).

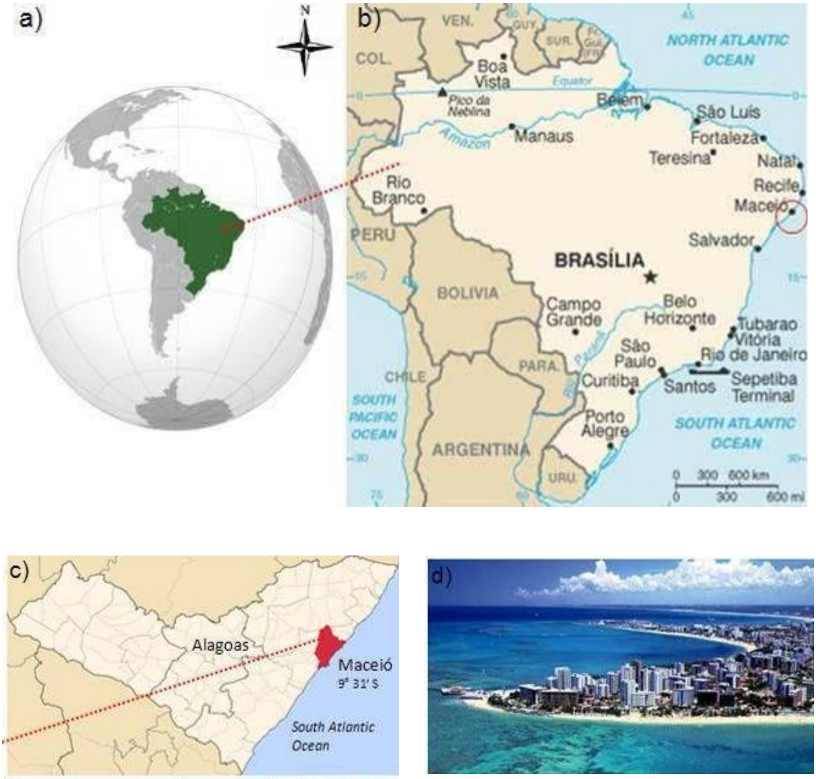


Figure 1 - South America and Brazil (a), Brazil’s capital cities (b), Alagoas state and Maceio city and (c) Maceio seacoast view (d).

Figure 2 presents Maceio’s annual temperature, rainfall and humidity and Table 1 summarizes the outdoor meteorological conditions during the surveys. The mean annual temperature is around 26ºC and the annual thermal amplitude is 3.4ºC (the highest monthly average occurs in February – 26.7ºC and the lowest monthly average in July – 23.7ºC) [2]. Typically, the hottest days occur between November to February and the coolest days from June through to August. The mean relative humidity is around 78% during the hot season and 84% during the cool season. However, it is possible to encounter saturation (100%) during cooler, rainier periods. The annual average rainfall is around 1654 mm and the typical rainy season occurs from April to July.

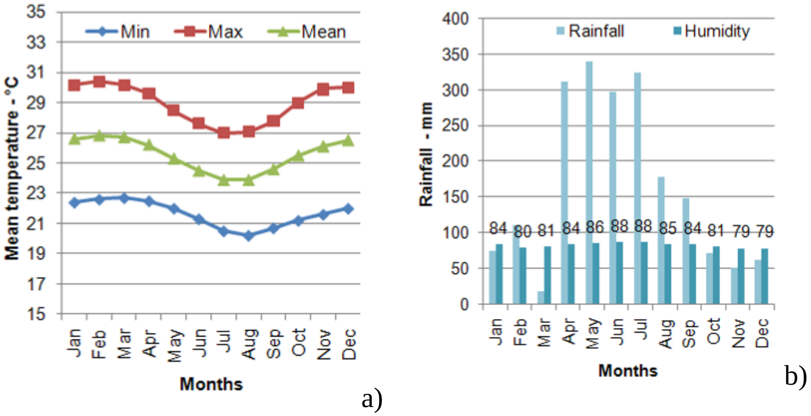


Figure 2 - Maceio's monthly temperature (a) and rainfall/humidity (b) [1].

Table 1 - Outdoor meteorological conditions during the surveys.

Measurement	Hot season			Cool season		
	Ave	Max	Min	Ave	Max	Min
Outdoor temperature (°C)	25.2	28.2	22.4	24.0	26.8	21.4
Outdoor relative humidity (%)	74.8	88.9	56.1	75.0	91.0	57.0
Mean monthly outdoor temperature (°C)	25.3	30.2	23.7	23.5	27.1	20.2

Maceio is under the influence of the south-east and north-east trade winds within the broad scale atmospheric circulation. As an overall frequency distribution, the most frequent direction is southeast, with the northeast presenting the higher values in air speed. Interestingly, the wind frequency increases in speed during the day, achieving the highest values during the afternoon coinciding with the period when air motion is needed the most for thermal comfort purposes [3]. During the warm season, there is an increase in speed from the northeast winds and in frequency from the southeast whereas the number of hours without breeze decreases. Moreover, during the cool season, southeast winds bring along the rain and there is a significant decrease in terms of frequency and speed for east quadrant winds.

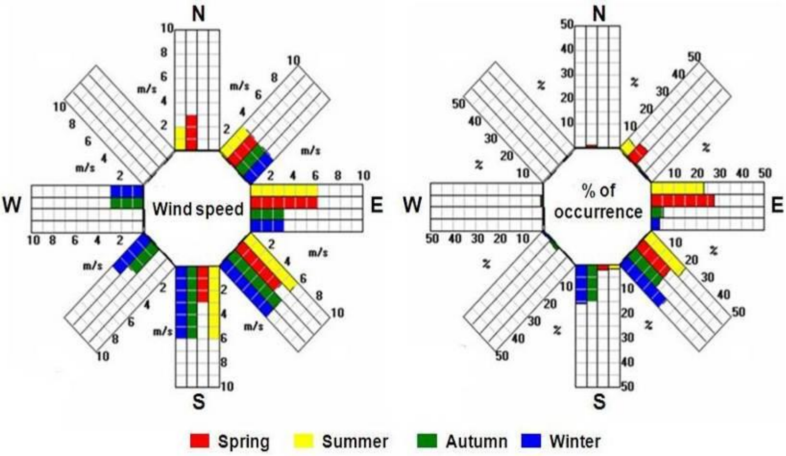
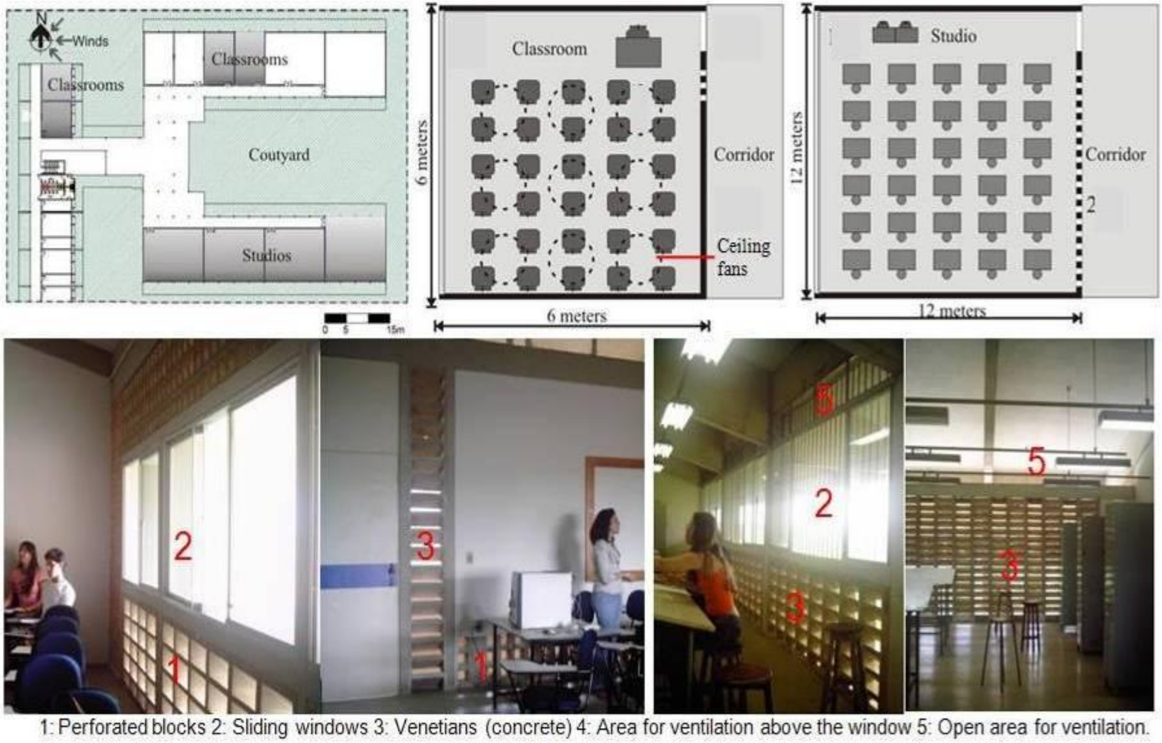


Figure 3 - Wind speed and direction rose.

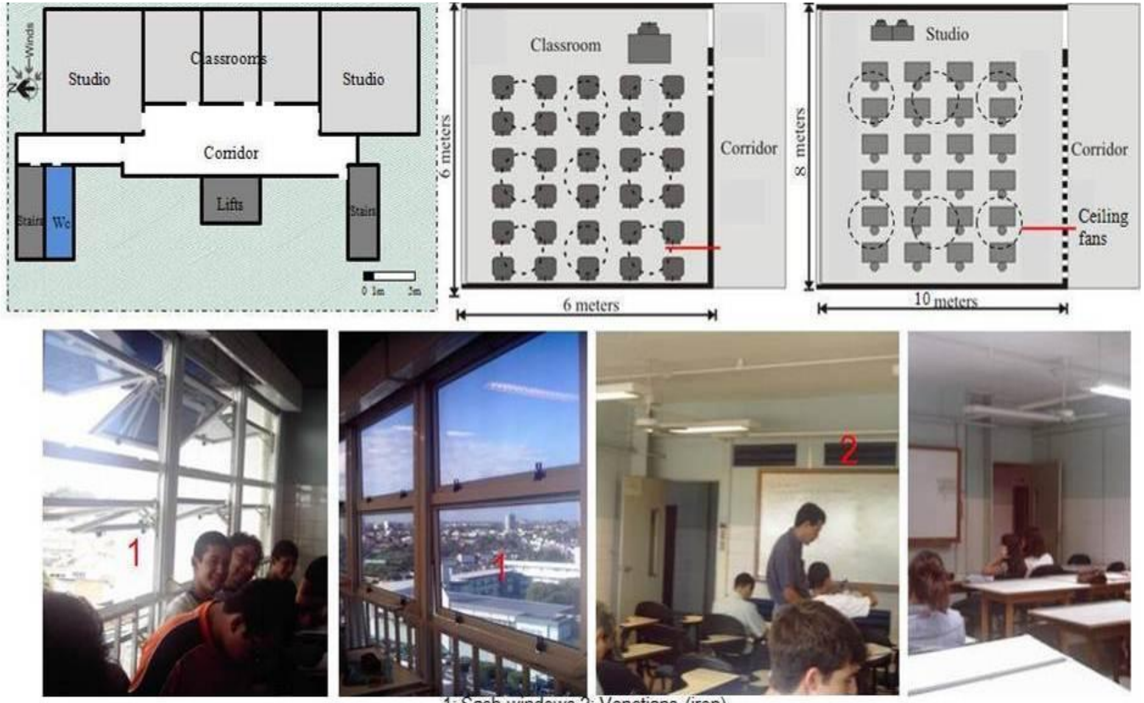
3.2 The sample buildings and its occupants

When choosing the indoor environments for this study the following criteria was applied: (i) windows had to be easy to access and operate; (ii) rooms could not have a mechanical cooling system (refrigerated air-conditioning); (iii) rooms could have complementary mechanical ventilation with unconditioned air (fans); (iv) opening and closing of windows had to be the primary means of regulating thermal conditions; and (v) the occupants had to be engaged in near sedentary activity (1-1.3 met)[4], and permitted to freely adapt their clothing to the indoor and/or outdoor thermal conditions[5].

Some rooms of the Federal University of Alagoas and the Superior Studies Centre of Alagoas fitted these selection criteria and were chosen for this survey. Figure 4 a and b shows detailed information about both buildings. Even though this research was conducted in educational buildings, the specific rooms selected were those in which occupant activities could potentially have been disturbed by higher air velocities; architecture design studios and classrooms occupied by students carrying out drawings or building delicate scale prototypes of buildings.


N
Winds
Classrooms
Classrooms
Coutyard
Studios
0 5 15m
Classroom
6 meters
6 meters
Corridor
Ceiling fans
Studio
12 meters
12 meters
Corridor
2
1
2
3
1
5
2
3
5
3
1: Perforated blocks 2: Sliding windows 3: Venetians (concrete) 4: Area for ventilation above the window 5: Open area for ventilation.

a)



1: Sash windows 2: Venetians (iron).

b)

Figure 4 - Classrooms and studios at Federal University of Alagoas (a) and Superior Studies Center of Alagoas (b).

Two field experiments took place in Maceio, during the cool (August - September) and also hot seasons (February - March). A total of 2,075 questionnaires were completed during field campaigns and Table 2 summarizes the occupant samples' profiles. The sample of respondents reflected the gender imbalance of Brazil's architecture student population, and was biased towards females. Occupants' activities were not deliberately influenced by the researchers and they were allowed to freely adapt their clothing as well as cooling devices that were accessible to them at the time of the survey (windows and ceiling fans). Occupants' clothing selection was also left to vary according to their wishes at the time of survey, and the sampled ensembles consisted of light garments, varying from 0.25 to 0.70 *clo* during the experiments, see Figure 5. These *clo* values were estimated according to garment check-lists in ASHRAE 55 [4].

Table 2 - Occupants' profile per season.

Season		Hot	Cool
Sample size		915	1160
Gender	Female	79%	66%
	Male	21%	34%
Age (year)	Ave	21.0	20.8
Height (m)	Ave	1.70	1.70
Weight (kg)	Ave	59.1	59.5

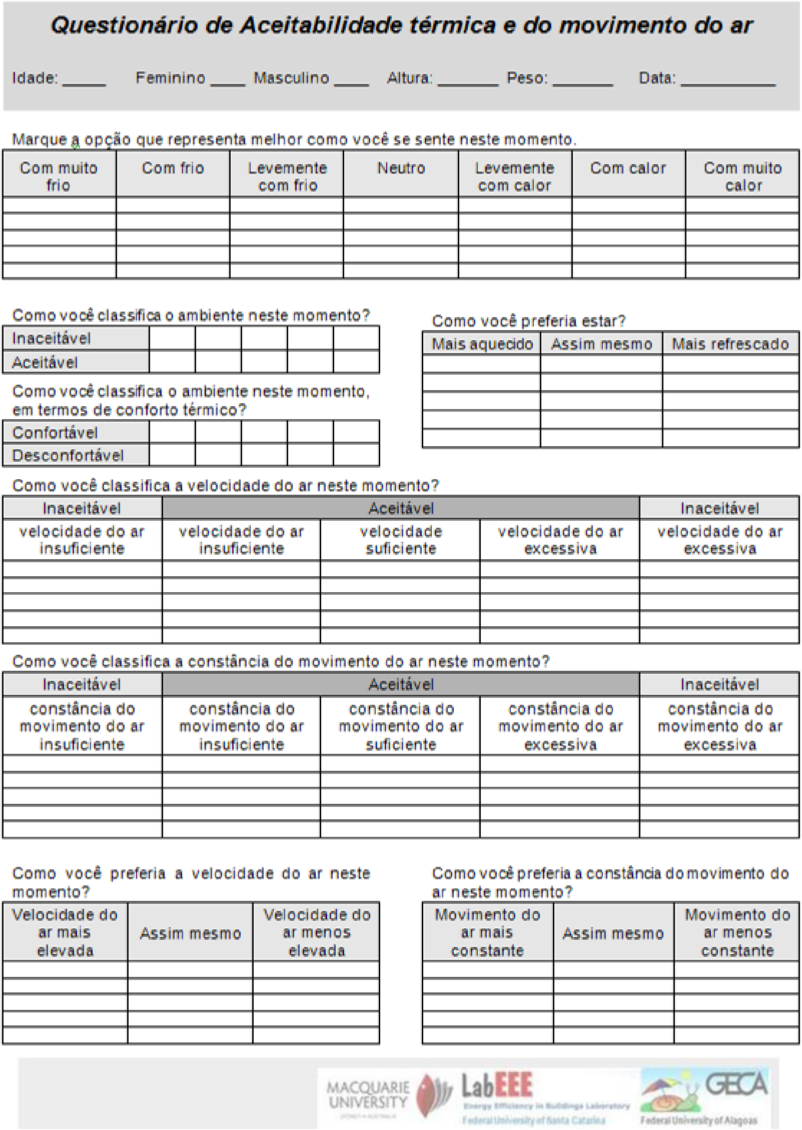
Figure 5 – Occupants' typical clothes for hot (a) and cool season (b).

3.3 Questionnaires

The questionnaire adopted for this research was focused on thermal and air movement issues aimed to characterize whole body thermal comfort and also identify the subjects' air movement acceptability. The questionnaire was applied in occupants' native language (Portuguese), see Figure 6. This version was tested and refined during pilot surveys before the final experiments in order to consider semantics' implications [6][7]. Figure 7 presents the English version.

The questionnaire was presented in three parts. The first corresponds to the subjects' demographic and anthropometric characteristics such as age, height, weight and gender. The second included questions relating to thermal comfort, air movement acceptability and their pattern of air-conditioning usage. In the thermal comfort section, subjects were asked about their own thermal comfort conditions, their personal preferences and also about the room itself, at the time of questionnaire. The well-established thermal sensation scale, preference and acceptability questionnaire items were excerpted from previously published field experiments [5].

The air movement questions focused on air movement acceptability as it related to air speed. In this case, subjects registered if the air velocity was "acceptable" or "unacceptable" and their reason, such as "too low air velocity", "too high air velocity", etc. The third and last part of the questionnaire related to the subjects' activities during the hour prior to the measurement process. It also recorded information about the subjects' clothing by way of a garment checklist. The subjects started answering the questionnaire at least thirty minutes after they arrived in the room in order to avoid any influence from their previous activities. Each subject answered the questionnaire on five separate occasions during the same experiment.



Questionário de Aceitabilidade térmica e do movimento do ar

Idade: _____ Feminino ____ Masculino ____ Altura: _______ Peso: _______ Data: __________

Marque a opção que representa melhor como você se sente neste momento.

Com muito frio	Com frio	Levemente com frio	Neutro	Levemente com calor	Com calor	Com muito calor

Como você classifica o ambiente neste momento?

Inaceitável					
Aceitável					

Como você classifica o ambiente neste momento, em termos de conforto térmico?

Confortável					
Desconfortável					

Como você preferia estar?

Mais aquecido	Assim mesmo	Mais refrescado

Como você classifica a velocidade do ar neste momento?

Inaceitável	Aceitável			Inaceitável
velocidade do ar insuficiente	velocidade do ar insuficiente	velocidade suficiente	velocidade do ar excessiva	velocidade do ar excessiva

Como você classifica a constância do movimento do ar neste momento?

Inaceitável	Aceitável			Inaceitável
constância do movimento do ar insuficiente	constância do movimento do ar insuficiente	constância do movimento do ar suficiente	constância do movimento do ar excessiva	constância do movimento do ar excessiva

Como você preferia a velocidade do ar neste momento?

Velocidade do ar mais elevada	Assim mesmo	Velocidade do ar menos elevada

Como você preferia a constância do movimento do ar neste momento?

Movimento do ar mais constante	Assim mesmo	Movimento do ar menos constante

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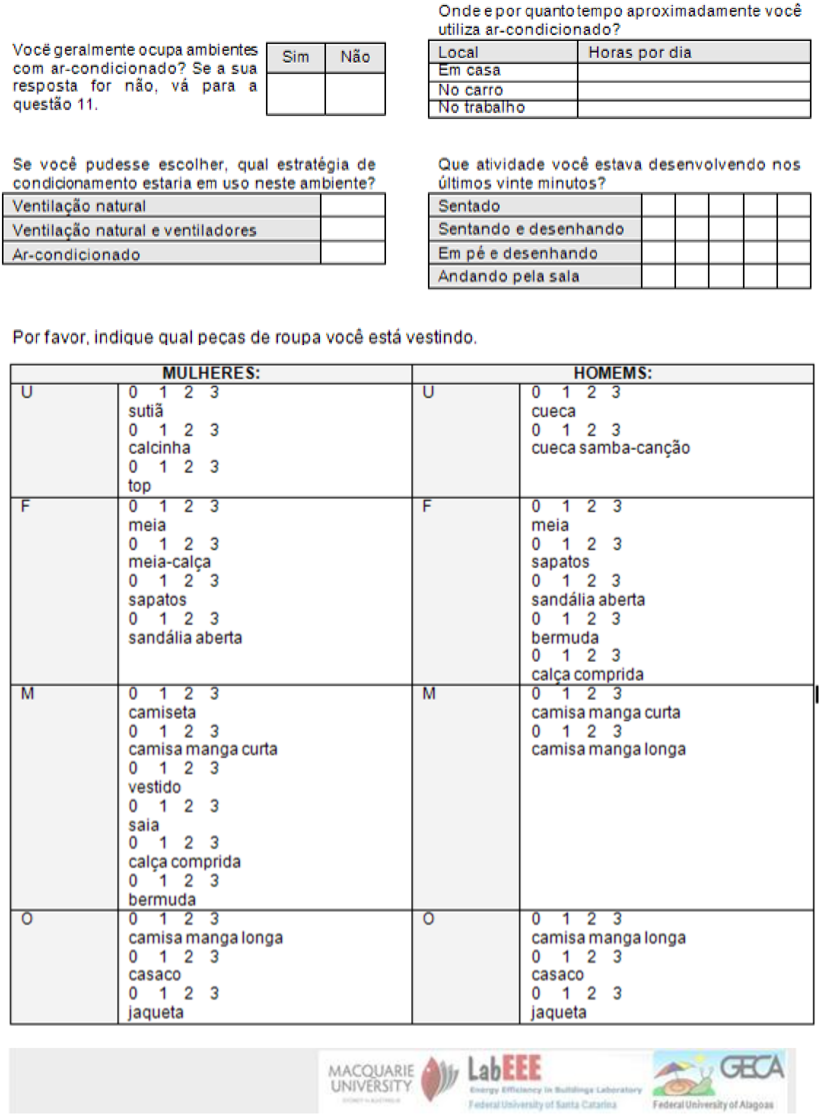
Figure 6 - Thermal comfort questionnaire – Portuguese version.



Você geralmente ocupa ambientes com ar-condicionado? Se a sua resposta for não, vá para a questão 11.

Sim	Não

Onde e por quanto tempo aproximadamente você utiliza ar-condicionado?

Local	Horas por dia
Em casa	
No carro	
No trabalho	

Se você pudesse escolher, qual estratégia de condicionamento estaria em uso neste ambiente?

Ventilação natural	
Ventilação natural e ventiladores	
Ar-condicionado	

Que atividade você estava desenvolvendo nos últimos vinte minutos?

Sentado					
Sentando e desenhando					
Em pé e desenhando					
Andando pela sala					

Por favor, indique qual peças de roupa você está vestindo.

MULHERES:		HOMEMS:	
U	0 1 2 3 sutiã 0 1 2 3 calcinha 0 1 2 3 top	U	0 1 2 3 cueca 0 1 2 3 cueca samba-canção
F	0 1 2 3 meia 0 1 2 3 meia-calça 0 1 2 3 sapatos 0 1 2 3 sandália aberta	F	0 1 2 3 meia 0 1 2 3 sapatos 0 1 2 3 sandália aberta 0 1 2 3 bermuda 0 1 2 3 calça comprida
M	0 1 2 3 camiseta 0 1 2 3 camisa manga curta 0 1 2 3 vestido 0 1 2 3 saia 0 1 2 3 calça comprida 0 1 2 3 bermuda	M	0 1 2 3 camisa manga curta 0 1 2 3 camisa manga longa
O	0 1 2 3 camisa manga longa 0 1 2 3 casaco 0 1 2 3 jaqueta	O	0 1 2 3 camisa manga longa 0 1 2 3 casaco 0 1 2 3 jaqueta

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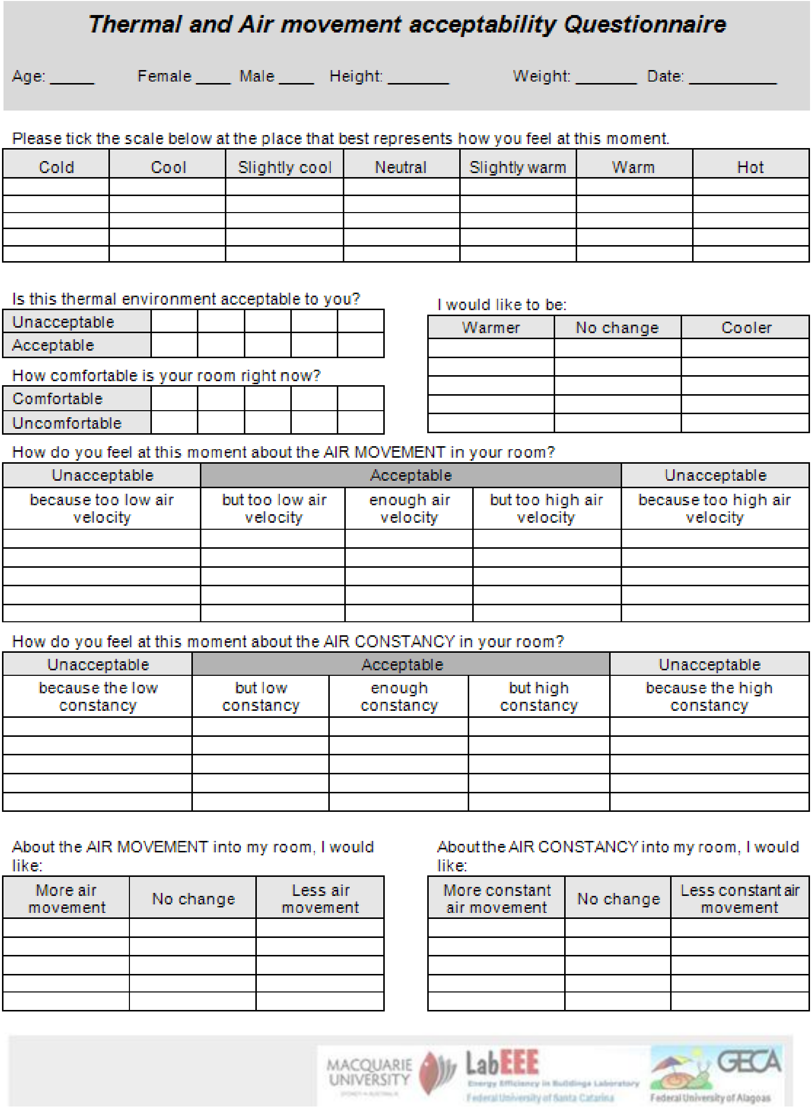

Thermal and Air movement acceptability Questionnaire

Age: _____ Female ____ Male ____ Height: _______ Weight: _______ Date: __________

Please tick the scale below at the place that best represents how you feel at this moment.

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

Is this thermal environment acceptable to you?

Unacceptable					
Acceptable					

How comfortable is your room right now?

Comfortable					
Uncomfortable					

I would like to be:

Warmer	No change	Cooler

How do you feel at this moment about the AIR MOVEMENT in your room?

Unacceptable	Acceptable			Unacceptable
because too low air velocity	but too low air velocity	enough air velocity	but too high air velocity	because too high air velocity

How do you feel at this moment about the AIR CONSTANCY in your room?

Unacceptable	Acceptable			Unacceptable
because the low constancy	but low constancy	enough constancy	but high constancy	because the high constancy

About the AIR MOVEMENT into my room, I would like:

More air movement	No change	Less air movement

About the AIR CONSTANCY into my room, I would like:

More constant air movement	No change	Less constant air movement

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Figure 7 - Thermal comfort questionnaire – English version.

Do you normally use air conditioned indoor environments? If NO, please go to question 11.	Yes	No

Where and for how long do you normally stay in air conditioning indoor environments?

Place	Hours per day (approx.)
at home	
in my car	
in my office	

If you could choose, which one of these cooling strategies would you like to have into this room?

Natural ventilation	
Natural ventilation and fans	
Air conditioned	

What activities have you been engaged during the last twenty minutes?

Sitting quietly					
Sitting drawing					
Standing, drawing					
Walking around					

Please indicate whether you are wearing any of the items listed below:

FEMALES:					MALES:				
Under layer:	0	1 top	2	3	Under layer	0	1 top	2	3
	0	1 bottom	2	3		0	1 bottom	2	3
	0	1 slip	2	3					
Footwear:	0	1 socks	2	3	Footwear:	0	1 socks	2	3
	0	1 pantyhose	2	3		0	1 shoes	2	3
	0	1 shoes	2	3					
Mid layer	0	1 short sleeved shirt	2	3	Mid layer	0	1 short sleeved shirt	2	3
	0	1 long sleeved shirt	2	3		0	1 long sleeved shirt	2	3
	0	1 dress	2	3		0	1 pants	2	3
	0	1 skirt	2	3		0	1 shorts	2	3
	0	1 pants or slacks	2	3					
	0	1 shorts	2	3					
Outer layers	0	1 sweater	2	3	Outer layers	0	1 sweater	2	3
	0	1 vest	2	3		0	1 vest	2	3
	0	1 jacket	2	3		0	1 jacket	2	3

3.4 Indoor climatic instrumentation and measurement protocol

Two field experiments took place in Maceio, during the cool (August - September) and also hot seasons (February - March). Subjects were requested to assess both their room's thermal comfort and air movement five times within a 110 minute period following a 30 minute settling-in period upon entering their studios/classrooms. Apart from permitting subjects' metabolic rates to settle down to approximately sedentary levels [8], this initial 30 minute period was used to set-up the indoor climatic instruments and to explain the questionnaire to the occupants in detail.

Figure 8 presents a schematic of the field measurement protocol. Measurements were taken during morning and afternoon lectures, for at least two hours in each period. Subjects' activities were not interrupted in order to characterize the typical use of rooms and studios, and they were also allowed to normally use ceiling fans, task lighting and also control the openings (to close or to open doors) as well as adjust their clothing, as described previously.

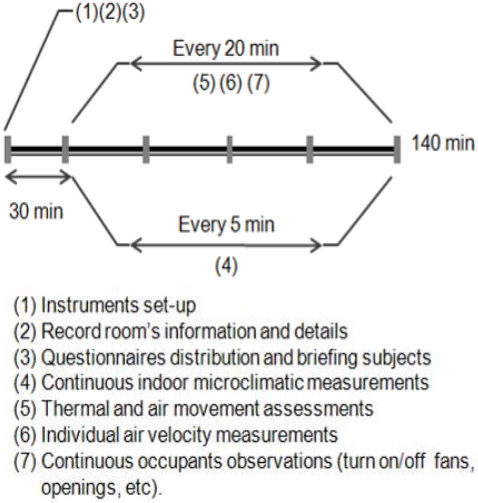

Figure 8 - Schematic representation of the measurement protocol.

Detailed and thorough indoor climatic observations were taken with a microclimatic station (Babuc A), including air temperature, globe temperature, air velocity and humidity, see Figure 9. These were recorded by a data logger with a 5 minute interval throughout the entire 140 minute period. The microclimatic station was located in the centre of the room and regulated to cater for two heights. The first height was 0.60m, corresponding to the subjects' waist height inside the classrooms. The second height was 1.10m which corresponded to the subjects' waist height while seated in the studio. The measurements recorded were averaged over the five minute period. The sensors on the microclimatic station measured air and globe temperatures, air speed and humidity.

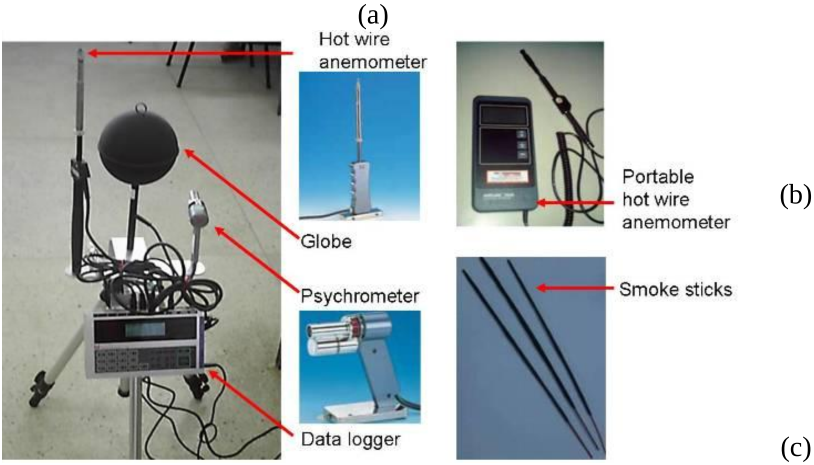

Figure 9 - Microclimatic station Babuc (a), hotwire anemometer and smoke sticks.

Because of the project's focus on occupant's perception of air movement, and the tendency for this parameter to vary in space and time more than the other comfort parameters, air velocity values were registered at exactly the same time as the occupants answered their questionnaires. The instrument used for these observations was a portable hot-wire anemometer (Airflow Developments, model TA35 sensor) installed within 1 metre of the subject filling in their questionnaire, and at a height of 0.60m above the floor for classrooms and 1.10m for studios. A sample of 30 instantaneous air speeds were registered for each subject each time they completed a questionnaire, yielding a total of 150 air speed values for each occupant. This procedure enabled a mean air velocity to be associated with each subject for each of their five repeat comfort questionnaires.

3.5 Complementary measurements and calculations

Outdoor climatic environment parameters for each building, including outdoor temperature, humidity, air speed and direction and dew point were requested from the nearest meteorological station. The first meteorological station was located at Zumbi dos Palmares International Airport which is located within 5km from Federal University of Alagoas. The second was located at the company of Water Supplying Services and Sewer Treatment of Alagoas, located within 2km from the Superior Studies Centre of Alagoas. The data collected corresponds to the period when experiments were carried out in Maceio city and were used in order to calculate mean outdoor temperature, humidity and mean air speed and direction.

Complementary calculations were developed using WinComf® software [9]. This software program “predicts human thermal response to the environment using several thermal comfort models, including PMV-PPD, ET*-DISC” [9]. This software was used especially for PMV and PPD calculations, as well draft risk and PS model comparisons.

3.6 References

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Results and Discussion

IV. Results and Discussion

This thesis is presented in accordance to Macquarie University's guidelines for a *thesis by publication*. Therefore this 'Results and Discussion' chapter comprises peer-reviewed papers that have been published in, or submitted to journals during the course of this candidature. Federal University of Santa Catarina requests thesis in A5 size as a consequence the original texts submitted or proof versions were included into this chapter. Minor different in terms of format might be found as the original journal's document was kept. This chapter is organized into four topics, each one corresponding to a journal paper.

Topic I: Air movement acceptability in hot humid climates

Cândido, C. M., de Dear, R., Lamberts, R., Bittencourt, L. S. (2010) Air movement acceptability limits and thermal comfort in Brazil's hot humid climate zone. *Building and Environment* **45** (1): 222-229. doi:10.1016/j.buildenv.2009.06.005

Topic II: Cooling exposure and air movement preferences in hot humid climates

Cândido, C. M., de Dear, R., Lamberts, R., Bittencourt, L. S. (2010) Cooling exposure in hot humid climates: are occupants "addicted"? *Architectural Science Review* **53** (1): 59-64. doi:10.3763/asre.2009.0100

Topic III: Applicability of thermal and air movement acceptability limits in hot humid climates

Cândido, C. M., de Dear, R., Lamberts, R. (2011) Combined thermal acceptability and air movement assessments in a hot-humid climate. *Building and Environment* **46**: 379-385. doi:10.1016/j.buildenv.2009.11.005

Topic IV: Towards a Brazilian standard for naturally ventilated indoor environments: guidelines for thermal and air movement acceptability in hot humid climates

Cândido, C. M., Lamberts, R., de Dear, R., Bittencourt, L. S. (2011) Towards a Brazilian standard for naturally ventilated buildings: guidelines for thermal and air movement acceptability. *BRI.* (submitted). (paper invited from *2010 Windsor Conference - Adapting to Change: New Thinking on Comfort*).

4.1. Air movement acceptability limits and thermal comfort in Brazil’s hot humid climate zone

Cândido, C. M., de Dear, R., Lamberts, R., Bittencourt, L. S. (2010) Air movement acceptability limits and thermal comfort in Brazil's hot-humid climate zone. *Building and Environment* **45** (1): 222-229. doi:10.1016/j.buildenv.2009.06.005

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ERA[6] 2010 Classification: A*

4.1.1 Paper Overview

In hot humid climates, natural ventilation is an essential passive strategy in order to maintain thermal comfort inside buildings and it can be also used as an energy-conserving design strategy to reduce building cooling loads by removing heat stored in the buildings thermal mass. In this context, many previous studies have focused on thermal comfort and air velocity ranges. However, whether this air movement is desirable or not remains an open area. This paper aims to identify air movement acceptability levels inside naturally ventilated buildings in Brazil. Minimal air velocity values corresponding to 80 and 90% (V80 and V90) air movement acceptability inside these buildings. Field experiments were performed during hot and cool seasons when 2075 questionnaires where filled for the subjects while simultaneous microclimatic observations were made with laboratory precision. Main results indicated that the minimal air velocity required were at least 0.4m/s for 26°C reaching 0.9m/s for operative temperatures up to 30°C. Subjects are not only preferring more air speed but also demanding air velocities closer or higher than 0.8m/s ASHRAE limit. This dispels the notion of draft in hot humid climates and reinforce the broader theory of alliesthesia and the physiological role of pleasure due to air movement increment.

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[6] ERA: Australian Research Council’s Excellence in Research of Australia.

4.1.2 Individual Contribution

Discussions with Professor Richard de Dear led to the idea of *minimal* air velocity values that 80 or 90% of occupants would consider as ‘acceptable’ at different operative temperature values. The statistical analysis, interpretation of results, and write-up of the manuscript were all undertaken by the candidate with guidance from all supervisors.

4.1.3 Introduction

Human perception of air movement depends on air velocity, air velocity fluctuations, air temperature, and personal factors such as overall thermal sensation, clothing insulation and physical activity level (metabolic rate) [1]. Air velocity affects both convective and evaporative heat losses from the human body, and thus influences thermal comfort conditions [2].

If we agree that thermal environments that are slightly warmer than preferred or neutral can still be acceptable to building occupants, as the adaptive comfort model suggests [3], then the introduction of airflow with higher velocities into such environments might be universally regarded as desirable. Higher velocities’ effect will be to remove sensible and latent heat from the body, so body temperatures will be restored to their comfort set-points. This hypothesis can be deduced from the physiological principle of *alliesthesia* [4].

Alliesthesia describes the phenomenon whereby a given stimulus can induce either a pleasant or unpleasant sensation, depending on the subject’s internal state [4]. The observation that cold receptors are closer to the skin surface than warm receptors explains why draft represents an *unpleasant* stimulus (negative alliesthesia) in cold environments whereas the same level of air movement is perceived as pleasant (positive alliesthesia) in warm environments. It also renders illogical the notion of draft in warm environments, which accounts for the widely reported inadequacy of the Fanger et al. [5], Draft Risk (DR) at explaining air movement preferences of occupants’ into warm environments [6].

Many previous studies have attempted to define when and where air movement is either desirable or not desirable [7][8][9][10][11]. Thermal comfort research literature indicates that indoor air speed in hot climates should be set between 0.2 - 1.50 m/s, yet 0.2 m/s has been deemed in ASHRAE Standard 55 [12] to be the threshold of draft perception inside air-conditioned buildings where occupants have no direct control over their environment [12]. None of the previous research explicitly addressed air movement acceptability, instead focusing mostly on overall thermal sensation and comfort [1].

Based on their experiments with occupant controlled air movement in climate chamber, Fountain et al [13] suggested an index, the PS model. PS model is a model of “predicted percent of satisfied people” as a function of locally controlled air movement in the occupied zone [13]. Providing the “percent satisfied” at a specific operative temperature and air velocity, this model offered a different approach focusing on the preferred air velocity rather than limits as the draft risk suggested. However, subjects’ conditions in climate chambers differ into real buildings and therefore experiments into indoor environments could provide complementary results [14].

Much of Brazil’s territory is classified as having a hot humid climate. In such regions, natural ventilation combined with solar protection are the most effective building design strategies to achieve thermal comfort without resorting to mechanical cooling. Despite these favourable conditions, the number of buildings using air-conditioned systems as main cooling design strategy has been dramatically increasing. Based on this scenario and the recent energy crises [15] Brazilian Government has been promoting energy conservation initiatives including a recent Federal Regulation for Voluntary Labelling of Energy Efficiency Levels in Commercial, Public and Service Buildings [16]. This new regulation summarizes an immense effort in order to provide guidelines based on Brazil’s climate requirements for designers in general with specific items related to lighting system, HVAC and building envelope. However, naturally ventilated indoor environments still appears as an open category and the references into this proposed regulation refers direct to current standards such as ASHRAE [12].

This paper is focused on the relationship between air movement acceptability and thermal comfort, inside naturally ventilated buildings in the north-east of Brazil (Maceio city). This research aims to define minimum air speeds necessary to produce 80% and 90% acceptability levels for the occupants of naturally ventilated buildings in hot-humid climates.

4.1.4 Method

The method adopted for this work is based on analysis of relationship between air movement acceptability and thermal comfort inside naturally ventilated buildings located in the north-east of Brazil (Maceio city). This method is based on design proximal indoor climate data with simultaneous questionnaires filled in by occupants of naturally ventilated spaces. A survey including 2075 questionnaires[7] during the cool (August - September) and also hot season (February - March) was carried out, where subjects were asked to inform their thermal preferences while microclimatic measurements were taken.

Maceio's climatic environment

Maceio is located on the north-east sea coast of Brazil (latitude 9º40' south of Equator and longitude 35º42' west of Greenwich). The low latitude combined with high solar radiation intensity, as well as the proximity of large warm water surfaces – ocean and lagoons – elevates the humidity level, hence the climate is classified as hot and humid, Aw according to Köppen's classification.

Maceio's climate is very equable, which is typical of the north-east coast of Brazil. Seasons are divided into just two: winter and summer, although the "winter" remains warmer than many mid-latitude climate zones' summers. Because of this, summer can be classified as a *hot season* and the winter as a *cool season* (these descriptions will be applied for this paper). The mean annual temperature is around 26ºC and the annual thermal amplitude is 3.4ºC (the highest monthly average occurs in February – 26.7ºC and the lowest monthly average is in July – 23.7ºC). Typically, the hottest days occur from November to February and the coolest days from June to August.

The mean relative humidity is around 78% during hot season and 84% during cool season. However, it is possible to encounter saturation (100%) during cooler, rainier periods. The annual average rainfall is

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[7] This value corresponds to valid questionnaires after data treatment and therefore does not consider those with any sort of problem (such as incomplete answers, occupants that left the room during the measurements, etc). the total number before the data treatment was 2099 questionnaires.

around 1654 mm and the typical rainy season occurs from April to July. Maceio is under the influence of the south-east and north-east trade winds within the planets broadscale general atmospheric circulation.

Measurement rooms and subjects' profile

When choosing the indoor environments for this study the following criteria were used: (i) windows had to be easy to access and operate; (ii) rooms could not have a mechanical cooling system (refrigerated air-conditioning); (iii) rooms could have complementary mechanical ventilation with unconditioned air (fans); (iv) opening and closing of windows had to be the primary means of regulating thermal conditions, and the occupants had to be engaged in near sedentary activity (1-1.3 met), and had to be permitted to freely adapt their clothing to the indoor and/or outdoor thermal conditions. Some rooms of the Federal University of Alagoas and the Centre of Superior Studies of Alagoas fitted these selection criteria and were chosen for this survey.

Monitored rooms were classrooms that were also used for drawing activities (studios) and normally occupied for twenty students; see Figure 1 and Appendix A. In addition, the buildings presented large open spaces and natural ventilation was intentionally the main cooling strategy. In both buildings, windows were easily controlled collectively by the occupants and ceiling fans provided supplemental air movement inside the rooms.

Figure 1 – Classrooms (a, c) and studios (b, d) at Federal University of Alagoas (above) and Centre of Superior Studies of Alagoas (bellow).

Subjects were, on average, 21 years old, weighed 59 kg and 1.7 m in height. The sample of respondents reflected the gender imbalance of Brazil's architecture student population, and was biased towards females. Table 1 summarizes subjects profile details for each season. Activities performed by the occupants of these environments were assessed as sedentary with a variation between 58 and 93W/m² because the subjects usually stayed seated whilst drawing or writing, see Figure 1. The clothes were light - around 0,30clo during the hot season and 0,50clo during the cool season (see Figure 2 a and b), as estimated from clothing garment checklists in ASHRAE Standard 55 [12].

Table 1 – Occupants' profile per season.

Season		Hot	Cool
Sample size		*915*	*1160*
Gender	Female	79%	66%
	Male	21%	34%
Age (year)	Ave	21	20.8
	Min	16	17
	Max	30	30
Height (m)	Ave	1.70	1.70
	Min	1.50	1.50
	Max	2.00	1.80
Weight (kg)	Ave	59.1	59.5
	Min	42	40
	Max	99	100


a) b)

Figure 2– Occupants' typical clothes for hot (a) and cool season (b).

Measurement equipment

In order to measure the ambient variables this research used a microclimatic station (Babuc A), hot wire anemometer and a surface temperature thermometer. This microclimatic station is able to take measurements and store the data collected into a data logger during the measurement period. In addition, instruments such as globe thermometer, psychrometer (dry and wet-bulb temperatures) and hot wire anemometer, were also applied (see Figure 3 a)

For air speed measurements near to participants hot wire anemometers were used. The equipment was portable, and had an Airflow Developments, model TA35 sensor, see Figure 3 b. The minimum air speed threshold was 0.05m/s, with resolution of 0.01m/s. The probe registered the maximum, minimum and average values of the air speed, and also indicated the standard deviation within the five minute sample interval. The portable hot wire anemometer was a unidirectional type, so smoke sticks were used to discern the predominant airflow before the anemometer was positioned near the subject, Figure 3 c.

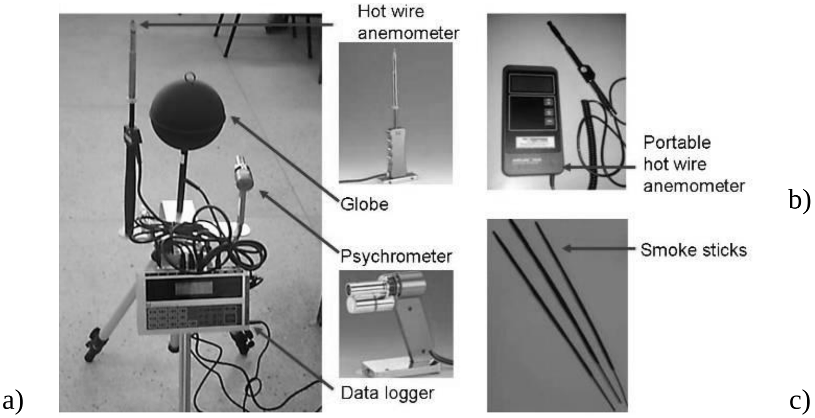

Figure 3 – Microclimatic station Babuc (a), hotwire anemometer and

Experimental procedures

The concept of this research design proximal indoor climate data with simultaneous questionnaires filled in by occupants of naturally ventilated spaces. Details related to indoor climate data and questionnaires are given bellow.

Indoor climate data

Measurements were taken during morning and afternoon lectures, for at least two hours in each period. The subjects' activities were not interrupted in order to characterize the typical use of rooms and studios, and they were also allowed to normally use ceiling fans, task lighting and also control the openings (to close or to open doors), as described previously.

The microclimatic station was located in the centre of the room and regulated to cater for two heights. The first height was 0.60m, corresponding to the subjects' waist height inside the classrooms. The second height was 1.10m which corresponded to the subjects' waist height while seated in the studio classrooms. The measurements recorded were averages of five minutes. The sensors on the microclimatic station measured air and globe temperatures, air speed and humidity.

The air speed measurements close to the subjects were taken simultaneously whilst they filled out the questionnaire. For each subject, the portable hot wire anemometer was located within a one meter radius and at the same work plan height. As a result, mean air velocities were recorded for each subject. The hot wire anemometer was oriented according to the dominant flow direction indicated by the smoke sticks.

Questionnaire

The questionnaire aimed to characterize whole body thermal comfort and also to identify the subjects' air speed and air movement acceptability. The questionnaire was presented in three parts (see Appendix B)[8]. The first corresponded to the subjects' demographic and anthropometric characteristics such as age, height, weight and gender. The second part included questions relating to thermal comfort, air movement acceptability and also their pattern of air-conditioning usage. In the thermal comfort part, subjects were asked about their own thermal

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[8] The questionnaire version presented into this paper is a translation from Portuguese to English. In order to consider semantics' implications [21][22] the Portuguese version of this questionnaire was tested and refined during pilot surveys before the final experiments presented and discussed into this paper.

comfort condition, their personal preferences and also about the room itself, at the time of questionnaire.

The air movement questions focused on air movement acceptability as it related to the air speed. In this case, subjects registered if the air velocity was “acceptable” or “unacceptable” and also if it was “too low” or “too high” air velocity. This specific questionnaire item is represented in Table 2.

Table 2 – Air movement acceptability scale.

-2	-1	0	1	2
Unacceptable	Acceptable			Unacceptable
because too low air velocity	but too low air velocity	enough air velocity	but too high air velocity	because too high air velocity

The third and last part of the questionnaire related to the subjects’ activities during the hour prior to the measurement process. It also recorded information about the subjects’ clothing by way of a garment checklist. The subjects started answering the questionnaire at least half hour after they arrived in the room in order to avoid any influence of their previous activities. Each subject answered the questionnaire on five separate occasions during the same experiment.

Statistical treatment

The statistical approach applied for this project followed commonly applied into this field. For air movement acceptability analysis the categorical data required a different treatment. Particularly for this data, probit analysis was conducted rather than linear regression [17]. In order to conduct these analysis, separate probit procedures were developed with software SAS$^{©}$ for each operative temperature and air velocity range. The fitted probit models achieved statistical significance at the p=0.05 level and the final result is discussed into this paper.

4.1.5 Results

The percentage of subjects who indicated thermal sensations of “neutral” represented more than 60% for cool season and less than 40% for the hot season. Less than 20% of the subjects reported that they were “slightly cool” or “slightly warm” during the cool season survey (see Figure 4). In this same season, only 3% of all subjects indicated that they were “cold” or “hot”. During the hot season survey, at least 34% of the subjects indicated that were “slightly warm”, and “warm” was registered more than 20% of cases. Less than 3% classified their thermal sensation as “hot”. Regarding specific thermal acceptability assessments, the levels were approximately 90% for both seasons (see Figure 5).These results met the 90% acceptability goal consider as “a higher standard of thermal comfort” [12].

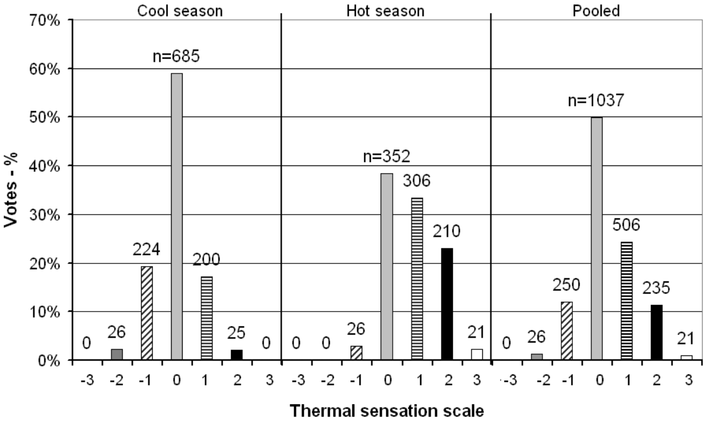

Figure 4 – Frequency distribution of thermal sensation votes (numerical values of -3, -2, -1, 0, 1, 2, and 3 indicate cold, cool, slightly cool, neutral, slightly warm, warm, and hot thermal sensations, respectively) for cool/hot season and also pooled.

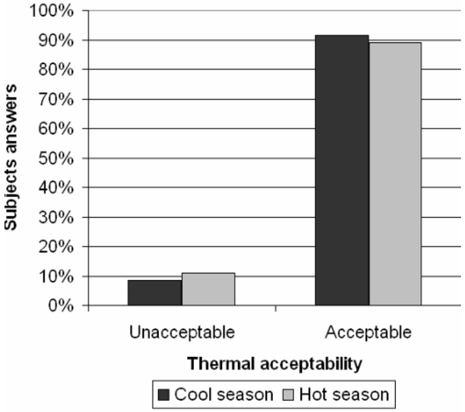

Figure 5- Overall thermal acceptability for both seasons.

Figure 6 presents simultaneous assessments of overall thermal sensation and air movement preferences. The subjects asking for “more air movement” were trying to restore their thermal sensation towards zero (neutral). The opposite situation, when subjects preferred “less air movement” is connected with cool or cold thermal sensations. However, the number of subjects for both groups is significantly different as indicated to the “n” underneath the thermal sensation scale in Figure 6. The majority of subjects were concentrated in thermal sensations of “slightly warm” and “warm” associated with a majority requesting “more air movement”.

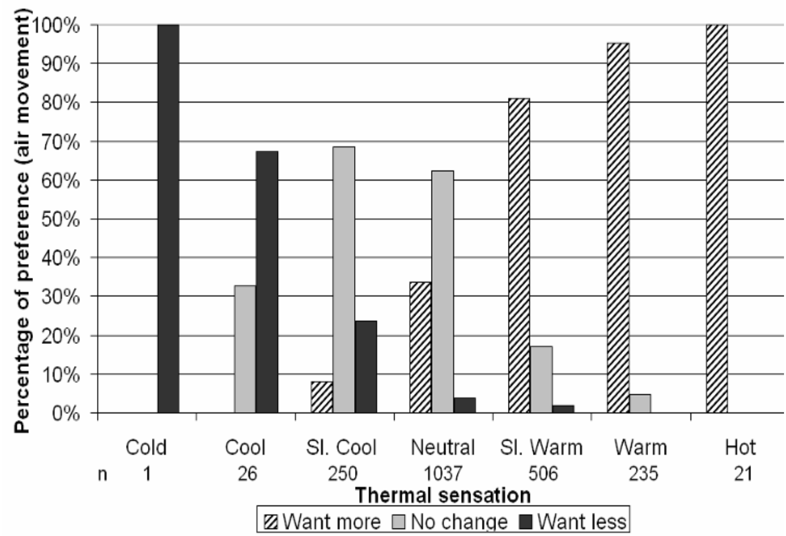

Figure 6 – Overall thermal sensation and air movement preference.

In attempt to identify subjects’ overall thermal dissatisfaction with their thermal environment, they were asked to indicate whether they would prefer to feel warmer or cooler. Figure 7 summarizes thermal preference votes. Most subjects’ thermal preferences were “no change” and “cooler” (44.6% and 50.7% respectively). Very few subjects preferred to feel “warmer” (4.7%). Table 3 cross-tabulates percentages thermal preferences with air movement preferences. Almost half of the subjects preferred “more air movement” (49.2%) than they were experiencing at the time of their questionnaire. The remaining half of the sample was split into two different groups, with the majority preferring “no change” (44.5%) and only 6.1% requesting “less air movement”.

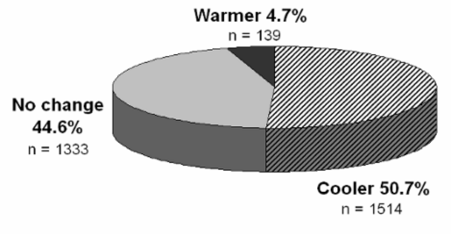

Figure 7 – Overall thermal preference.

Table 3 – Cross tabulated percentages for thermal and air movement preferences.

Thermal preference	Air movement preference					
	More		No change		Less	
	%	n	%	n	%	n
Warmer	6.0	8	44.0	59	50.0	67
No change	21.2	220	74.5	773	4.3	45
Cooler	88.3	797	10.1	91	1.7	15
Total	49.4	1025	44.5	923	6.1	127

When crossed with thermal preference, subjects’ air movement preference for “more” were concentrated into “cooler” and “no change” thermal preferences. Those subjects indicating a preference for “less air movement” were concentrated in the “warmer” thermal preference group. Similar results were found for Zhang et al [18] for office workers’ preferences for air movement from a database of indoor environmental quality surveys performed in over 200 buildings. According to their results, dissatisfaction with the amount of air motion is very common, with “too little air movement” cited far more commonly than “too much air movement”.

Our questionnaire requested subjects to assess the air movement within their work environment both in terms of *preference and acceptability*. Figure 8 summarizes the overall air movement preferences binned according to air velocity values recorded at the time of the questionnaire. The percentage requesting “no change” in air speed remained around 45% of subjects who were exposed to air speeds in the range 0.1 to 0.5m/s, but then the percentage voting for “no change” in air speed increased at an almost linear rate as measured air speeds increased from 0.5 to 0.9m/s. The percentage of subjects requesting “less air movement” remained below 10% across the entire range of measured air speeds. For those subjects asking for “more air movement”, the percentages demonstrate an opposite pattern in Figure 8 to the “no change” votes described earlier (i.e. static rate of “want more” votes between 0.1 and 0.5m/s air speeds, but then a steady decrease in the percentage of such requests as measured air speeds increased from 0.5 to 0.9m/s.

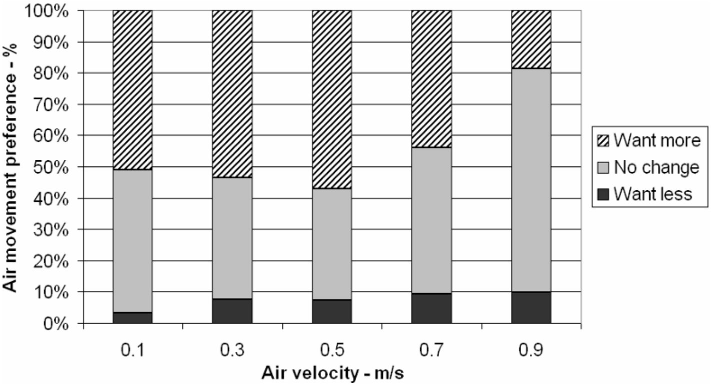

Figure 8 - Overall Air movement preference and air velocity range

Figure 9 sorts the samples into those who found the air movement at the time of their questionnaire to be “acceptable” (Figure 9 a) and those who assessed it as “unacceptable” (Figure 9 b). In Figure 9 a (air movement acceptable) the percentage preferring “no change” in air movement increased as air velocity increased. On the other hand, the percentage of subjects asking for “more air movement” decreased with increasing air velocity. The number of subjects preferring “less air movement” remained below 10% across the entire velocity range. Based on this and in combination to the operative ranges, it was possible to identify the demand to higher air velocity values, even up to 0.8m/s which is indicated as the maximum limit in ASHRAE 55 [12].

Figure 9 b summarizes the subjects who indicated that the air movement at the time of questionnaire was unacceptable combined with their air movement preference, binned according to measured air velocity values. For this group, the subjects expressed necessity for “more air movement” in a majority (maximum of 90% for 0.5m/s and minimum of 45% for 0.9m/s). The number of subjects requesting “less air movement” was in the minority, with a maximum percentage of 10% occurring at 0.7 and also 0.9m/s.

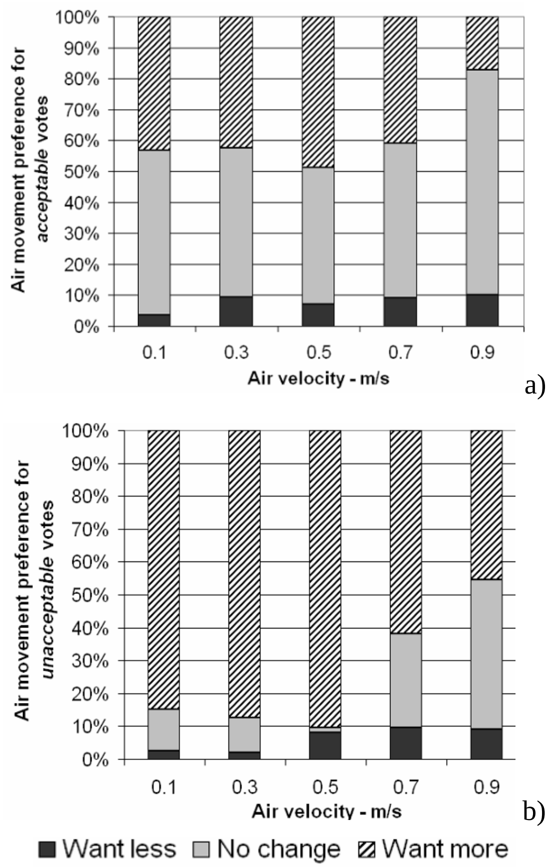

Figure 9 - Air movement preferences of those subjects for whom the air movement was *acceptable* (a) or *unacceptable* (b).

Subjects were asked to assess air velocity acceptability and also to give their reasons (*too low, enough, or too high).* For both extremes (too low and too high air velocity), the subjects indicated their acceptability as described in Table 2 previously (see Method section).

The overall air velocity acceptability votes binned according to air velocity at the same time of questionnaire is indicated on Figure 10. It is possible to identify a majority of the sample concentrated into the three *acceptable* categories (-1, 0 and 1).

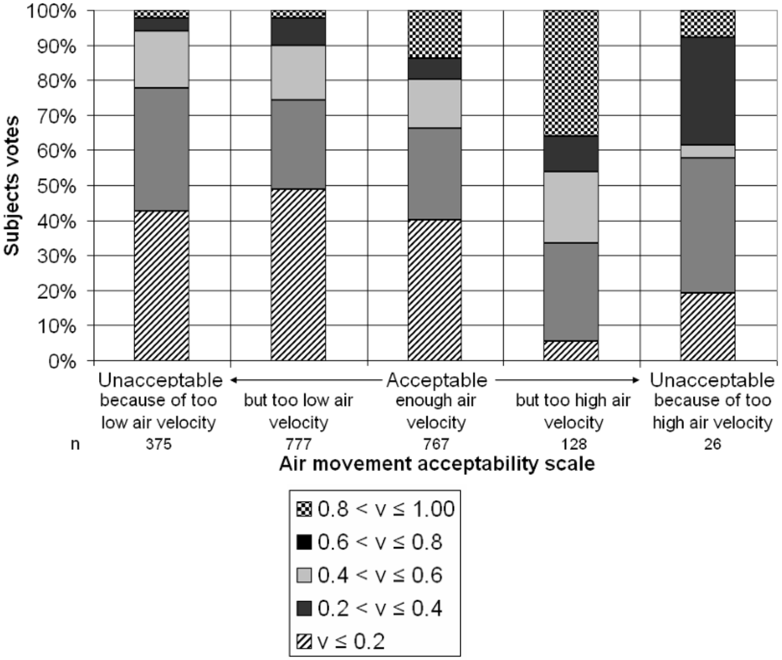

Figure 10 - Air velocity acceptability assessments within different prevailing air velocities.

For the “acceptable but too low air velocity” (-1) answers in Figure 10, the values were approximately 50% at an air velocity of 0.1m/s decreasing for 22% at 0.3m/s, 15% at 0.5m/s and less than 8% up to 0.7m/s. As for the “acceptable but too high air velocity” answers, 35% of the sample was concentrated in the air velocities between 0.8 and 1.00m/s. Of the two *unacceptable* categories, most fell into the “too low air velocity” rather than “too high air velocity”. Over 40% of the subjects exposed to air velocity < 0.2m/s assessed it as “unacceptable because of too low air velocity”. For air velocity in the range 0.2 ≤ v ≤ 0.4m/s, this percentage decreased to 33% and decreased further to less than 15% for the air velocities up to 0.5m/s. On the other hand, approximately 20% of those subjects voting unacceptable “because of too high air velocity”, were concentrated at air velocities less than 0.2m/s, and another 35% were registered at velocities between 0.2 and 0.4m/s.

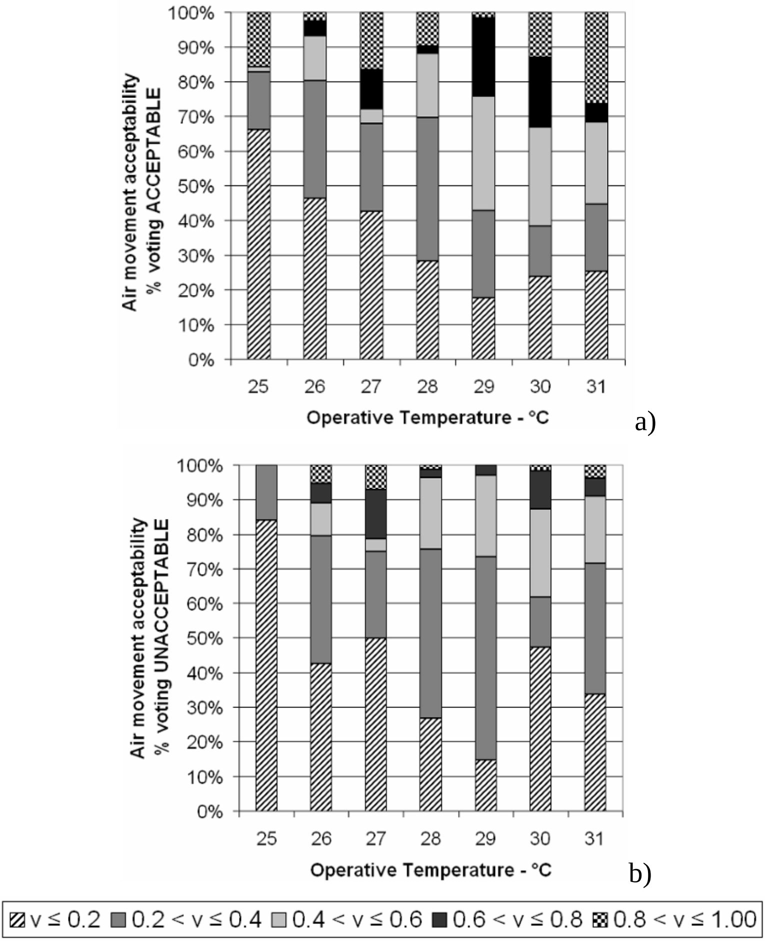

Figure 11 - Air movement *acceptable* (a) or *unacceptable* (b) votes binned to air velocity range and operative temperature.

As indicated earlier, the number of subjects assessing the air velocity at the time of questionnaire as being “too low” was overwhelmingly higher than those voting “too high”. These sub-samples were binned by operative temperature within each of the five air velocity ranges. For each degree of operative temperature (varying from 24 to 30°C) the subjects' air movement acceptability votes were binned into the five air velocities (from 0.1 to 0.9m/s). Based on these cross-tabulations it was possible to identify minimal air velocity values necessary for air movement acceptability percentages of 80% (V_{80}) and also 90% (V_{90}). Air movement acceptability votes have been binned into 1°C of operative temperature and 0.1m/s air velocity intervals and the resulting percentages within each bin have been subjected to probit analyses. For this analysis only the three acceptable votes were used *acceptable but too low air velocity, enough air velocity* and *acceptable but too high air velocity*. The resulting Probit models are presented as curves in Figure 11. The 25°C Probit model of air movement acceptability has been omitted because the skewed distribution of the votes led to an insignificant Probit model.

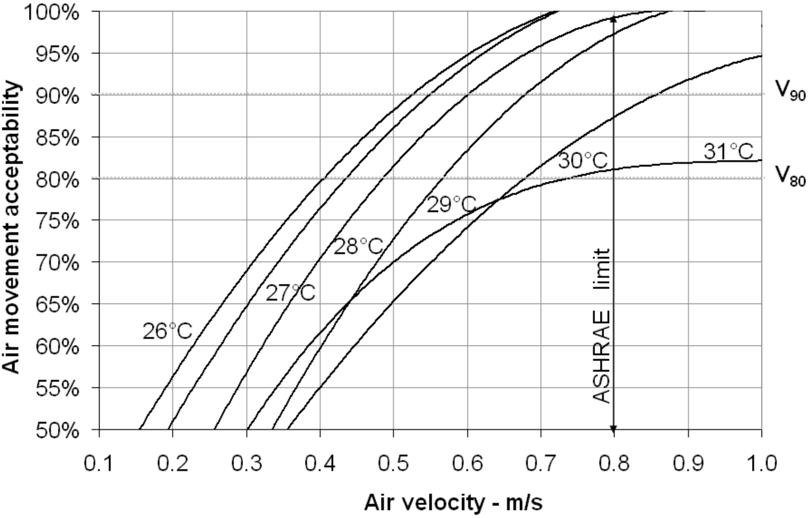

Figure 12– Air movement acceptability and operative temperature binned by air velocity values resulted from the probit regression analysis (95% confidence levels).

According to ASHRAE 55 [12], *"the required air speed may not be higher than 0.8 m/s"*, (lightly clothed person - clothing insulation between 0.5 clo and 0.7 clo who is engaged in near sedentary physical activity - metabolic rates between 1.0 met and 1.3 met). Figure 11 and Table 4 stet *minimal* air velocity values indicated as acceptable for 80% (V_{80}) of the subjects were near this maximum limit and above it for 90% of acceptability (V_{90}) for operative temperatures above 29°C. For air movement acceptability of 80% (V_{80}), the minimal air velocity required was 0.4m/s at an operative temperature of 26°C and for operative temperatures of 27 and 28°C air velocity values required for 80% acceptability were 0.5m/s. For operative temperatures of 29°C and 30°C air velocity values were slightly higher (0.6 and 0.7m/s, respectively).

Table 4 – Minimum air velocities required to achieve 80% and 90% acceptability in relation to operative temperature.

Operative temperature (°C)	Air movement acceptability	
	V_{80}	V_{90}
	m/s	m/s
26	0.4	0.5
27	0.5	0.6
28	0.5	0.6
29	0.6	0.7
30	0.7	0.9
31	0.7	-

Considering an air movement acceptability of 90%, there is an increase in required air velocities values. For an operative temperature of 26°C the air velocity required for 90% of acceptability (V_{90}) was 0.5m/s. Minimal air velocities values required were equal to 0.6m/s when operative temperature where 28°C, 0.7m/s for 29°C and 0.9m/s for 30°C. For 30°C of operative temperature, the maximum acceptability was 85% even when air velocities were increased for more than 0.9m/s.

4.1.6 Discussion

In relation to thermal preference it is clear to identify that a majority voted for the maintenance of “no change” and “cooler”. When cross-tabulated percentages with air movement preferences, subjects’ voting for “more air movement” were concentrated in the “cooler” and “no change” categories. For those subjects indicating an air movement preference for “less air movement” there was a concentration of “want warmer” preferences votes. In relation to air movement preference, most subjects requested “more air movement” even in air speeds above 0.50m/s. On the other hand, subjects who requested “less air movement” were few in number. These two generalizations combined indicate clearly that these Brazilian subjects prefer higher air speed values in order to improve their thermal comfort condition.

In addition, this study demonstrates a tolerance for air speeds up to 0.7m/s. Subjects’ responses suggested that air movement and also air velocity were acceptable for the most part. Nevertheless we found a few cases in which the air movement was unacceptable and these were generally those subjects who indicated “cool” or “slightly cool” as their thermal sensation. Draft due to elevated air velocity values was much less than the opposite complaint of “too low” air velocity values. In summary, the main complaint was due “too low air velocity” and the percentages were overwhelmingly higher than those subjects’ classifying air movement as “too high”. Draft risk is definitely not the main complaint for these samples in naturally ventilated buildings in for a hot and humid climate such as Maceio city, Brazil.

In an attempt to identify subjects’ minimal air velocity values requirements, two different percentages were defined as goals for air movement acceptability: 80% and 90% (V_{80} and V_{90}, respectively). The minimal air velocities were at least 0.4m/s for an operative temperature of 26°C and rising to 0.9m/s at 30°C. Subjects are not only preferring more air movement but also indicating minimal air velocities values close or greater than the 0.8m/s AHSRAE limit. These findings suggest a strong demand for air movement inside naturally ventilated buildings but also a tolerance for higher air velocity values.

4.1.7 Conclusions

Our results lead to the conclusion that air movement can be quite acceptable at speeds well above of the previous values suggested in the literature. For natural ventilation in hot and humid climates, higher air speeds may be desirable in order to improve subjects’ thermal comfort. This dispels the notion of draft in hot and humid climates and it is consistent with the broader theory of *alliesthesia* and the physiological role of pleasure due to air movement increment. By linking the physiological concept of alliesthesia with knowledge about cutaneous thermoreceptors it is possible to understand the simple *pleasure* that we derive from effective natural ventilation, particularly in warm climates

[6]. These findings also corroborate to previous studies addressed to the pleasantness associated with transient conditions [19][20].

Subjects preferring “more air movement” were significantly more numerous than those demanding “less air movement”. The majority of subjects considered air movement “acceptable”. For the minority percentage classifying air movement as “unacceptable”, their main reason was “too low air movement”. Based on this strong demand for more air movement, subjects’ acceptability was investigated based on two goals for movement acceptability (80 and 90%). Minimal air velocities values obtained based on these goals were close to or above 0.8m/s which is considered as the maximum air velocity for ASHRAE 55 [12].

These results suggest that subjects’ acceptance of higher air velocities increased to compensate for elevated temperature and humidity. In summary, air movement can be quite acceptable at speeds well excess of the previous values suggested in the literature and standards. Focusing in future Brazilian standards, these results suggested the necessity of more experiments related to minimum air velocity requirements for naturally ventilated environments.

In addition, it is important that the occupants should be able to control the airflow inside the buildings according to their personal preferences. Future experiments should be carried out in order to identify air movement acceptability inside indoor environments, which differ from the ones investigated into this research, such as office and residential buildings.

4.1.8 References

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4.2. Cooling exposure and air movement preferences in hot humid climates

Cândido, C. M., de Dear, R., Lamberts, R., Bittencourt, L. S. (2010) Cooling exposure in hot-humid climates: are occupants "addicted"? *Architectural Science Review* **53** (1): 59-64. doi:10.3763/asre.2009.0100

ISI Impact Factor: -

ERA 2010 Classification: A

4.2.1 Paper Overview

According to the Fourth Assessment Report of the IPCC, it is clear that the buildings sector presents the biggest potential for deep and fast CO_2 emission reductions on a cost-effective basis. Interestingly this assessment was premised exclusively on technical (engineering) measures, but ignoring completely the behavioral and life style dimensions of energy consumption in the buildings sector. Behavioral change in buildings, however, can deliver even faster and zero-cost improvements in energy efficiency and greenhouse gas (ghg) emission reductions. With this in mind, designers are beginning to shift their attention to how they widen the range of the opportunities available in a building to provide comfort for occupants, both in new-build and retrofit contexts. This in turn has re-awakened an interest in the role of natural ventilation in the provision of comfort. This discussion about adaptive comfort raises several questions, including: how can we shift occupants' comfort expectations away from the static indoor climates of the past towards the more variable thermal regimes found in naturally ventilated buildings? Are building occupants "addicted" to static environments i.e. air-conditioning? If so, how tolerant or compliant will they be when the thermally constant conditions provided by air conditioning are replaced by the thermally variable conditions that characterize naturally ventilated spaces? Does the frequency of prior exposure to air conditioning bias building occupants' thermal expectations and, if so, what are the implications of this bias for their acceptance of naturally ventilated indoor climates? Does prior exposure to air conditioning lead building occupants to actually prefer air conditioning over natural ventilation? This paper addresses these questions in the context of a large field study of building occupants in a hot and humid climate zone in Brazil (Maceio). The temperature preferences registered on 975 questionnaires in naturally ventilated buildings are statistically analyzed in relation to occupants' prior exposure to air conditioning in their workplaces.

4.2.2 Individual Contribution

Results from air movement acceptability limits provided indications of the influence of prior cooling exposure on occupants' perception of their thermal environment. Supervisors provided continuous advice on analytic techniques and the write-up of the manuscript was done by the candidate, also with their feedback.

4.2.3 Introduction

The Fourth Assessment Report of the IPCC (IPCC, 2007) highlighted the high potential of the buildings sector potential to achieve ghg emission reductions, above other sectors such as transport and industry. This assessment was premised on a technical approach related to architectural and engineering solutions that can be grouped into four themes: (1) reduce heating, cooling and lighting loads; (2) improving and using the thermal mass of the building; (3) increasing the efficiency of appliances, HVAC systems and (4) lighting systems.

Interestingly this assessment was premised exclusively on technical (engineering) measures but ignored completely the behavioral and life style dimensions of energy consumption in the buildings sector. Behavioral change in buildings, however, can deliver even faster gains in energy efficiency, and ghg reductions, at zero cost. Bearing this concept in mind, designers would benefit from shifting their attention to opportunities available in all buildings to adapt to a wider range of indoor thermal conditions. Building designers should explore ways of maximizing the adaptive opportunities within indoor environments as much as possible, so reinforcing passive cooling strategies as an essential energy conservation strategy. Maintenance of narrow temperature ranges requires significant energy inputs, but these static environments do not necessarily result in appreciably higher levels of occupant satisfaction (Arens et al, 2009). This focus is re-awakening an interest in natural ventilation (Tanabe, Kimura, 1989; de Dear, Brager, 2002; Toftum, 2004; Zhang et al, 2007).

Particularly in hot and humid regions, buildings should avoid external heat gains while dissipating internal ones. Shading is crucial and thermal mass designed to maximise the storage potential for free heating and cooling whilst avoiding discomfort from over-heating or cooling, especially during the night time. Natural ventilation is the main bioclimatic strategy to improve thermal comfort conditions inside buildings without resorting to air-conditioning. In addition, naturally ventilated buildings provide more dynamic environments that have been shown to be associated with more stimulating and pleasurable indoor environments (Cabanac, 1971; de Dear, 2009). Despite these positive characteristics, naturally ventilated environments have been increasingly replaced by air-conditioned ones as result of a myriad of complex reasons that vary from early design stage decisions to occupants expectations (Brown, 2009).

The discussion about widening the acceptable indoor temperature comfort bands raises the question of the extent to which occupants' comfort expectations can vary from the narrow temperature bands promoted by the PMV and PPD methodologies used internationally the HVAC engineers, allowing natural ventilation with limited acceptance penalties. Previous results suggested that occupants of air conditioned buildings tended to prefer such buildings, while occupants of non-air conditioned buildings preferred not to have air conditioning (de Dear, Auliciens, 1988) and also that occupants' thermal history influences their thermal perception (Chun et al, 2008). These observations suggest that building occupants become "addicted" to static environments i.e. air-conditioning but does it mean that they will present differences in terms of thermal preference when the thermal constancy of air conditioning is replaced by the thermal variability that characterizes natural ventilation? Does prior exposure to air conditioning lead building occupants to actually prefer air conditioning over natural ventilation? This paper addresses these questions in naturally ventilated indoor environments located for the hot and humid climatic zone of Brazil (Maceio city).

4.2.4 Method

Researchers combined nearby indoor climate measurements with simultaneous questionnaires filled in by occupants of naturally ventilated spaces. A survey including 975 questionnaires was used for this study. Air temperature, humidity, globe temperature and air velocity were measured with laboratory precision as well as individualized air velocity values for each occupant. The instruments used to perform the field experiments were: (1) Microclimatic station, including globe thermometer, psychrometer for dry and wet-bulb temperatures and a hot wire anemometer); (2) Portable hot wire anemometer (Airflow Developments, model TA35 sensor) and (3) Smoke sticks.

The microclimatic station was able to take measurements and store the data collected into a data logger during the experiment period and it was located in the centre of the room. The portable hot wire anemometer was used in order to register air velocity values for each occupant. Complementarily smoke sticks were applied in order to verify the main airflow direction during the measurements the individualized air velocity measurements. The method for obtaining instantaneous thermal comfort and sensation responses as well as the indoor microclimatic measurement procedures have been detailed in an earlier paper (Cândido et al, 2009).

Maceio's climatic environment and outdoor meteorological conditions during the survey.

Maceio city is located on the northeast coast area of Brazil (latitude 9º40' South). The climate is classified as hot and humid, with small daily and seasonal temperature fluctuations combined with a high vapor pressure. Seasons are divided in two: winter and summer. Summer is classified as a hot season and winter as a cool one. The mean annual temperature is around 26ºC and the annual thermal amplitude is 3.4ºC (the highest monthly average occurs in February – 26.7ºC and the lowest monthly average is in July – 23.7ºC). Typically, the hottest days take place from November to February and the coolest days occur from June to August. Despite Maceio's equable climate, the surveys were performed during the cool and hot seasons for comparative purposes. Table 1 shows statistical summaries of these outdoor conditions.

Table 1 - Outdoor meteorological conditions during the surveys.

Measurement	Seasons					
	Hot			Cool		
	Ave	Max	Min	Ave	Max	Min
Outdoor temperature (°C)	25.2	28.6	22.4	24	26.8	21.4
Outdoor relative humidity (%)	73.8	88.9	56.1	75	91	57
Mean monthly outdoor temperature (°C)	25.3	30.2	23.7	23.5	27.1	20.2

Measurement rooms and occupants' profile

The buildings were occupied by university students performing sedentary activities. Monitored rooms were used for drawing activities (studios) and were normally occupied by twenty students. All rooms offered large open spaces and natural ventilation was intentionally the main cooling strategy. The windows were easily controlled collectively by the occupants and ceiling fans provided supplemental air movement inside the rooms. The study was carried out considering concepts of personal control and the adaptive model (de Dear, Brager, 2002). For this analysis, occupants were classified into two groups according to their responses for their cooling exposure at their work place: occupants exposed to air conditioning systems at their work environment and those without exposure to air conditioning at their work environment. Table 2 summarizes biographical characteristics of the sample.

Table 2 - Biographical characteristics of the samples.

Characteristic	Cooling exposition at their work place	
	exposed to air conditioning systems	without exposure to air conditioning systems
Number of occupants	445	530
Percentage females	75.3%	69.8%
Percentage males	24.7%	30.2%
Age – average (years)	22.4	21.2

Questionnaire

The questionnaire was presented in three parts. The first one corresponded to the subjects' demographic and anthropometric characteristics such as age, height, weight and gender. The second part included questions related to thermal comfort, air movement acceptability and also their pattern of air-conditioning usage. In the thermal comfort part, subjects were asked about their own thermal comfort condition, their personal preferences and also about the room itself, at the time of questionnaire. This paper focuses on cooling exposition and preference questions. The third and last part of the questionnaire related to the subjects' activities (metabolism) during the measurement process. It also recorded information about the occupants' clothing by way of a garment checklist (insulation).

4.2.5 Results

The research questions posed resulted in a set of responses, identifying how occupants inside naturally ventilated buildings classify their indoor environment depending on their previous exposure to work places with and without AC systems. Results were analysed for thermal sensation votes, thermal preference and cooling preferences. The occupants' thermal sensation rated on the seven point scale was similar for both groups, as depicted in Figure 1. No significant differences were observed when comparing thermal sensation votes for occupants with AC systems at their work place and occupants without exposure to AC systems at their work place. For both groups the majority of thermal sensation votes were concentrated into "neutral", "slightly warm" and "warm" categories. Only occupants without AC systems at their work place voted for "slightly cool" (5%) as well as only occupants with AC systems at their work place voted for "hot" (4%).

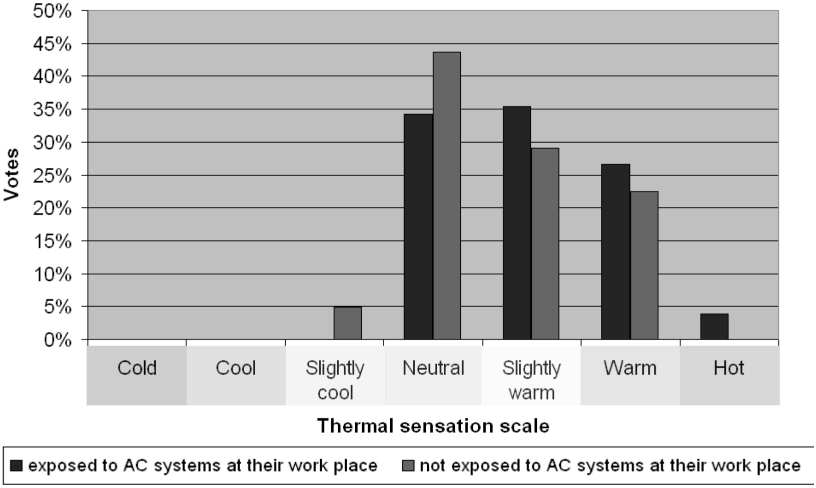

Figure 1 - Occupants thermal sensation votes exposed to A/C system at their work place.

Despite the similarity of their thermal sensations votes, preferences varied depending on AC exposure. Figures 2 a and b show the distribution of occupants' thermal preference votes within operative temperature bands. The percentages of occupants preferring "no change” were significantly higher for those without AC systems at their work place. This fact is noticeable within all operative temperature bands. Thermal preferences for “cooler” were significantly higher for occupants whose had been exposed to AC systems at their work place compared to occupants without AC exposure.

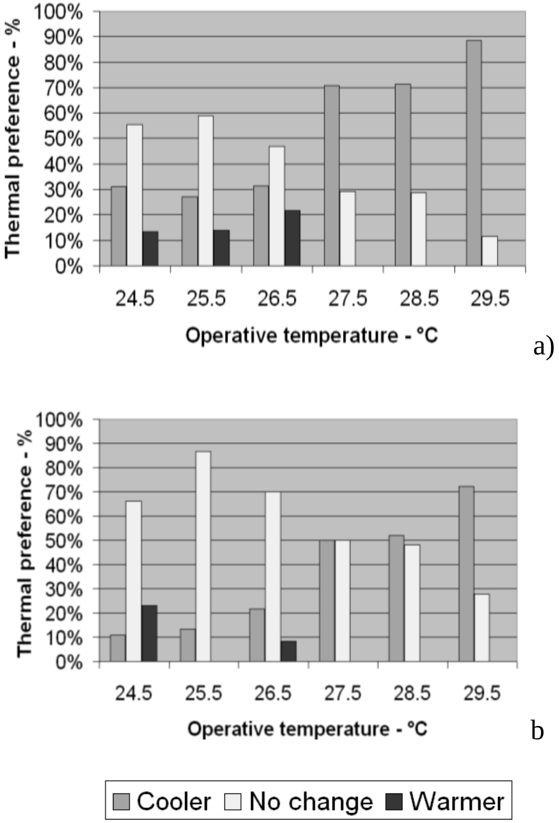

Figure 2 - Occupants’ thermal preference votes within operative temperature values: a) Occupants exposed to AC systems at their work place and b) Occupants without exposure to AC systems at their work place.

Occupants were also asked about their *cooling preference* at that moment as a complement to their thermal sensation and preference votes. The question was: “If you could choose, which one of these cooling strategies would you like to have in this room?” Their options were natural ventilation, natural ventilation and fans, and air conditioning. The overall cooling preference results were subsequently cross-tabuled with occupants’ cooling exposure at their work place. See Figures 3 a and b. Two thirds of occupants exposed to AC systems at their work place preferred air conditioning systems (65.7%), while the remaining third (34.3%) indicated preference for natural ventilation or natural ventilation plus fans. In contrast, the results were completely the opposite for those occupants without exposure to AC systems at their work place. In this sample, two thirds of cooling preferences responses was for natural ventilation and natural ventilation and fans while only one third preferred AC systems.

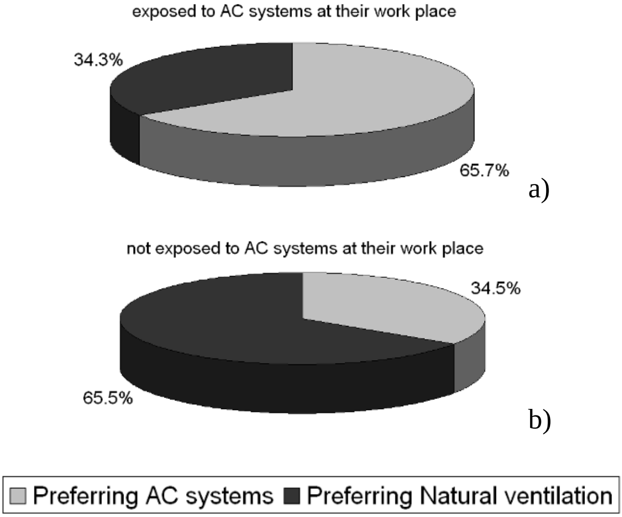

Figure 3 - Overall cooling preference votes: a) Occupants exposed to AC systems at their work place and b) Occupants without exposure to AC systems at their work place.

Figure 4 shows occupants’ cooling preference votes across operative temperature bins. Once more it is clear that occupants with AC systems at their work place indicated preference for AC system, and these percentages increased when operative temperature also increased (from 50% for operative temperature of 24.5ºC increasing to 88% at 29.5 ºC). In contrast, the percentage of occupants preferring natural ventilation and natural ventilation and fans decreased with increasing operative temperature values from 50% at 24.5ºC down to only 12% for 29.5 ºC. For occupants without AC systems at their work place, the preference for natural ventilation and natural ventilation and fans was significantly higher than for those preferring AC systems. The percentages of occupants preferring natural ventilation decreased from 98% at 24.5 ºC operative temperature to 60% for 29.5 ºC.

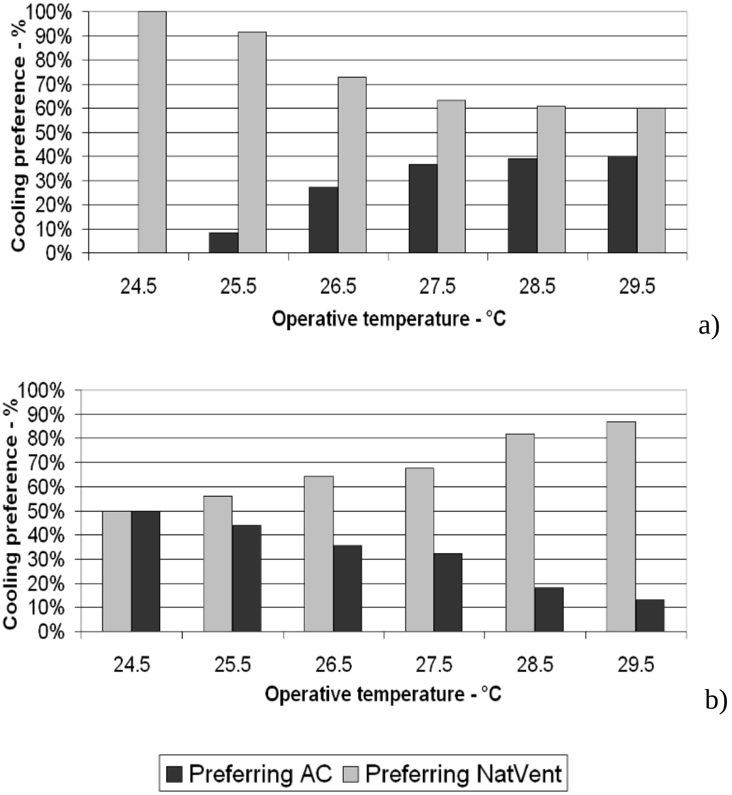

Figure 4 - Occupants' cooling preference votes within operative temperature values: a) Occupants exposed to AC systems at their work place and b) Occupants without exposure to AC systems at their work place.

Table 3 shows the cross-tabulated percentages for cooling and thermal preference for both *AC* and *no AC exposed* samples. These results showed variations in terms of thermal preferences between occupants with the same cooling exposure at their work place but preferring different cooling strategies. For those occupants without AC exposure at their work place, thermal preferences were broadly similar regardless of AC and natural ventilation preference. Occupants with AC systems at their work place results presented significant differences in their cooling preference. In this sample, occupants who preferred AC systems also indicated preference for being “cooler” in a majority (78.3%). However, 52% of occupants who preferred natural ventilation indicated “want cooler” as their thermal preference.

Table 3 - Cross-tabulated percentages for cooling and thermal preferences.

Cooling exposure	Cooling preference	Thermal preference		
		Cooler	No change	Warmer
Occupants not exposed to AC systems at their work place	*Preferring AC systems*	70.0%	30.0%	0.0%
	Preferring Natural Ventilation	68.4%	31.6%	0.0%
Occupants exposed to AC systems at their work place	*Preferring AC systems*	78.3%	21.7%	0.0%
	Preferring Natural Ventilation	52.0%	48.0%	0.0%

4.2.6 Discussion and conclusions

This paper investigated differences in terms of thermal sensation, preference and cooling preferences into naturally ventilated buildings based on occupants’ prior cooling exposure in their workplace (air conditioned or naturally ventilated indoor environments).

Thermal sensation votes were broadly similar for both samples, for those with AC at their work environments and without. However, expectations of their indoor environments were significantly different in terms of thermal preferences and also cooling preferences. Occupants with AC systems at their workplace were less tolerant of operative temperature variations when exposed to naturally ventilated indoor environments than those without prior AC exposure. The majority of AC occupants also voted “want cooler” for their thermal preference even though they happened to be experiencing broadly similar indoor temperatures at the time of questionnaire as the occupants who did not have prior AC exposure. The AC exposed sample seemed to be less tolerant, less adaptable, when the thermal constancy of air conditioning environment was replaced with thermally variable.

Occupants who were constantly exposed to air conditioned buildings tended to prefer such buildings, while occupants of non-air conditioned buildings preferred not to have air conditioning. These results suggest an “addiction” to static thermal environments. They also indicate that occupants’ thermal history directly influences their thermal perception and preferences (Chun, 2008). Past experience and behavior influence occupants’ thermal perception the indoor environment, and so they should be taken in consideration in the design of bioclimatic architecture. It is indeed a hard mission to control which sort of environment occupants will be exposed outside their workplace. However, when inside these indoor environments, they will bring their expectations with them.

4.2.7 Conclusions

This paper has demonstrated the importance of an occupants’ thermal history as an influence on their perception of indoor thermal environment. The percentages of occupants preferring natural ventilation or natural ventilation combined with fans, provide unequivocal indication that passive strategies are welcomed by these occupants, and should be exploited as much as possible. For warm and humid regions such as Maceio. It is important to consider whether prior AC exposure also influences preference and acceptability of indoor air movement levels and humidity values. Complementary field experiments are necessary in order to understand these important subjective aspects of indoor air quality.

Conversley these findings raise important questions about the role that rising comfort expectations resulting from increased AC usage might play in hindering implementation of adaptive comfort principles in bioclimatic buildings and the return to more naturally ventilated buildings ? Can this upward trend in comfort expectations that has accompanied rising AC penetration rates in recent decades be reversed as designers attempt to scale back society’s reliance on energy-intensive compressor-based cooling over coming decades? To what extent are comfort expectations amenable to modification with information and “ethical persuasion”?

These questions are currently being addressed by the japanese Ministry of Environment’s “Cool Biz” campaign in which summertime AC set points have been raised to 28°C in conjunction with a vigorous education campaign regarding that country’s Kyoto Protocol commitments is being aired across the media. In Brazil, educational campaigns were effective during the energy crisis of 2001, when the population had to consider energy conservation strategies on daily basis.

4.2.8 References

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Zhang, H., Arens, E., Fard, S. A., Huizenga, C., Paliaga, G., Brager, G., Zagreus, L. (2007) Air movement preferences observed in office buildings. *Int J Biometeorol*: 51, 349 – 360.

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Cândido, C., de Dear, R., Lamberts, R. and Bittencourt, L. (2009). "Air movement acceptability limits and thermal comfort in Brazil's hot humid climate zone" *Building and Environment* in Press.

4.3. Combined thermal acceptability and air movement assessments in a hot-humid climate

Cândido, C. M., de Dear, R., Lamberts, R. (2011) Combined thermal acceptability and air movement assessments in a hot-humid climate. *Building and Environment Building and Environment* **46**: 379-385.
doi:10.1016/j.buildenv.2009.11.005

ISI Impact Factor: 1.797 (August 2010)

ERA 2010 Classification: A*

4.3.1. Paper Overview

In the ASHRAE comfort database [1], underpinning the North American naturally ventilated adaptive comfort standard [2], the mean indoor air velocity associated with 90% thermal acceptability was relatively low, rarely exceeding 0.3m/s. *Post hoc* studies of this database showed that the main complaint related to air movement was a preference for ‘more air movement’ [3][4]. These observations suggest the potential to shift thermal acceptability to even higher operative temperature values, *if* higher air speeds are available. If that were the case, would it be reasonable to expect temperature and air movement acceptability levels at 90%? This paper focuses on this question and combines thermal and air movement acceptability percentages in order to assess occupants. Two field experiments took place in naturally ventilated buildings located on Brazil’s North-East. The fundamental feature of this research design is the proximity of the indoor climate observations with corresponding comfort questionnaire responses from the occupants. Almost 90% thermal acceptability was found within the predictions of the ASHRAE adaptive comfort standard and yet occupants required ‘more air velocity’. Minimum air velocity values were found in order to achieve 90% of *thermal and air movement acceptability*. From 24 to 27°C the minimum air velocity for thermal and air movement acceptability is 0.4m/s; from 27 to 29°C is 0.41 to 0.8m/s, and from 29 to 31°C is > 0.81m/s. These results highlight the necessity of combining thermal and air movement acceptability in order to assess occupants’ perception of their indoor thermal environment in hot-humid climates.

4.3.2. Individual Contribution

Data analyses conducted by the candidate revealed that occupants’ thermal acceptability related strongly to air velocity values in which occupants were being exposed. Discussions with Professor Richard de Dear led to the decision of extending the analysis made on Topic I, considering a combination of thermal and air movement acceptability when assessing occupants in hot humid climates. The statistical analysis, interpretation of results and write-up of the manuscript were undertaken by the candidate with guidance and feedback from all supervisors.

4.3.4. Introduction

Regulatory documents such as comfort standards are strategic in stimulating market acceptance of design approaches based on natural ventilation, as illustrated by the adaptive comfort models that are included in the North American and international comfort standard ASHRAE 55-2004 [2] and its European counterpart EN15251 2007 [5]. Based on an analysis of twenty thousand row data from buildings around the world, the RP-884 database found that indoor temperatures eliciting a minimum number of requests for warmer or cooler conditions were linked to the outdoor temperature at the time of the survey [1].

The approach adopted in the ASHRAE adaptive comfort standard was to define the indoor operative temperatures statistically associated with observed mean thermal sensation votes (TSV) of ± 0.5 and ± 0.85. According to Fanger’s PMV/PPD model [6], these mean thermal sensation values corresponded with Predicted Percentages Dissatisfied of 20 and 10% respectively. By adopting the same PMV/PPD logic and applying it to observed thermal sensation models in the ASHRAE comfort database, it was possible to define 80% and 90% indoor thermal acceptability levels as a function of outdoor climate. The results were integrated into ASHRAE 55 [2] and have been applied and studied worldwide ever since [7][8].

China, Brazil and India are moving towards standards for naturally ventilated buildings [9 – 12]. Recent developments toward a Chinese thermal comfort standard highlight the interest in incorporating the adaptive model for naturally ventilated buildings [11]. There is an ongoing research project aiming to establish a database of occupant’s comfort, thermal performance and energy consumption across commercial, office and public buildings in India [9]. Based on the research outcomes from this project, an India adaptive comfort standard is expected to be released [10].Apart from defining temperature limits, the regulatory documents surrounding indoor thermal comfort also specify limits for indoor air speed.

Traditionally, air speed has been framed in terms of *maximum* permissible limits [13 - 15]. In cold and temperate climates, the maximum permissible air speed is typically quite low (i.e. 0.20m/s) in order to avoid occupants complaints of ‘draft’ [6]. These limits are also chosen to avoid disturbance or annoyance due to higher air velocities, such as dry eyes or papers flying in work environments [16]. In warmer environments, however, it is likely that the cooling power of higher air motion will offset these non-thermal irritations [16] and might in fact be preferred by occupants in spaces with elevated temperature and humidity [17]. Numerous authors have proposed a variety of maximum acceptable indoor air speeds ranging from 0.5 to 2.5m/s [14 - 26].

ASHRAE 55 [2] specifies 0.80m/s as the maximum air speed within the occupied zone of naturally ventilated environments in which occupants are provided with control mechanisms such as operable windows or personal fans. Recently a review of this limit was proposed in which specific requirements were established according to occupant’s access to control: (1) up to 0.80m/s the occupants’ control of air movement devices is not required, and (2) up to 1.20m/s occupant control is required [25]. These proposed inclusions in ASHRAE Standard 55 are an important encouragement for designers to rely less on refrigerated air and more on air movement in indoor environments, but can these proposed limits be stretched even further? Previous studies in hot-humid climates have already demonstrated that even higher air speeds are *thermally* acceptable to building occupants [14-26], but these studies rarely focused on air movement *acceptability* [13]. As noted earlier, in the ASHRAE comfort database, the mean air velocity associated with 90% *thermal* acceptability was about 0.3m/s. However, *post hoc* re-analyses of that database demonstrated that the main occupant complaint related to indoor air movement was a desire for “*more air movement*” [3][4][25].

These complaints by occupants and their preferences for air speeds higher than those they are experiencing at the time of survey, beg the question; would it be reasonable to expect 90% temperature and air movement acceptability levels if temperature and velocities were increased any further? This paper focuses on this question and combines thermal and air movement acceptability percentages in order to assess more thoroughly occupant comfort in hot humid naturally ventilated environments.

4.3.5. Method

Two field experiments took place in Maceio city, located on Brazil’s North-East coast, during the cooler (August - September) and also hotter seasons (February - March). The fundamental feature of this field research design is the proximity in time and space of the indoor climate observations with corresponding comfort questionnaire responses from the occupants of naturally ventilated buildings.

Located on the coastline of Brazil at Lat 9°S, Maceio has a wet-dry tropical climate with warm-to-hot temperatures and high humidity, with negligible temperature variations, diurnally nor seasonally (mean monthly temperatures ranging from 24 to 26°C). The two seasons are differentiated by rainfall: in summer the temperature reaches higher values but rainfall is less, while in “winter” the temperature is slightly lower but precipitation is higher. Table 1 summarizes the outdoor climatic data observed for this city during this project’s two field campaigns.

Table 1 - Outdoor meteorological conditions during the surveys.

Measurement	Hot season			Cool season		
	Ave	Max	Min	Ave	Max	Min
Outdoor temperature (°C)	25.2	28.6	22.4	24	26.8	21.4
Outdoor relative humidity (%)	73.8	88.9	56.1	75	91	57
Mean monthly outdoor temperature (°C)	25.3	30.2	23.7	23.5	27.1	20.2

The sample buildings and profiles of their occupants

The field experiments were conducted in two university buildings with subjects performing sedentary activities (metabolic rate: 1 to1.3

met). Even though this research was conducted in educational buildings, the specific rooms selected were those in which occupant activities could potentially have been disturbed by higher air velocities; architecture design studios and classrooms occupied by students carrying out drawings or building delicate scale prototypes of buildings. A total of 2,075 questionnaires were completed during the two field campaigns and Table 2 summarizes the occupant samples' profiles.

Table 2 - Building occupants' sample profiles

Season	Gender		*Clo*	*Met*
	F	M		
Cool (n = 1160)	66%	34%	0.70	1.2
Hot (n = 915)	79%	21%	0.25	1.1

Occupants' activities were not deliberately influenced by the researchers; they were allowed to freely adapt cooling devices that were accessible to them at the time of survey (windows, ceiling fans, etc). Occupants' clothing selection was also left to vary according to their wishes at the time of survey, and the sampled ensembles typically consisted of light garments, with clothing insulation varying from 0.25 to 0.70 *clo* during the experiments, estimated using the standard garment check-lists in ASHRAE 55 [2].

Questionnaires

The comfort questionnaire adopted for this research focused on thermal and air movement issues. The well-established thermal sensation, preference and acceptability questionnaire items were extracted from previously published field experiments [1]. However, in relation to perception of air movement, subjects were specifically invited to express air speed preferences and assess air movement acceptability at the time of survey.

Indoor climatic instrumentation and measurement protocol

Subjects were requested to assess both their room's thermal comfort and air movement five times within a 110 minute period following a 30min settling-in period upon entering their studios/classrooms. Apart from permitting subjects' metabolic rates to settle down to approximately sedentary levels [27], this initial 30min period was used to set-up the indoor climatic instruments and also to explain the questionnaire in detail to the occupants. Figure 1 presents a schematic of the field measurement protocol.

Detailed and thorough indoor climatic observations were taken with a microclimatic station (Babuc A), including air temperature, globe temperature, air velocity and humidity. These were recorded by a data logger with a 5 minute interval throughout the entire 140 minute period. Because of the project's focus on perception of air movement, and the tendency for this parameter to vary through space and time much more than the other comfort parameters, air velocities values were registered at exactly the same time as the occupants answered their questionnaires. The instrument used for these observations was a portable hot-wire anemometer (Airflow Developments TA35) installed within 1 metre of the subject filling in their questionnaire, and at a height of 0,60m above the floor for classrooms and 1,10m for studios. A sample of 30 instantaneous air speeds was registered for each subject each time they completed a questionnaire, yielding a total of 150 air speeds for each occupant. This procedure enabled a mean air velocity to be associated with each subject for each of their five repeat comfort questionnaires.

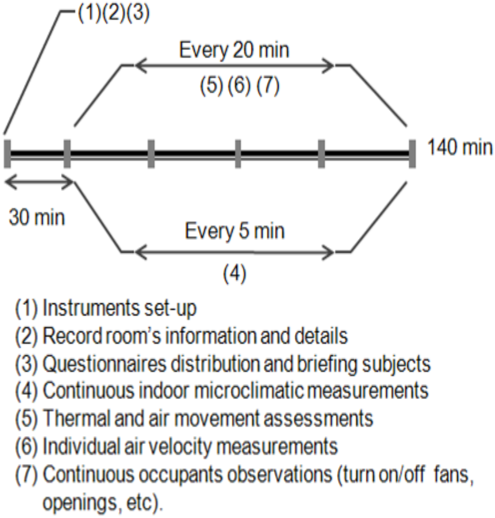


Figure 1 - Schematic representation of the measurement protocol.

4.3.6. Results and discussion

Statistical analyses were performed on pooled subjective thermal sensation votes within each of the rooms under study. This subjective comfort data, in conjunction with the corresponding indoor climatic measurements, were then used to define thermal neutrality and preferred temperatures for the group by following analytical procedures set out by [28][29]. Thermal neutrality is defined as the indoor operative temperature coinciding with the group's mean thermal sensation of "*neutral*" on the 7-point ASHRAE scale. Preferred temperature is defined as the indoor operative temperature coinciding with equal numbers of preference votes for "warmer" and "cooler" temperatures.

Figure 2 shows the regression line as a result of this analysis for a range of outdoor temperature varying from 25 to 32 °C (R^2 indicated in the graph). This temperature range equates to Maceio's thermal amplitude throughout the year. The regression line illustrates the relationship between neutral thermal sensation and outdoor temperatures, showing that occupants' thermal neutralities increased as outdoor temperatures became warmer, up to an operative temperature of 32°C. Occupants are therefore accepting warmer environments throughout the seasons when exposed to these naturally ventilated environments.

Figure 2 also shows that indoor temperature fluctuations are very close to outdoor temperature and the difference between indoors and outdoors was rarely more than 1°C. This fact can be explained by the combination of light construction and high porosity of the rooms, in addition to low heat generated inside the rooms. These factors result in an effective dissipation of internal heat gains, especially by natural ventilation. In addition to thermal neutralities, this study also directly addressed occupants' thermal preferences and these results offered insight into semantics of subjective warmth. The results are shown in Figure 2.

It is possible to identify a slight difference of approximately 0.5°C in preferred temperature being cooler than neutrality. Semantics can be used to explain occupant's preference for "cooler" when exposed to warm environments and "warmer" in cold environments [30][231]. The resultant regression line varies accordingly to outdoor temperature and represents occupant's adaptation throughout the seasons. Originally in the ASHRAE 55 [2] adaptive model, thermal acceptability was defined based on Fanger’s PMV/PPD relationship. As a result, the operative temperature range corresponding to 80% acceptability was neutral ±0.85 mean thermal sensation (votes varying from slightly cool to slightly warm). The 90% acceptability range was found in the same fashion, but this time the acceptable mean thermal sensation votes were zero ± 0.50 (neutral). Because many of the original studies in the ASHRAE database did not have an acceptability question, so it had to be inferred from their thermal sensation data, in the same way that PPD is inferred from PPD.

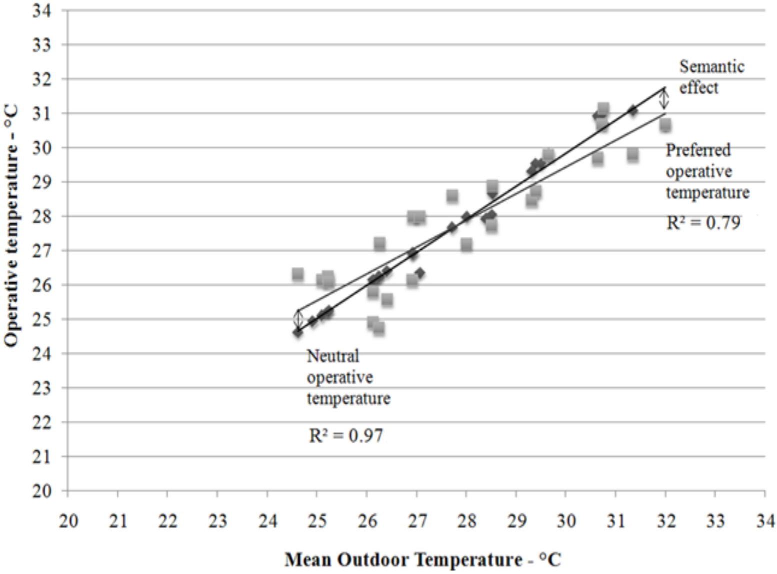


Figure 2 - Observed differences in neutral and preferred temperatures in relation to mean daily outdoor temperatures.

In the present study, however, thermal acceptability was explicit in the questionnaire, permitting a direct approach to the analysis of this item. Before the thermal acceptability analysis, the results for mean daily outdoor temperature and mean indoor operative temperature were plotted against the ASHRAE 55 [2] adaptive model. Figure 3 shows the samples distribution, based on the simple variation of daily mean outdoor temperature and mean indoor operative temperature during the experiments (each symbol corresponds to one room, with a sample size of 100 questionnaires, on average). The rooms used for this study complied with the ASHRAE 55 adaptive model’s 90% acceptability operative temperature prescriptions.

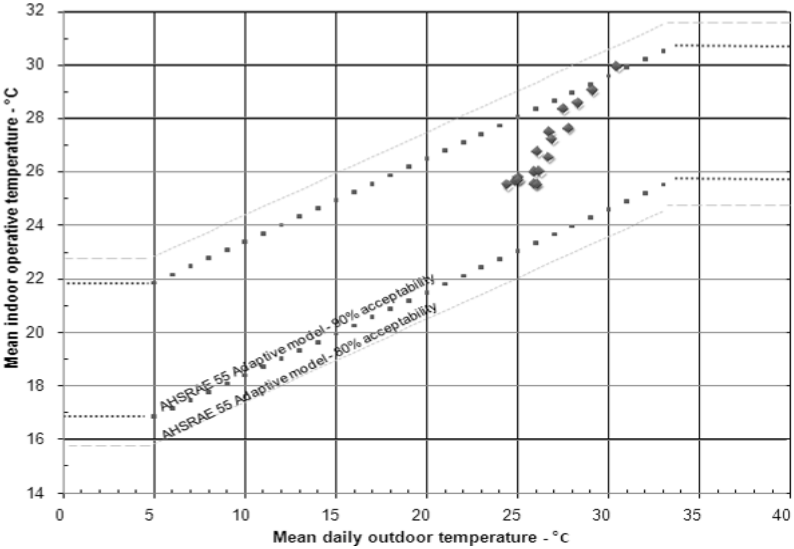


Figure 3 - Mean daily room operative temperatures plotted against to mean outdoor temperatures during the experiments. The ASHRAE 55 [2] adaptive model has been superimposed for comparison.

Within the sample rooms plotted in Figure 3, thermal acceptability votes were then analyzed. Figure 4a shows thermal acceptability percentages within 1°C indoor operative temperature bins. Occupants classified their thermal environment as “acceptable” in overwhelming majority occasions (91.5% in average during the hot season and 88.9% for cool season). Figure 4b shows the results for occupants voting for “unacceptable”. When crossed with thermal preference votes, the occupants classifying their thermal environment as “unacceptable” clearly preferred it to be “cooler” (50% during the cool season and 100% for hot season).

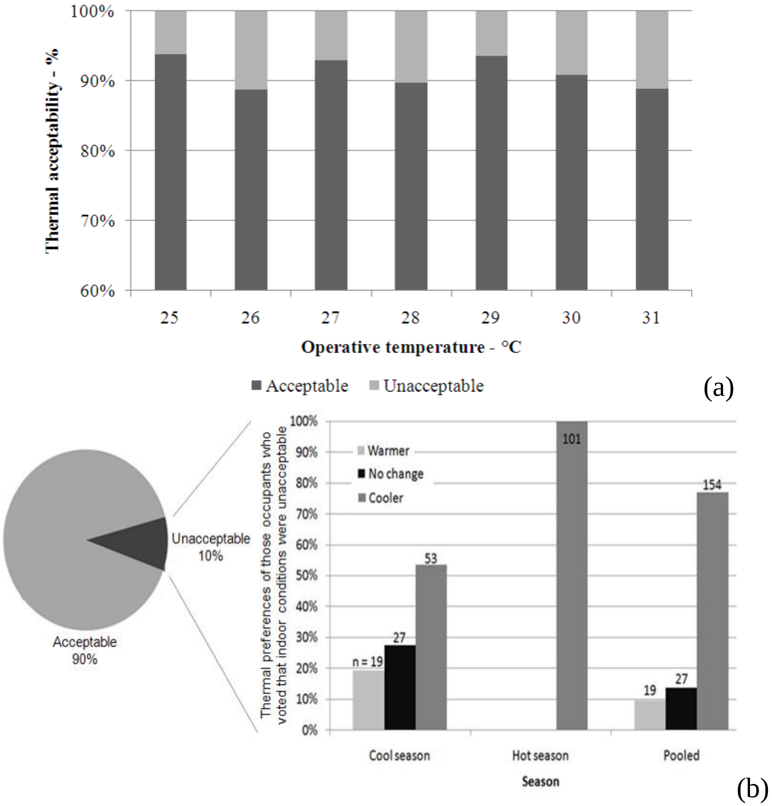
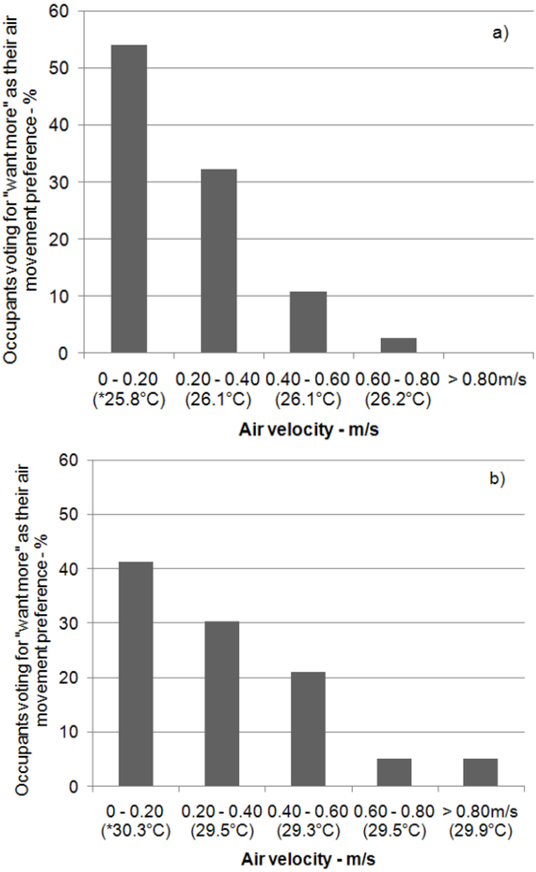


Figure 4 - (a)Thermal acceptability percentages across this study and (b) thermal preference votes separated by hot and cool seasons.

Even though occupants’ thermal acceptability percentages were high, direct assessments of for air movement acceptability reveal another interpretation of their thermal indoor environment indoors. Figure 5 shows the results for air movement preference binned for 0.2m/s increments of air speed, according to occupants’ overall thermal acceptability votes in both hot and cool seasons. Pooling the results for air velocity up to 0.40m/s, the percentage of occupants preferring “more air movement” represented 86% of dissatisfaction during the cool season and 74% for the hot season.



*mean indoor operative temperature

Figure 5 - Occupants voting for “want more” as their air movement preference for (a) cool and (b) hot season.

A major contributor to thermal acceptance in naturally ventilated buildings is the adaptive opportunity that such environments present to occupants. Research confirms the importance of having some level of direct control over the environmental conditions within the workplace [30][25] as “being paramount to occupant’s satisfaction” [32]. In naturally ventilated buildings, active occupants will adapt their indoor environment and themselves in order maintain thermal comfort. In this study, the main behavioral adaptations were related to clothing adjustments and increasing air motion within the room. Occupants could freely adapt their clothing and cooling devices that were accessible to them at the time of survey.

Figure 6 shows the percentage of fans usage binned for indoor operative temperatures. This result contrasts to one of the assumptions of the Griffiths constant: “the Griffiths constant describes the relationship between subjective warmth and temperature *assuming no adaptation takes place”* [33]. The tendency to use ceiling fans suggests that air movement increment is definitely an important item in order to restore occupants’ thermal comfort, and they actively tried to do so, when they had the opportunity.

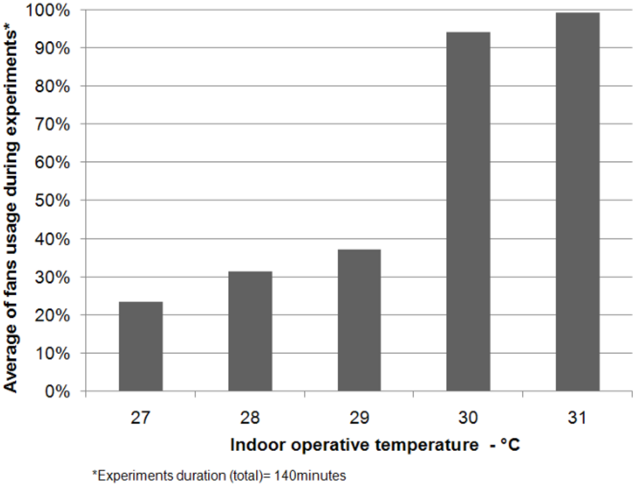


Figure 6 - Average of fans usage binned to indoor operative temperatures as an example of occupants’ adaptive behavior.

Almost 90% thermal acceptability was found within operative temperature range prescribed in the ASHRAE 55 adaptive comfort. Brazilian occupants required higher air velocities values than the subjects found in the ASHRAE RP 884 database in order to achieve air movement acceptability. In the warm and humid indoor environments studied in this paper, overall occupant satisfaction cannot be defined simply in terms of an operative temperature range alone. Air movement appears to be a major determinant of whether or not operative temperature in the high 20s will be acceptable. The questionnaire in this study facilitated a quantitative analysis of the interaction between thermal and air movement acceptability levels and the results are presented into Figure 7.

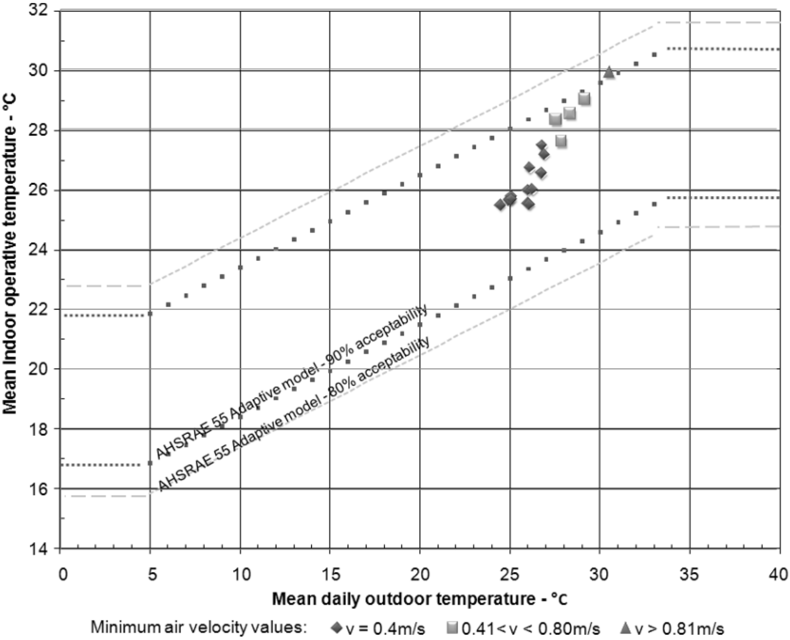


Figure 7 - Minimal air velocity values found for 90% of air movement acceptability plotted against mean daily outdoor temperatures and mean indoor operative temperatures.

Maximum permissible air velocity values are commonly included as one of the requirements in indoor climate and comfort standards. The alternative approach adopted corresponding this study was to find the *minimum air velocity* value for 90% air movement acceptability, based on probit analysis of these Brazilian field data (each symbol in Figure 7 corresponds to one room, with a sample size approximately 100 questionnaires, on average). These threshold air velocity values observed in this study differed from 0.80m/s prescribed as maximum acceptable limits in ASHRAE [2]. Minimal air velocity values required for these occupants varied from 0.40m/s to up to 1m/s and the results were organized in Figure 7 within three categories: v = 0.40m/s; 0.41m/s < v < 0.80m/s and v > 0.81m/s. These results again highlighted the necessity of combining thermal and air movement acceptability when assessing occupant’s perception of their indoor thermal environment in hot humid climates.

One possible explanation is related to the pleasure associated to air movement. Cold and warm thermoreceptors are located in different depths in the human skin and the thermoreceptors provide data from the environment to compare against deep body temperature (the controlled variable) [34]. This difference in depth where cold and warm thermoreceptors are located on skin might explain the trigger of pleasant of unpleasant due to air movement. Thermo-sensitive neuronal structures can be found in skin and deep body tissue and they can be classified as either cold or warm thermoreceptors. de Dear [35] explains that skin thermoreceptors provide the data from the environment to compare against deep body temperature (the controlled variable). The rate of firing (i.e. intensity of output) of skin thermoreceptors has a steady-state component, and a transient component (i.e. firing frequency) Accelerations in air velocity trigger dynamic discharges from the skin’s cold thermoreceptors. So, in the warm adaptive comfort zone these turbulence-induced dynamic discharges from exposed skin’s cold thermoreceptors elicit small bursts of positive alliesthesia. When the core temperature is warmer than the core set-point, any peripheral stimulation of cutaneous cold receptors will trigger positive alliesthesia. Peripheral stimulation can be through any of the heat transfer modes - radiative heat loss, convective heat loss, latent heat loss, or conductive heat loss.

4.3.7. Conclusions

Interest in naturally ventilated buildings has been revived in recent years, primarily as a result of potential energy conservation, improved indoor air quality and occupants’ thermal comfort. This interest is reflected in possibly led by standards that incorporate adaptive comfort models such as ASHRAE Standard 55 [2] and its European counterpart EN15251 [5]. When applying these adaptive comfort standards, particularly in hot humid environments where elevated indoor air speeds are essential for occupants’ thermal comfort, there are questions remaining in terms of thermal acceptability. This study addressed thermal and air movement acceptability issues for hot and humid climates, focusing not only on thermal acceptability but also air movement acceptability in Brazil.

Thermal acceptability percentages were uniformly high in this study, never falling below 89% and well within the prescriptions of the ASHRAE 55 – 2004 adaptive standard. Nevertheless these occupants required much higher than standard air velocities in order to achieve air movement acceptability. However, when the occupants reported their air movement preferences and acceptability they typically requested for ‘more air movement’. Apparently thermal acceptability *alone* does not reflect properly occupants’ perception of their thermal environment.

Minimum air velocity values were found order to achieve 90% of *air movement acceptability* in combination with thermal acceptability. From 24 to 27°C the minimum recommended air velocity is 0.4m/s; from 27 to 29°C the minimum recommended velocity is 0.41 to 0.8m/s, and from 29 to 31°C the minimum velocity for thermal and air movement acceptability is > 0.81m/s. These indications are however limited to Brazil’s hot humid climate zone and complementary field experiments are, with no doubt, necessary in order to understand with occupants in different climate zones would react when exposed to the air movement limits presented in this paper. Higher air velocity values are, certainly, an essential item in order to evaluate indoor environments in hot humid climates and thermal acceptability alone may not provide enough information about occupants’ perception of their thermal indoor environments.

Air movement definitely figures prominently in building occupants’ *preference and acceptance* of the thermal environment, and thermal acceptability alone was not enough to satisfy occupants. Combining thermal acceptability *and* air movement acceptability seems to be a challenge that must be faced.. Brazil is moving towards this combination, incorporating these items and specific requirements for occupant’s control into a standard for naturally ventilated buildings [12]. These thermal environment requirements will certainly contribute to energy savings in Brazil, focusing on naturally ventilated buildings without relaying in air conditioned indoor environments. As yet too early to know if this will satisfy occupants in naturally ventilated buildings, but definitely a step forward in considering air movement enhancement as a welcome breeze.

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4.4. Towards a Brazilian standard for naturally ventilated indoor environments: guidelines for thermal and air movement acceptability in hot humid climates

Cândido, C. M., Lamberts, R., de Dear, R., Bittencourt, L. S. (2011) Towards a Brazilian standard for naturally ventilated buildings: guidelines for thermal and air movement acceptability. *BRI.* (submitted). (paper invited from *2010 Windsor Conference).*

ISI Impact Factor: 1.253 (August 2010)

ERA 2010 Classification: A*

4.4.1. Paper Overview

The Brazilian Federal Government has been promoting energy conservation initiatives, including the Thermal Performance in Buildings – Brazilian Bioclimatic Zones and Building Guidelines for Low-Cost Housing and the Federal Regulation for Voluntary Labelling of Energy Efficiency Levels in Commercial, Public and Service Buildings. These new regulations summarize an immense effort in order to provide information for designers, based on Brazil's climate requirements, with specific items related to lighting systems, HVAC and building's thermal envelope. Yet, requirements for naturally ventilated indoor environments appear as an open category. This paper summarizes guidelines for naturally ventilated environments in which specific requirements for thermal and air movement acceptability goals must be achieved. In these guidelines, adaptive potential will be considered as well as thermal and air movement acceptability goals. Permissible operative temperatures are based on ASHRAE 55 adaptive model and *minimal* air velocity values within the occupied zone are specified. Thinking about 'active' occupants, specific control over openings and fans were also considered.

4.4.2. Individual Contribution

Discussions with supervisor, Professor Roberto Lamberts, led to the decision of organizing a provocative paper focusing on guidelines for naturally ventilated buildings in Brazil. Professor Richard de Dear provided essential input about indoor thermal environment requirements. The statistical analysis, interpretation of results and write-up of the manuscript were all undertaken by the candidate with guidance and feedback from all supervisors.

4.4.3. Introduction

The building sector potential in terms of energy conservation is a fact (IPCC, 2007). In order to achieve this, technical solutions are commonly indicated as the main mitigation path, such as insulation, cooling and heating systems, efficiency in appliances, etc. One of the key lessons is that the ultimate success or failure, in terms of building's long-term viability, energy use and occupant satisfaction, depends heavily upon the indoor environmental quality delivered to building occupants. Baring this concept, designers are beginning to shift their attention to how they widen the range of the opportunities available in a building to provide comfort for occupants, both in new-build and retrofit contexts. This in turn has re-awakened an interest in the role of natural ventilation in the provision of comfort also in terms of regulations and standards worldwide (ASHRAE, 2004, van der Lidden, 2006).

In Brazil, where there is a broad range of climatic differences, the idea of a unified standard that takes into consideration both technical and behavioral issues is a challenge. Much of Brazil's territory is classified as having a hot humid climate. In such regions, natural ventilation combined with solar protection, consists on the most effective bioclimatic design strategy in order to improve thermal comfort by passive means. Despite these conditions, the number of buildings relying on active systems as the main cooling strategy continues increasing inexorably.

In 2001, Brazil endured a major electricity energy crises as a result of meteorological conditions (lack of rain for the hydroelectricity based system) and poor strategic investments (transmission lines and backup generation plans). As consequence, the imposed consumption reduction was 20% for the entire country and some of this reduction became permanent as a result of government actions and population engagement (Lamberts, 2008). The Brazilian Government has been promoting energy conservation initiatives including the Thermal Performance in Buildings – Brazilian Bioclimatic Zones and Building Guidelines for Low-Cost Housing (ABNT, NBR 15220-3, 2005) and the Federal Regulation for Voluntary Labelling of Energy Efficiency Levels in Commercial, Public and Service Buildings (Carlo and Lamberts, 2008).

These new regulations summarize an immense effort in order to provide guidelines based on Brazil's climate requirements for designers with specific items related to lighting systems, HVAC and building's thermal envelope. Requirements for naturally ventilated indoor environments are yet to be defined. This paper summarizes a first attempt in order to define guidelines for non-residential naturally ventilated environments in which specifications for thermal and air movement acceptability goals must be achieved.

4.4.4. Revisiting Brazilian energy efficiency initiatives

In Brazil, power generation is heavily weighted towards hydroelectricity, accounting for approximately 91% of the total energy sources. Brazil's total hydroelectric power potential is 260 GW, of which approximately 22% has already been implemented (Brazil, 2009). A large proportion of hydroelectric power potential is in the Amazon region (40%), where demand is low, while most of the potential for large developments in the Southeast have already been exploited (Brazil, 2009). Recently, due to the lack of investments in the supply side and constant growth of demand, energy efficiency investments became essential.

Energy used in buildings accounts for about 48.3% of the total electrical energy consumption in Brazil (Brazil, 2009); with 23% of this amount being dedicated to commercial and public buildings and, approximately, 22% to residential sector (Ministério das Minas e Energia, 2007). Based upon this, the Federal Government released a *National Policy of Conversation and Rational Use of Energy* focusing on energy efficiency in buildings and equipment. Among the several actions on energy efficiency promoted by the Brazilian government there are two that might be highlighted: design guidelines for residential sector and the labeling system for commercial buildings.

For the residential sector, the "Thermal performance in buildings – Brazilian Bioclimatic Zones and Building Guidelines for Low-Cost Housing" (ABNT, NBR 15220-3, 2005) is the main reference. The requirements were related to thermal envelope, lighting and acoustics, along with minimum requirements for ventilation and opening areas. One important contribution of this document was the definition of bioclimatic zones and Figure 1 shows their definitions. Eight zones were defined according to climate characteristics from 330 cities across Brazil. Based upon this division, a set of specific bioclimatic design strategies was indicated focusing its application during the early design stage.

For commercial and public buildings, there is the “Federal Regulation for Voluntary Labeling of Energy Efficiency Levels in Commercial, Public and Service Buildings”. This new regulation is based on a study focusing on Brazil’s climate requirements with specific items related to lighting system, HVAC and building envelope. In similar fashion to the residential sector, the eight bioclimatic zones and design strategies are intended as a reference for designers and architects (Carlo and Lamberts, 2008).

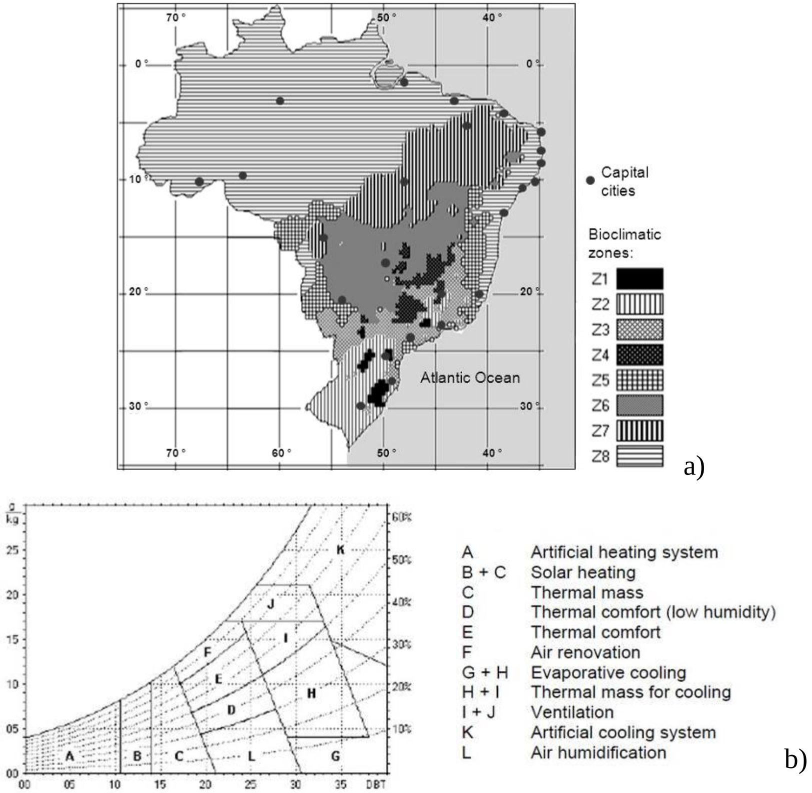

Figure 1 - (a) Bioclimatic zoning and (b) bioclimatic chart (ABNT, NBR 15220-3, 2005).

Figure 2 shows different bioclimatic strategies and recommended ventilation pattern for zones 1 to 8. Three different patterns for natural ventilation are provided. The first is “cross-ventilation”, which is self-explanatory, indicating necessity of airflow through the indoor environments for Zones 2, 3 and 5. The second one is called “selective ventilation” and its application is specific for warmer seasons and/or when the indoor temperature is higher than the outdoor temperature for Zones 4, 6 and 7. The third, and last pattern, is “permanent ventilation” and it is suggested to Zone 8, where there is the strongest dependence on natural ventilation for occupants’ thermal comfort. The only bioclimatic zone where ventilation is not indicated is the number 1, corresponding to the coldest regions in Brazil.

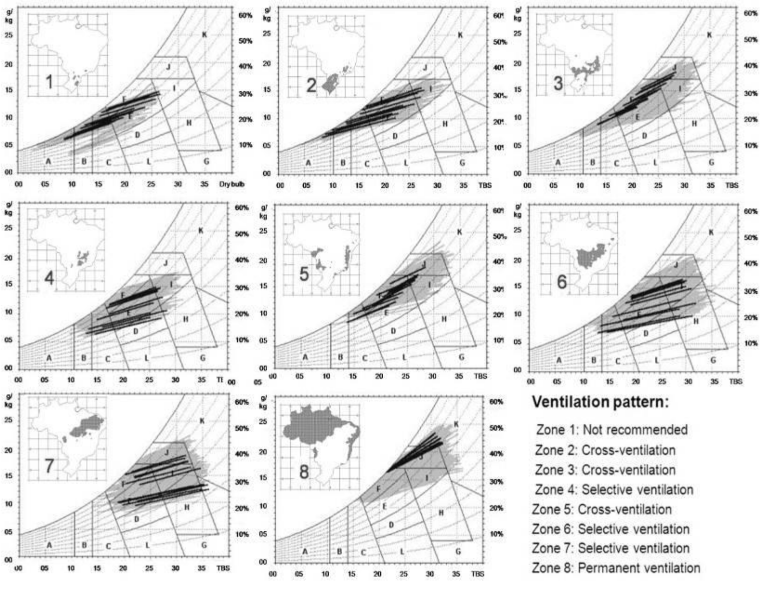

Figure 2 - Bioclimatic design strategies and ventilation pattern for different zones (ABNT, NBR 15220-3, 2005).

These regulations established a consistent amount of technical information about building’s thermal envelope. In terms of naturally ventilated environments, however, there is a gap willing to be fulfilled. Natural ventilation is frequently associated with a strong concern about airflow distribution in indoor environments, hence the recommendations related to opening areas and ventilation pattern (ABNT, NBR 15220-3, 2005). This is also the traditional reference for regional buildings' codes all over Brazil, with requirements focused exclusively on minimal opening area, without much consideration of energy efficiency or thermal comfort issues.

These requirements are undoubtedly a contribution to occupant's thermal comfort but a more accurate relationship with thermal indoor environments is necessary. Naturally ventilated buildings receive high incentives; as far as it is proved that they provide thermal comfort to the occupants. Thermal acceptance in general is not completely fulfilled in existing regulations. Field experiments developed in Brazil offer more insight into this necessity and will be presented in the next section of this paper. Considering that natural ventilation is indicated in seven of the eight bioclimatic zones in Brazil, a set of guidelines that focuses on air movement enhancement in combination to thermal comfort is therefore necessary.

4.4.5. Adapting a model for Brazilian occupants

Field experiments' evidence

Results presented and discussed here are based on original research produced by field experiments carried-out in non-residential naturally ventilated buildings located in different climatic zones in Brazil. The meta analysis classified experiments based on its method and measurement protocol. Results allowed analysis focusing on thermal acceptability inside these thermal environments.

Based on the wide range of climate conditions found in Brazil, differences in terms of thermal acceptance is not surprising. Previous studies attempted to understand the limits for temperature considered as 'acceptable' in naturally ventilated buildings. As expected, there is a significant variation in terms of acceptable temperatures. For instance, in the South of Brazil, acceptability can be found in a range from 14 to 24°C (Xavier, 2000; Lazarotto et al, 2007) while in the Northeast these values can be easily extended from 24.5 to 32°C without, however, compromising occupants' thermal comfort (Araújo,1996). Despite minor differences, it is noticeable that the range of temperatures that were found as acceptable for occupants felt in similar range predicted by the ASHRAE 55 (2004) adaptive model. As pointed-out by the authors, field experiments results indicated that adaptive opportunities played a major role in these thermal environments particularly by means of clothing adjustments (Lazarotto et al, 2007; Andreasi et al, 2010) and air movement enhancement, especially by use of fans (Gonçalves, 2001).

Interestingly, discrepancies were found also related to occupant's adaptive opportunities, in terms of clothing insulation (Ruas, 1999; Andreasi, 2001) and air movement (Araújo, 1996, Cândido et al, 2010). In the first case, the main complains are derived from the degree of freedom within the dress code (Andreasi, 2009) and, conversely, occupants were satisfied with a flexible one (Lazarotto et al, 2007). In the second case, occupant's complains were related to the preference for 'more air movement' (Cândido et al, 2010), especially for the hot-humid zone, lays the strongest demand for higher air velocities. This demand was more noticeable for operative temperatures above 26°C (Araújo, 1996; Andreasi et al, 2010; Gonçalves, 2001). In addition to higher air velocities, occupants also appreciated having control over fans as complementary source of ventilation, especially for periods without breeze. Ceiling fans tend to be a useful device in order to increase air movement for these occupants (Gonçalves, 2010).

Field experiments carried out in Brazil's hot-humid zone showed that almost 90% thermal acceptability was found within operative temperature range prescribed in the ASHRAE 55 adaptive comfort (Cândido et al, 2011). However, occupants required higher air velocities values higher the average 0.3m/s found within the ASHRAE RP 884 database in order to achieve air movement acceptability. In this hot humid context, occupants overall satisfaction cannot be defined simply in terms of an operative temperature range. Therefore, air movement will be determinant of whether or not operative temperature in the high 20s will be acceptable or not. Based upon these results, occupants in naturally ventilated buildings (i) accept temperature swings during the day and year, (ii) prefer higher air velocities *if* (iii) control and fans are provided. These results can be easily related to the three categories of responses that occupants undertake in order to reestablish thermal comfort summarized by de Dear et al (1997): behavioral, physiological and psychological adaptation.

The guidelines suggested in this paper are related to naturally ventilated environments and it comprises two main items: adaptive capacity opportunities and acceptable indoor conditions, including specific requirements for thermal and air movement acceptability. These guidelines are specific for non-residential buildings with occupant's activities and adaptive opportunities regarding specifically openings and control over fans. Occupants must be developing sedentary activity (1.0 to 1.3 *met*) for at least thirty minutes and they must be able to actively modify their thermal indoor environment at least in terms of garments and openings. Windows must be accessible and controllable primarily by the occupants and they might be combined to fans in order to improve air velocity.

Adaptive capacity potential

Buildings will be assessed in terms of their "adaptive capacity potential" (Kwog and Rajkovich, 2010). The adaptive potential can be defined as "a design approach that relies on an implicit understanding of the ecological and physical context of the site, orientation, site planning, passive heating and cooling design strategies, openings in the envelope for optimal daylight natural ventilation, shading, insulation, and envelope strategies" (Kwog and Rajkovich, 2010). Buildings' design must be in compliance with bioclimatic strategies for its specific zone. The following information must be provided as minimal design requirements:

- Orientation and site planning;
- Design strategies applied according to its specific bioclimatic zone;
- Openings design: location, dimension and detailed information of its operability;
- Complementary devices for ventilation (if applicable), such as wind catchers, ventilated sills, pergolas, verandahs, etc.;
- Complementary mechanical devices (if applicable), i.e. ceiling and/or desk fans, its distribution in the indoor environment and occupants control availability (individual or group).

There will be no grading of adaptive capacity potential and all buildings must provide design evidences of *at least* the above-mentioned strategies. In this level, buildings will be assessed in a *qualitative* way, in order to offer the highest adaptive opportunities potential for occupants of these indoor environments. Buildings complying with this item will be then considered for subsequent analysis regarding acceptable indoor conditions.

Acceptable thermal conditions

A combination of thermal and air movement acceptability will be considered in order to evaluate thermal indoor environmental conditions. The following items will provide more details about these requirements.

Indoor operative temperatures

The acceptable thermal conditions applied will be established according to ASHRAE 55 adaptive model (de Dear and Brager, 1998). Allowable indoor operative temperatures will be presented as a variation of mean monthly outdoor temperatures and thermal acceptability goals will be 80 and 90%. Extensions of the neutral temperature will be of ±2.5°C for 90% of thermal acceptability and ±3.5°C for 80% of thermal acceptability.

Air movement

Air velocity values are recognized as one of the essential variables to improve occupant's thermal comfort and it has been considered in comfort standards worldwide. Typically, *maximum* limits are established in order to avoid dissatisfaction, especially due draft. This might be true in cold climates, but questionable for warm environments (Arens et al, 1998, Khedari et al, 2000, Tanabe and Kimura, 1989, Zhang et al, 2007). Field studies suggest, however, that there may be a zone of temperatures and air velocities in which devices and designs that move air across large areas can do so without creating an 'appreciable' draft risk for the occupants. Many previous studies focused on air movement in field studies, including the maximum air velocity range that could be regarded as 'acceptable' for occupants during their activities. In this case, the considerations were constantly related to the concept of avoiding any disturbing or undesirable air movement (draft).This discussion has been revived due to occupant's complaints, often related to preferences for "more air movement" (Toftum, 2004, Zhang et al, 2007). Revisions to limits have been proposed considering also more specific requirements for occupant's control (Arens et al, 2009).

For these guidelines, air movement acceptability must be considered and the target values will be for 80 and 90%. In order to achieve these targets indoor environments must fulfil *minimal* air velocity requirements according to Figure 3. The air velocity requirements must be achieved during the occupied period. Complementary ventilation can be achieved by use of fans and are encouraged in order to supply airflow for occupants especially during periods of absence of exterior wind or/and areas with low porosity (city centres, for example). Nocturnal ventilation techniques also are encouraged but limits will not be established in terms of air velocity values. Table 1 summarizes occupant's control requirements over openings and complementary mechanical devices. Three different categories were defined. This classification can be applied *in combination with* air velocity values above detailed.

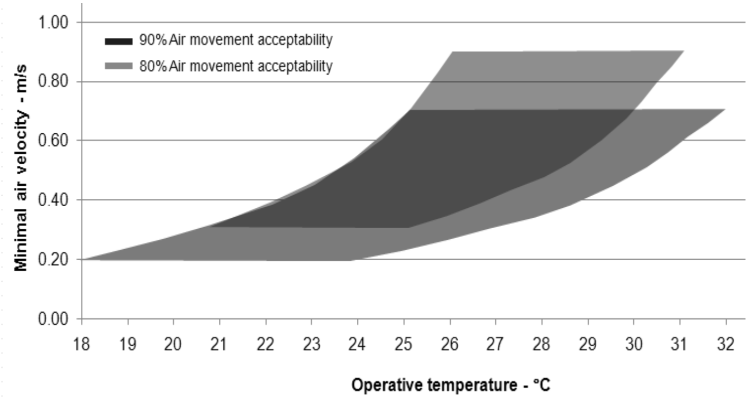

Figure 3 - Minimal air velocity values required within the occupied zone, corresponding to 80 and 90% air movement acceptability.

Table 1- Categories related to occupants' control over openings and fans.

Categories	Available occupant's control within the occupied zone	
	Openings	Fans
☆☆☆	Individual access - Operable and airflow directional design	Individual
☆☆	Group access - operable and airflow directional design	Every four occupants
☆	Group access - Operable	Every six occupants

Labeling categories

Naturally ventilated buildings willing to receive a thermal comfort and energy efficiency label will be graded into three different categories. Table 2 summarizes the suggested requirements for natural ventilation. Building must be in conformity to the adaptive capacity potential and thermal and air movement acceptability percentages must be accomplished in order to be classified into one of the three categories. Category *1* comprises indoor environments where air movement acceptability achieved 90% and received three stars for occupant's control. Category *2* corresponds to buildings where air movement acceptability was 80% and two stars for occupants control. The last category, *3*, considers indoor environments where 80% of air movement acceptability was achieved but only one star for complementary occupants' control. In order to be in conformity to the existing Federal Regulation for Voluntary Labelling of Energy Efficiency Levels in Commercial, Public and Service Buildings presented in detail in Carlo and Lamberts (2009), the following classification is suggested. The NatVent category will be combined to the percentage of hours into the comfort zone (PHC). The results for the suggested label were summarized in Table 3.

Table 2 -Suggested design requirements for naturally ventilated buildings.

NatVentCategory	Adaptive capacity potential	Thermal and air movement acceptability	
		Acceptability	Occupant's control
1	Yes	90%	☆☆☆ and ☆☆
2	Yes	80%	☆☆
3	Yes	80%	☆
4	Yes	-	☆

Table 3 - Suggested labelling categories for naturally ventilated buildings.

Label Category	% Hours into the comfort zone (PHC)	NatVent Category
A	PHC ≥ 80%	1
B	70% ≤ PHC < 80%	2
C	60% ≤ PHC < 80%	3
D	60% ≤ PHC < 80%	4

Conformity

Buildings willing to receive this labelling must provide proof of conformity according to the above requirements. Adaptive capacity must be shown by detailed information related to building's design strategies, according to its specific bioclimatic zone.

Thermal and air movement acceptability must be shown by means of calculation and/or simulation and/or wind tunnel experiments for buildings in design stage. For existing buildings, comprehensive indoor climatic measurements must take place. Simulations/experiments must represent:

- Indoor operative temperature ranges within the thermal comfort zone;
- Air velocity values *and* airflow distribution within the occupied zones;
- Air velocity provided by the complementary mechanical devices and occupant's control pattern applied; within the occupied zones;
- Complete plans, descriptions, detailed information for maintenance and operation must be provided and kept during building's life occupancy;
- Identification and distribution of all mechanical cooling devices must be indicated and detailed, especially in terms of occupant's control.

Field experiments must be in compliance with minimal requirements specified into the measurement protocol. In this document, the method will be described including step-by-step measurement procedures, instrumentation and questionnaires. Indoor environmental data must consider, but not be limited to air temperature, mean radiant temperature, humidity, air speed, outdoor temperature, occupants' clothing and activity. More detailed information will be provided in the guidelines.

4.4.6. Conclusions

This study proposed a set of guidelines for a Brazilian standard focusing on naturally ventilated indoor environments considering thermal comfort and air movement acceptability issues. The main criteria of indoor environmental quality considered in these guidelines were a combination of thermal and air movement acceptability. Based upon this, operative temperature ranges were based on the de Dear and

Brager adaptive model combined with minimum air velocity requirements from this thesis.

Air movement definitely assumed a major significance in terms of preference and acceptance of the indoor thermal environment, and thermal (i.e. temperature) acceptability alone was not enough to satisfy occupants. Combining thermal acceptability and air movement acceptability is the key challenge that must be faced in these indoor environments. Based upon this, operative temperature permissible ranges were based on ASHRAE 55 adaptive model and minimal air velocity requirements within the occupied zone were also determined. Thinking about 'active' occupants, specific control over openings and fans were also considered.

This is a first attempt in combining guidelines for naturally ventilated buildings in Brazil and more detailed information is therefore necessary. Future comfort field experiments will be, undoubtedly, a crucial source of information for further refinements of these guidelines. However, there are enough indications that providing occupants with control and requiring an active behaviour over passive design techniques will be a successful path towards more healthy, stimulating and sustainable buildings in Brazil, In other words, moving away from 'thermal boredom' towards 'thermal delight' (Heschong, 1979), architects might have the opportunity of not only satisfying occupants but also applying a more holistic design approach, more culturally relevant and environmentally *responsible* design. The recent revival of natural ventilation might help architects in (re) discovering such potential and in returning back to basics, considering again buildings as the third skin, a response to the climate and culture. After all, buildings are built for their occupants. It can be a sculpture, but not only that.

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Conclusions

V. Conclusions

The overwhelming weight of evidence from a large number of studies indicates that increased air movement in warm environments is essential in improving occupants' thermal comfort, and therefore higher air velocity values are suggested for these contexts. A relatively small volume of data from Danish laboratory experiments was used to justify that 0.2m/s as the maximum allowable air speed and it has been deemed in Standard 55-2004 to be the threshold of draft perception inside air-conditioned buildings. However, for occupants possessing air velocity control, this limit can be extended to 0.8m/s in ASHRAE 55-2004. Field studies suggest, however, that there may be a zone of temperatures and air velocities in which devices and designs that move air across large areas can do so without creating an 'appreciable' draft risk for the occupants. Many previous studies focused on air movement in field studies, including the maximum air velocity range that could be regarded as 'acceptable' for occupants during their activities. In this case, the considerations were constantly related to the concept of avoiding any disturbing or undesirable air movement (draft).

This thesis has investigated the relevance and appropriateness of currently mandated air velocity limits inside naturally ventilated buildings in hot-humid climates. Occupants polled for their air movement preferences and *acceptability*. This novel approach allowed the definition air velocity values that occupants considered to be the *minimum* requirement for their thermal comfort. Air movement was investigated based on two goals for acceptability: 80 and 90%. Minimal air velocities values obtained based on this analysis were close to, or above 0.8m/s, which is currently mandated as the maximum air velocity for ASHRAE 55-2004 [1]. The current results lead to the conclusion that air movement can be perceived by inhabitants of hot-humid climates as quite acceptable at velocities well above the previous values suggested in the literature. For natural ventilation in these climates, higher air velocities are desirable in order to improve subjects' thermal comfort. This dispels the notion of draft in hot climates, and it is consistent with the phsycological hypothesis of alliesthesia. By linking the physiological concept of alliesthesia with knowledge about cutaneous thermo receptor function, it is possible to explain the simple pleasure derived from effective natural ventilation, particularly in warm climates. These findings also corroborate previous laboratory studies addressing the pleasantness associated with transient thermal conditions.

This project also investigated the influence of prior exposure to air conditioned environments to thermal and air movement acceptability and preference. This analysis allowed the influence of thermal history occupant's perception of their indoor thermal environment. The percentages of occupants preferring natural ventilation on its own or natural ventilation combined with fans strongly confirmed indication that passive strategies are welcomed by these occupants, and should be exploited as much as possible. The 'addiction' to AC indoor environments that was revealed in this study clearly influences occupant's thermal comfort expectations and, interestingly, air movement preferences. These findings also indicated that occupant's rising comfort expectations; resulting from constant AC exposure, militate against the implementation of adaptive comfort principles in bioclimatic buildings and the return to more naturally ventilated buildings.

This study also proposed a set of guidelines for a future Brazilian standard focusing on naturally ventilated indoor environments considering thermal comfort and air movement acceptability issues. The main criteria of indoor environmental quality considered in these guidelines were a combination of thermal and air movement acceptability. Based upon this, operative temperature ranges were based on the de Dear and Brager adaptive model [2] combined with minimum air velocity requirements from this thesis. Thinking about 'active' occupants, specific control over openings and fans were also considered. This was a first attempt to combine temperature and air movement guidelines for naturally ventilated buildings in Brazil.

Air movement definitely assumes a major significance in terms of preference and acceptance of the indoor thermal environment, and thermal (i.e. temperature) acceptability alone was not enough to satisfy occupants. Combining thermal acceptability and air movement acceptability is the key challenge that must be faced in these indoor environments. Brazil should be moving towards this combination, incorporating these separate but also connected dimensions of environment, as well as specific requirements for occupant's control into a standard for naturally ventilated buildings. It is too early to know if this will be sufficient to satisfy occupants in naturally ventilated buildings, but a fundamental step towards considering air movement enhancement as a welcome breeze in hot humid climates has clearly been made.

This study provided an insight into air movement and thermal comfort in hot humid climates. There are, however, questions that were beyond the scope of this project but might help in understanding occupant's thermal comfort expectations of their indoor environment. Perhaps the study's main limitation is related to the application, and therefore extrapolation, of minimal air velocities values found in this project. Additional field experiments in naturally ventilated buildings should be carried-out in order to compare the results from this particular study with corresponding field data from different climatic regions in Brazil. Another limitation is related to the buildings in which these experiments were carried out. They were all educational institutions and we need to assess how representative they are of other types of occupancy. Again, field experiments would be essential in order to understand differences in terms of air movement acceptability. Another item that was out of the scope of this project, but no less important is humidity. As pointed-out in the thermal comfort literature so far, humidity plays a major role in occupant's thermal comfort in high temperatures and it should be explored in more detail in hot-humid climates.

Results also indicated that there is indeed a pleasure associated with natural ventilation. The emergent topic of alliesthesia can provide more insightful information about this complex and fascinating interaction between physiology and pleasure. Clearly, a specific air speed has many possible physiological and subjective effects ranging from a pleasant sense of coolness to an unpleasant sense of draft, depending on the status of the indoor climate variables and the occupants' individual factors.

In hot-humid climates, air motion should be encouraged rather than being considered as detrimental. Designers should therefore explore it more fully in their design, focusing on more sustainable, energy efficient and, why not, pleasurable built environmental designs. In Heschong's words [3] "…the thermal environment has the potential for sensuality, cultural roles, and symbolism that need not, indeed should not, be designed out of existence in the same of a thermally neutral world". Moving away from 'thermal boredom' towards 'thermal delight', architects will have the opportunity of not only satisfying occupants but also applying a more holistic approach and, perhaps a more culturally relevant and environmentally *responsible* design. The recent revival of natural ventilation might help architects in (re) discovering such potential and in returning back to basics, considering again buildings as the third skin, a response to the climate and culture. Afterall, buildings are built for their occupants. It can be a sculpture, but not only that.

5.1. References

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