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Candido, Christhina Maria

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Macquarie University

Department of Environment and Geography

Indoor air movement acceptability and thermal comfort in hot-humid climates

Christhina Maria Cândido

Supervisors:
Professor Richard de Dear
Dr. Paul Beggs

Adjunct supervisors:
Professor Roberto Lamberts
Professor Leonardo Salazar Bittencourt

Sydney, September 2010.

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

Abstract

Much has been done in order to understand when air movement enhancement is *unwelcome.* 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 occupant's rising comfort expectations; resulting from constant air-conditioning exposure, militate against the implementation of adaptive comfort principles in bioclimatic buildings. 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. And combining thermal and air movement acceptability is the key challenge that must be faced in these indoor environments. Based on these results, this project suggested a set of guidelines for a 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 potential, 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).

x

Publications list

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

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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

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.

Cândido, C. M., Lamberts, R., Bittencourt, L. S., de Dear, R. (2010) 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 purposes in hot-humid climates). *Ambiente Construído* (Online). **10**: 59 - 68.

Cândido, C. M., Lamberts, R., de Dear, R., Bittencourt, L. S., de Vecchi, R. (2011) Towards a Brazilian standard for naturally ventilated buildings: guidelines for thermal and air movement acceptability. *Building Research and Information* **39**: 145 – 153. *BRI.* doi: 10.1080/09613218.2011.557858.

Cândido, C. M., de Dear, R., Ohba, M. Effects of artificially induced heat acclimatization on subjective assessments of indoor thermal environments. Part I: Thermal sensation, acceptability and preference. *Indoor Air.* (submitted).

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: *X Encontro Nacional e VI Encontro Latino Americano de Conforto no Ambiente Construído - ENCAC*, Natal, Brazil.

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Cândido, C. M., Lamberts, R., Bittencourt, L. S., de Dear, R. (2008) Aceitabilidade do movimento do ar e conforto térmico em edificações naturalmente ventiladas em Maceió/AL (Air movement acceptability in naturally ventilated buildings in Maceio city). In: *XII Encontro Nacional de Tecnologia do Ambiente Construído - ENTAC*, Fortaleza, Brazil.

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.

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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 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 [3 - 12]. Indeed, occupants have been demanding 'more air movement' in numerous field studies [8 – 12]. 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 research 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 regions, 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 final-use in Brazil (public and commercial sectors combined) [14]. The role of natural ventilation as an energy conservation strategy is a path towards environmentally 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 contect of this project and identified 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.

1.3. References

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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 will be presented. 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 assess 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

[2] IPCC: Intergovernmental Panel on Climate Change.

buildings (both newly-built and retrofitted projects) meet the 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 [2 – 7].
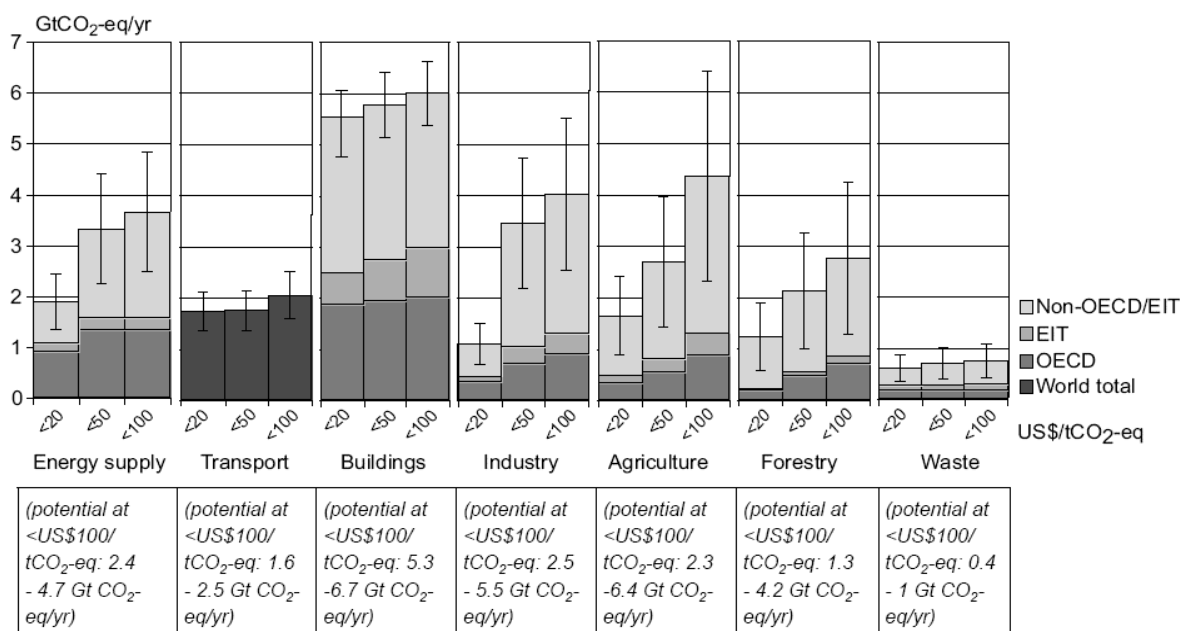
Figure 1 - Assessment of 2030 greenhouse gas emission mitigation potential for three costs per tonne of carbon (<US$20, 50 and 100). EIT refers to Economies in Transition [4].

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 solutions are feasible to implement, they are also limited to a technical approach

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

related to the building's performance, without much consideration of the potential related to behavioural change.

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 avoided signing the Kyoto protocol; approximately half of the states have embarked on state-level carbon restriction laws [6]. 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 undertatings 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 necktie (*circa* de 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 growth 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 of floor area 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 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

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

are (or at least should be) becoming aware that their lack of understanding of how 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 of 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 [21]. Figure 2 shows the evolution of the energy consumption in the residential, commercial and public sectors from 1982 to 1998.
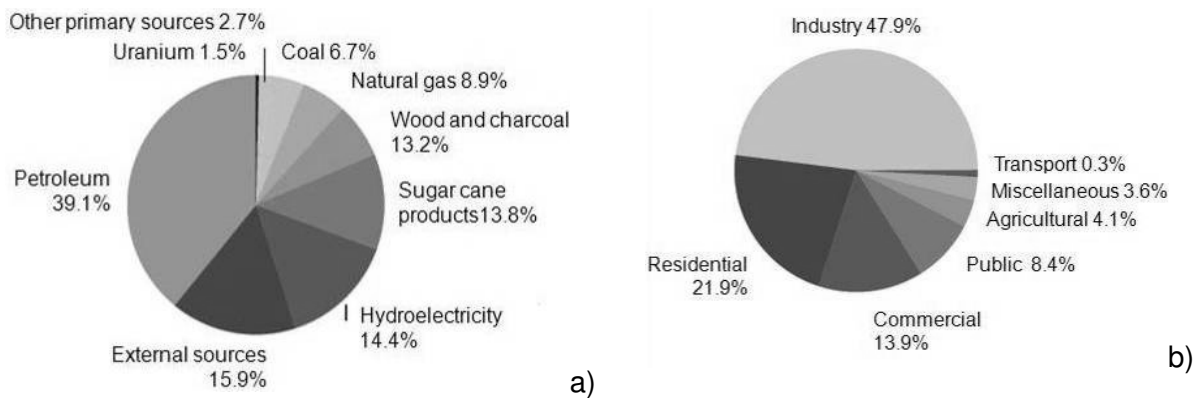
Figure 2 - Energy source availability (a) and electricity consumption per sector in Brazil (b) [23].

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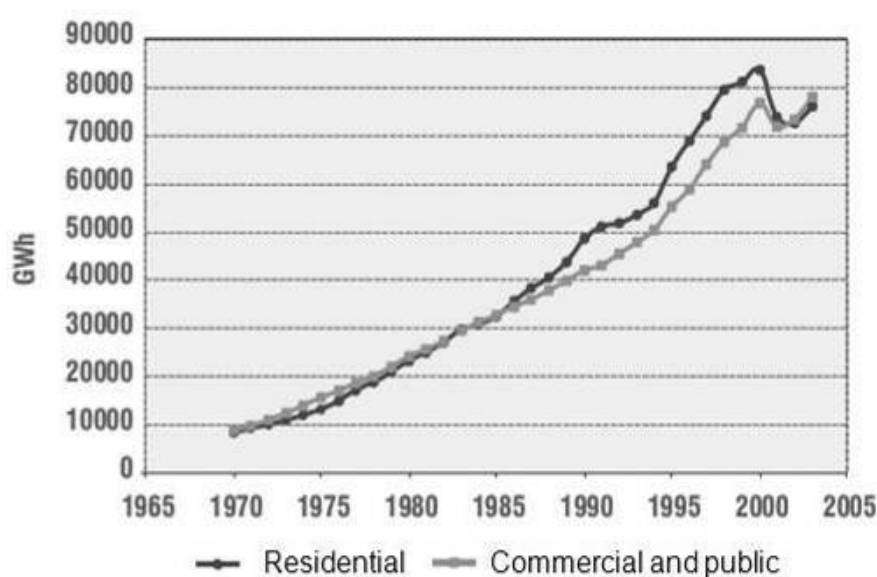
Figure 3 - Electricity consumption growth in residential, commercial and public sectors in Brazil from 1970 to 2005 [22].

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 interdisciinary 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].

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 incredients 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, 19, 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].
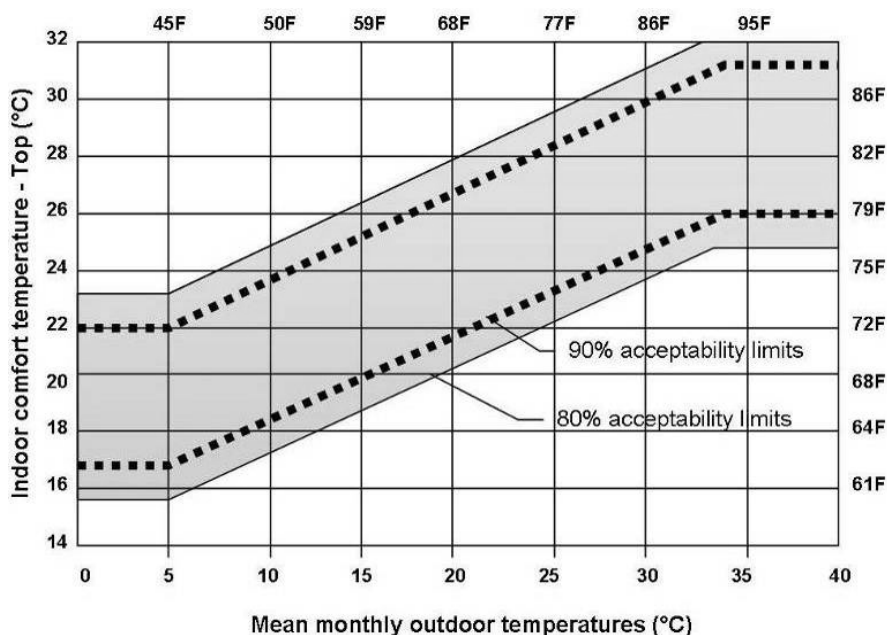
Figure 4 - The adaptive model of thermal comfort [40].

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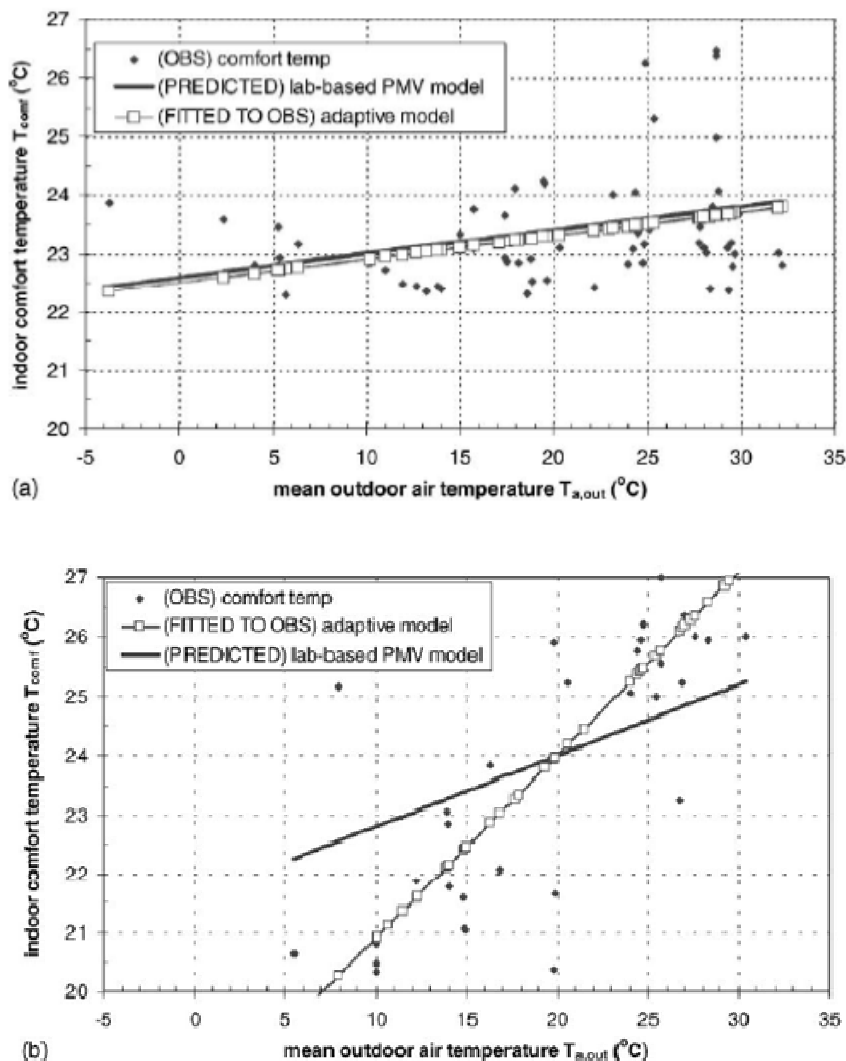
Figure 5 - (a) Observed (OBS) and predicted indoor comfort temperatures from RP-884 database, for HVAC buildings and (b) Observed (OBS) and predicted indoor comfort temperatures from RP-884 database, for naturally ventilated buildings. [2].

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 27 ºC). 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].

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].

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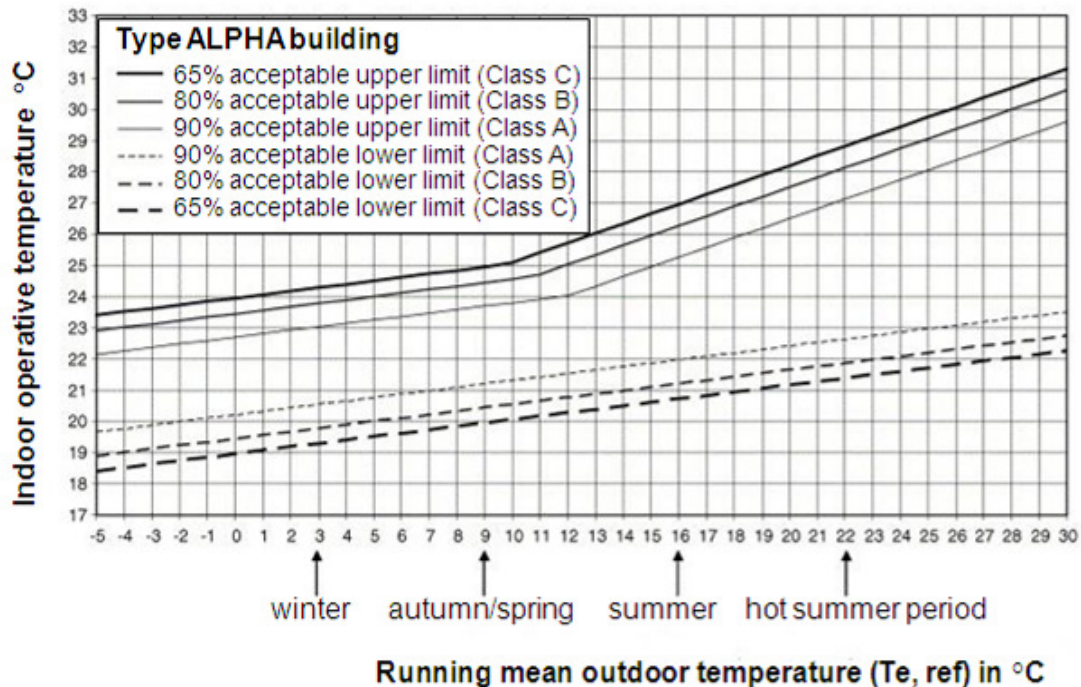
Figure 6 - Maximum allowed operative temperatures for a specific acceptability level, as a function of the outdoor temperature [41].

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].
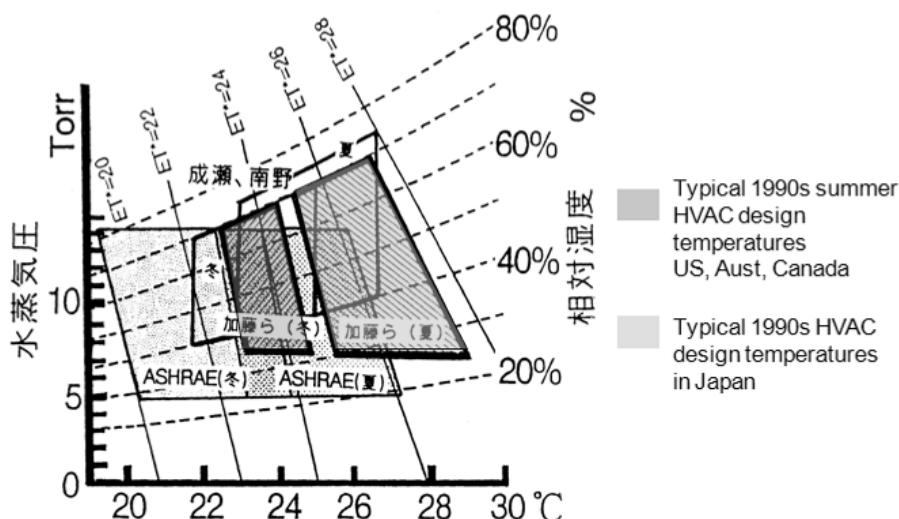
Figure 7 - Differences in typical 90's HVAC design temperatures in Japan and other parts of the world (US, Australia and Canada) [42].

China, Brazil and India are moving towards standards for naturally ventilated buildings [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 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. Brazil is encouraging naturally ventilated buildings and actively considering standardizing the adaptive model of thermal

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

comfort along with requirements for air movement and occupant's control [52]. 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. Currently, energy efficiency labelling for residential buildings is in progress and will be made public towards the end of 2010. 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.

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. Currently it is voluntary but will become mandatory in 2013 with scheduled reviews every five years [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 to air temperature and air speed but also other factors such as area and variability and which part of the body 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

$$DR = (34 - t_a) \times (\bar{v} - 0.05)^{0.62} \times (0.37 \times \bar{v} \times Tu + 3.14)(\%)$$

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]. When people are more likely to feel warmer than neutral, the situation is qualitatively different. In this case, the same airflow perceived as draft will be welcomed by occupants as a way of increasing their overall thermal comfort [70 – 75].

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 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℃ to 28.5℃). 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℃.

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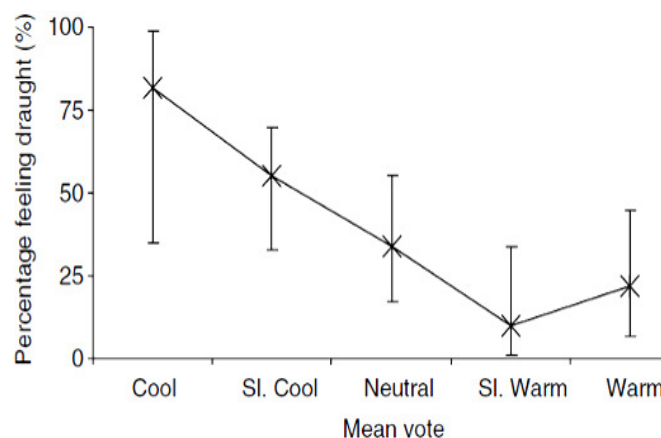
Figure 8 - Percentage of people feeling draft as a function of their mean thermal vote. Error bars show 95% upper and lower confidence limits [65].

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	46	52
	0.15-0.25	2	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 and 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]. In hot humid climates, people could live comfortably in naturally ventilated buildings as long as they were provided with appropriate air velocities within the occupied zone. 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℃. In a similar investigation [71] it was found that at least 80% of the occupants can be comfortable for a temperature limit of 28℃ 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℃ [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 indicates 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 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).
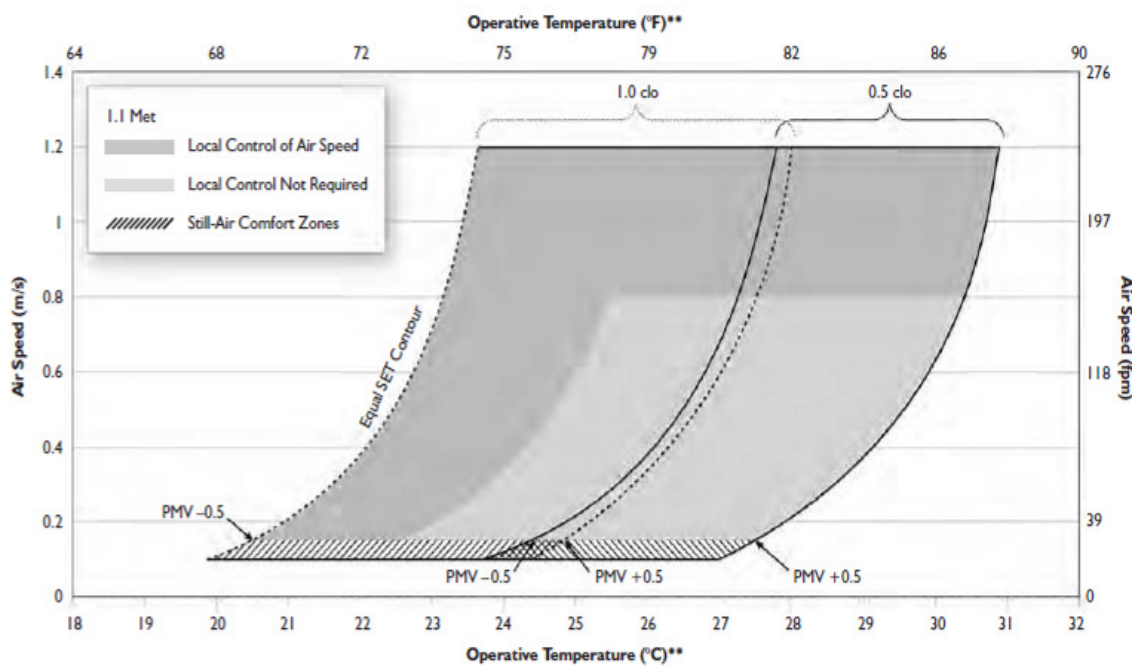
Figure 9 - Air speed limits proposed by Arens et al. [20].

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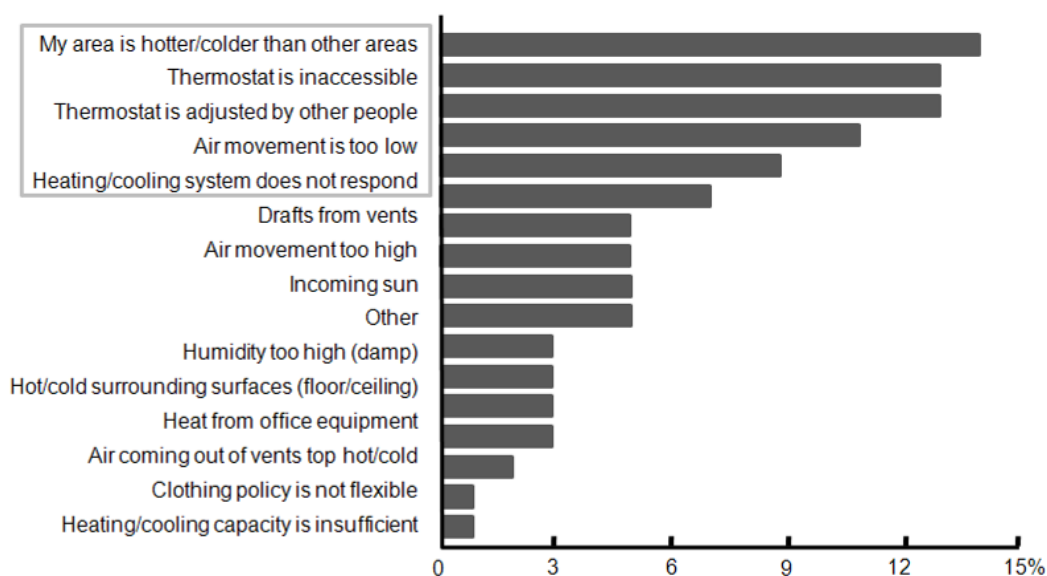
Figure 10 - Reasons for thermal dissatisfaction in mixed-mode buildings in US [87].

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. Therefore it seems logical to include the aspect personal control over indoor climate in future (thermal) comfort standards. 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 of aspect 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.
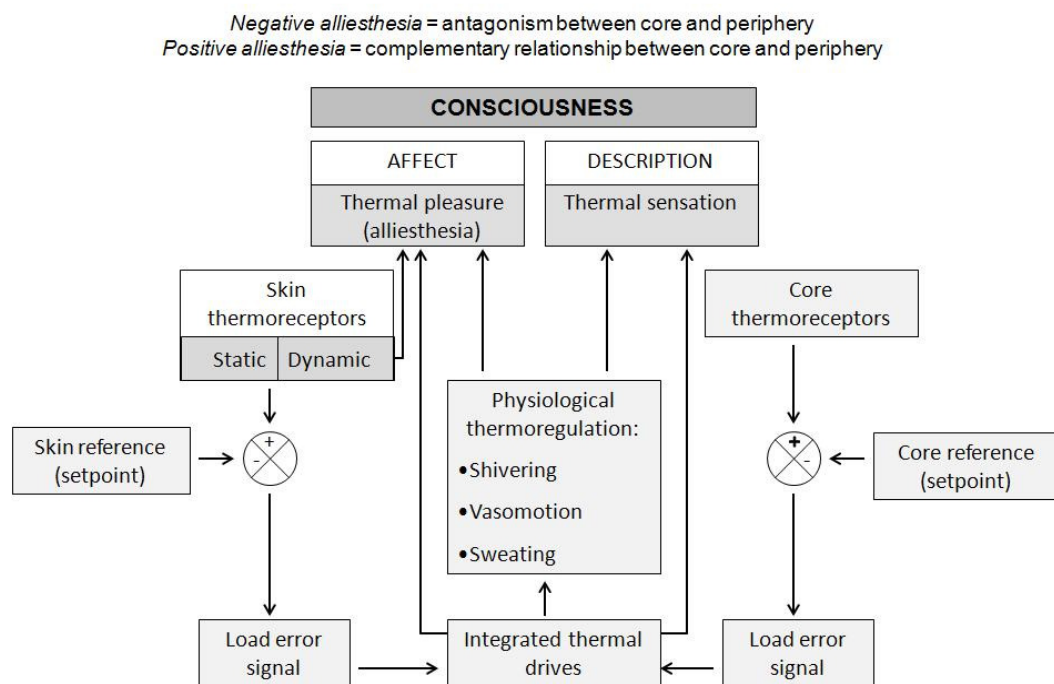
Figure 11 - Negative and positive alliesthesia [93].

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.

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 it's broadly influence is recognized within the thermal comfort reseach 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 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 enormous 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 city, 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 8,574.761 km2 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.

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

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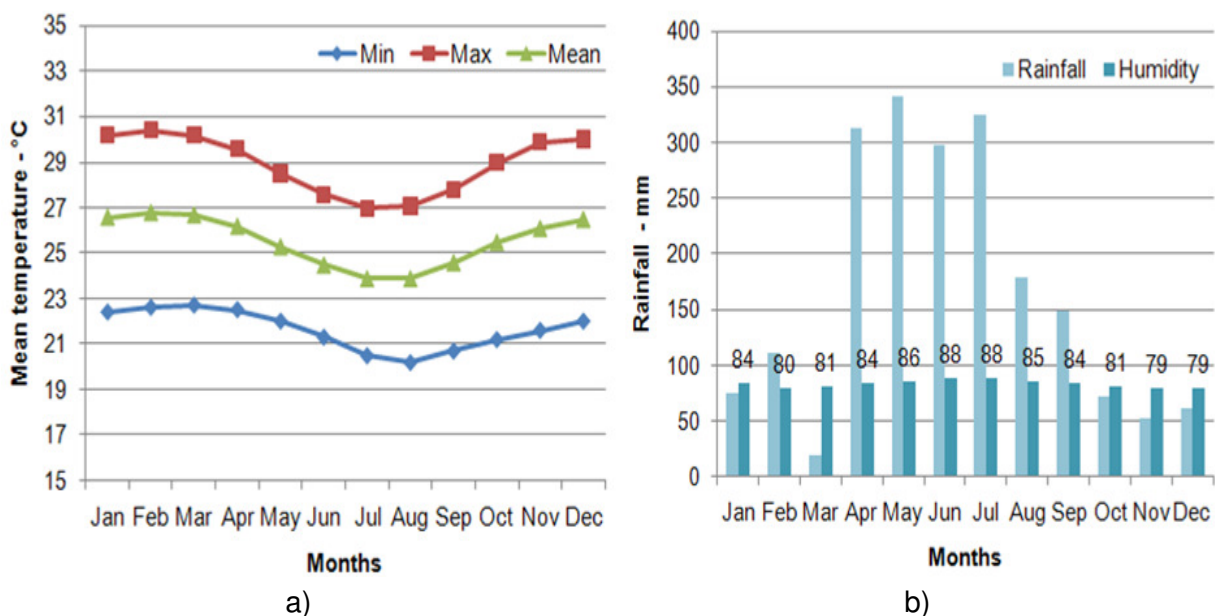
Figure 2 - Maceio's annual temperature (a) and rainfall/humidity (b) [1].

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	26.8	21.4
Outdoor relative humidity (%)	74/8	88.9	56.1	75	91	57
Mean monthly outdoor temperature (°C)	25.3	30.2	23.7	23.5	27.1	20.2

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.
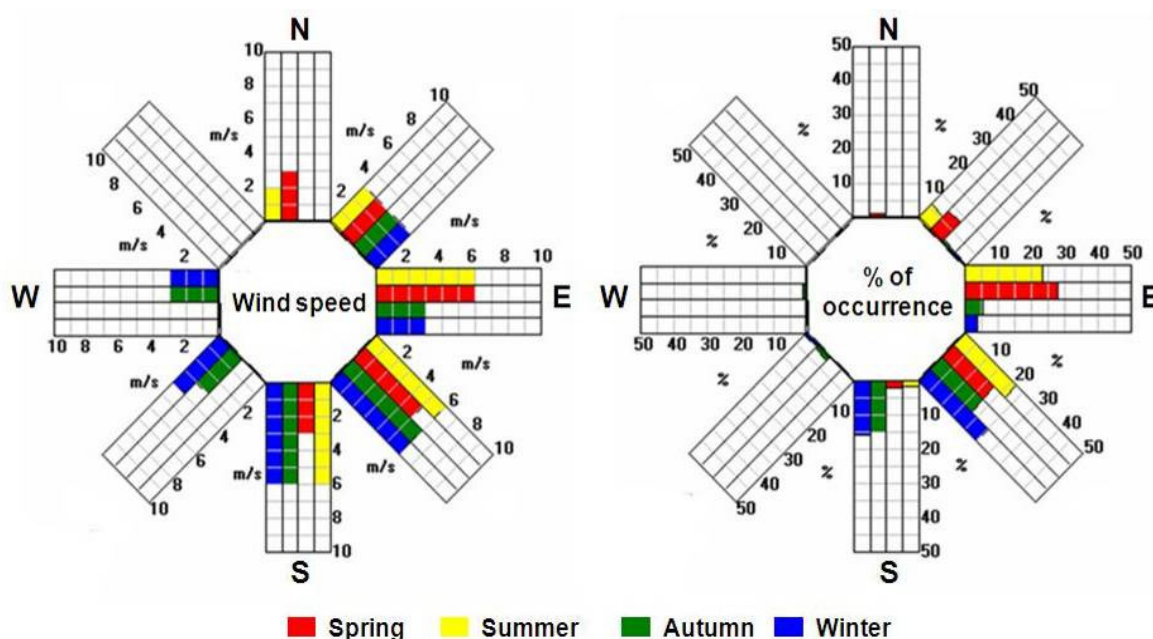
Figure 3 - Wind speed and direction rose.

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.
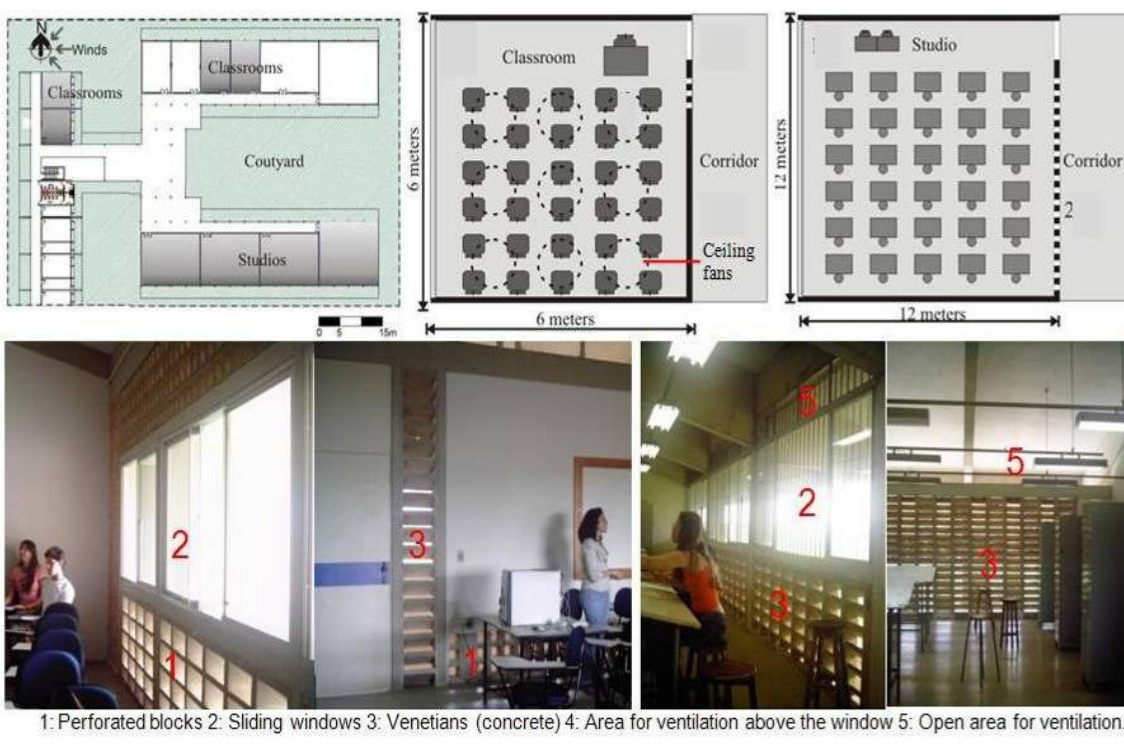
1: Perforated blocks 2: Sliding windows 3: Venetians (concrete) 4: Area for ventilation above the window 5: Open area for ventilation. a)
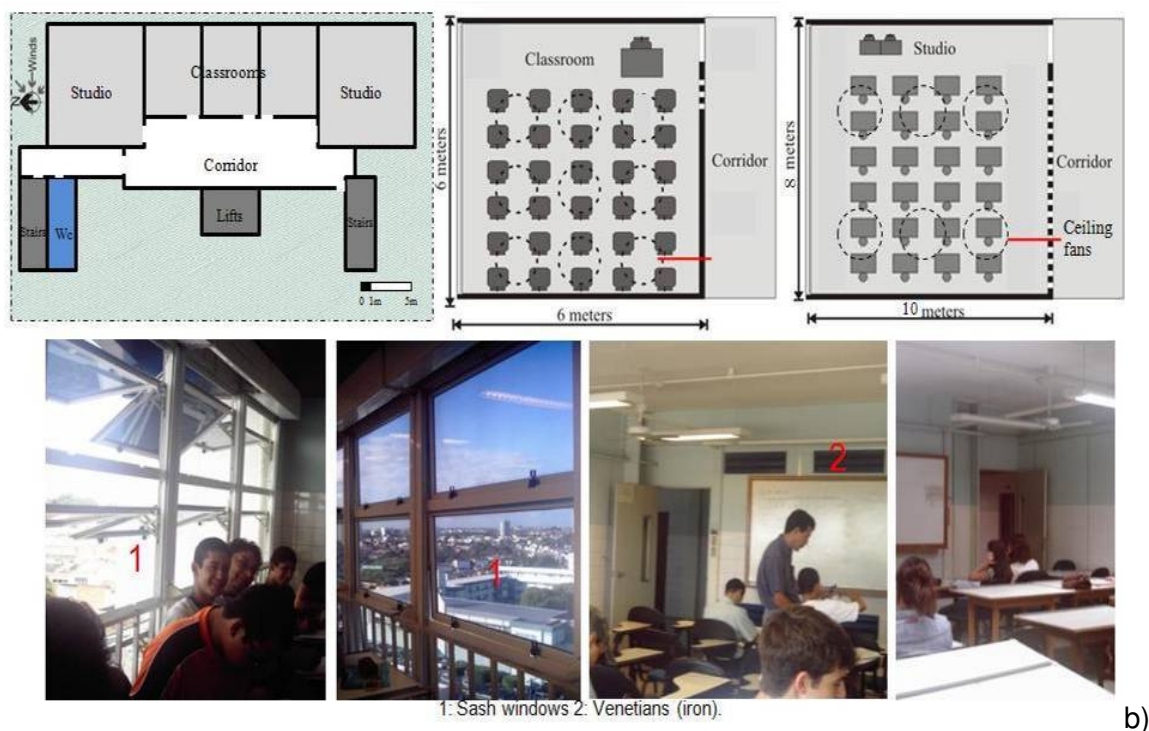
Figure 4 - Classrooms and studios at Federal University of Alagoas (a) and Superior Studies Center of Alagoas (b).

A total of 2,075 questionnaires were completed during the two 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	20.8
Height (m)	Ave	1.7	1.7
Weight (kg)	Ave	59.1	59.5
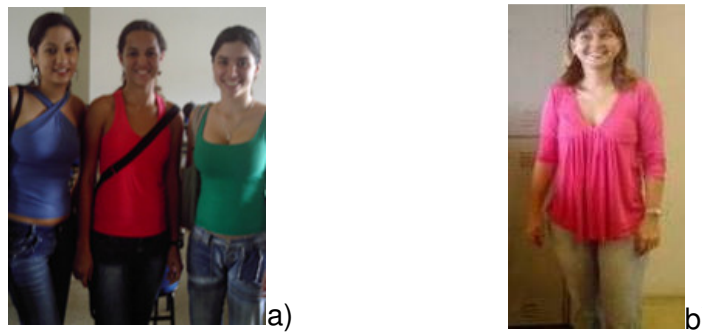
Figure 5 – Occupants' typical clothes for hot (a) and cool season (b).

3.3 Questionnaires

The comfort 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

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					Homens				
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

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Figure 6 - Thermal comfort questionnaire – Portuguese version.

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				

I would like to be:

Warmer	No change	Cooler

How comfortable is your room right now?

Comfortable				
Uncomfortable				

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

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

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Figure 7 - Thermal comfort questionnaire – English version.

3.4 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 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.
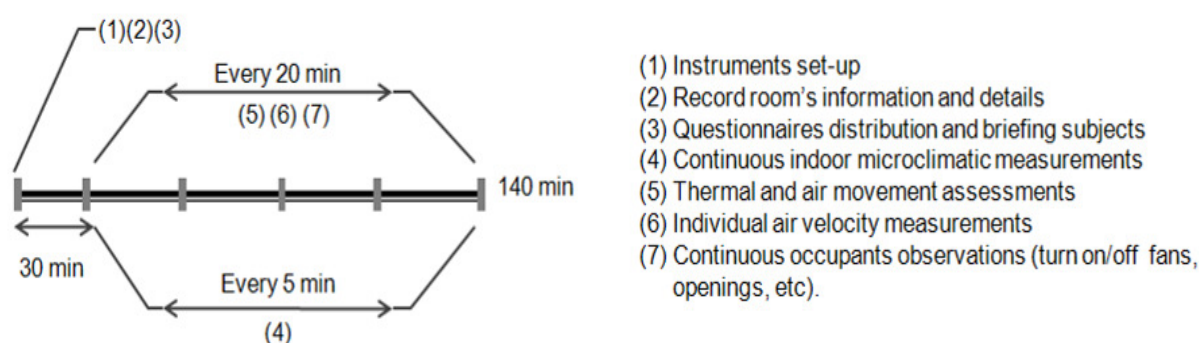
Figure 8 - Schematic representation of the measurement protocol.

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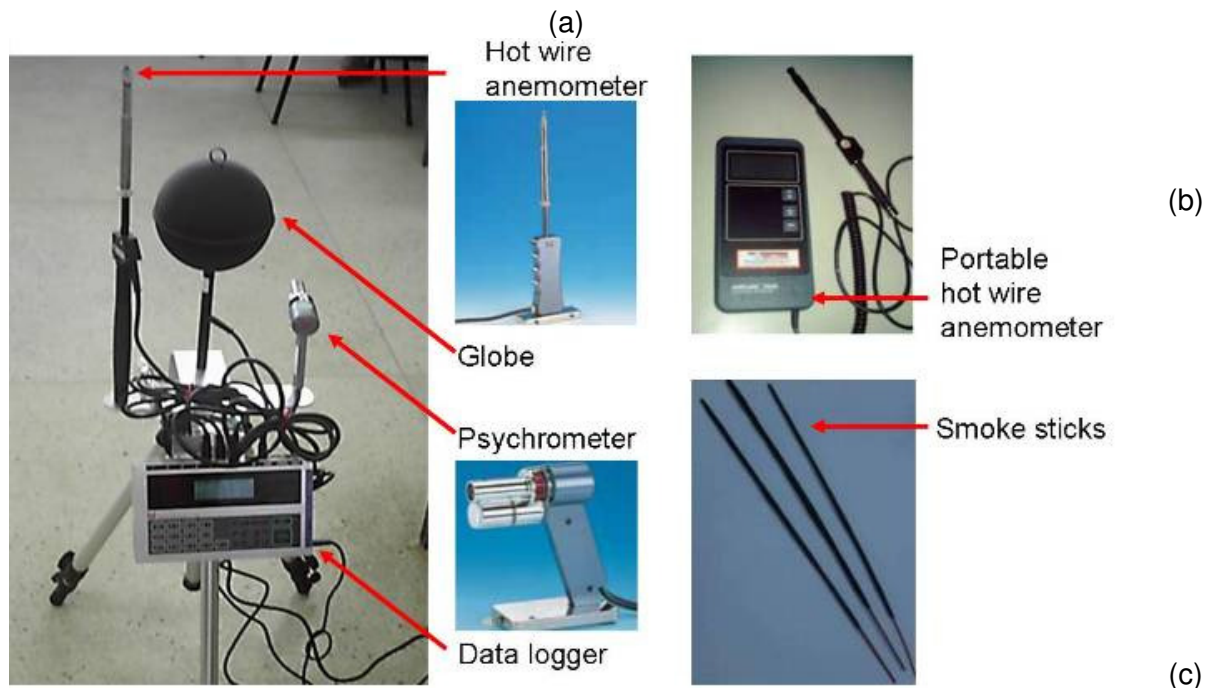
Figure 9 - Microclimatic station Babuc (a), hotwire anemometer and smoke sticks.

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. Complementary publications that have been published in peer-reviewed journals and/or conference proceedings are included in Appendix A.

This chapter is organized into four topics, each corresponding to a journal paper. Differences in terms of format will be found in this chapter because it was decided to keep exactly the same formatting in which the paper was published. The four topics and corresponding publications are summarized below:

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

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

4.1.1 Paper Overview

This paper aims to identify air movement acceptability levels inside naturally ventilated buildings. Minimal air velocity values corresponding to 80 and 90% (V_{80} and V_{90}) air movement acceptability inside these buildings. 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 the current 0.8m/s limit in ASHRAE 55-2004. This dispels the notion of draft in hot humid climates and reinforces the broader theory of alliesthesia and the physiological role of pleasure due to air movement.

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.

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6 ERA: Australian Research Councill''s Excellence in Research of Australia.

Air movement acceptability limits and thermal comfort in Brazil's hot humid climate zone

C. Cândido [a,b,*], R.J. de Dear [c], R. Lamberts [b], L. Bittencourt [d]

[a] Macquarie University, Department of Environment and Geography, Faculty of Science, NSW 2109 Sydney, Australia
[b] Federal University of Santa Catarina, Brazil
[c] The University of Sydney, Australia
[d] Federal University of Alagoas, Brazil

ARTICLE INFO

ABSTRACT

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 were 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 0.4 m/s for 26 °C reaching 0.9 m/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 0.8 m/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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1. 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 [7–11]. Thermal comfort research literature indicates that indoor air speed in hot climates should be set between 0.2 and 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.

2. 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[1] 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.

2.1. Maceio's climatic environment

Maceio is located on the north-east sea coast of Brazil (latitude 9°40′ south of Equator and longitude 35°42′ 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 26 °C and the annual thermal amplitude is 3.4 °C (the highest monthly average occurs in February – 26.7 °C and the lowest monthly average is in July – 23.7 °C). 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 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.

2.2. 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 about 20 students; see Fig. 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.

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 93 W/m^2 because the subjects usually stayed seated whilst drawing or writing, see Fig. 1. The clothes were light – around 0.30 clo during the hot season and 0.50 clo during the cool season (see Fig. 2a and b), as estimated from clothing garment checklists in ASHRAE Standard 55 [12].

2.3. 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 Fig. 3a)

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 Fig. 3b. The

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[1] 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.

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

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

Fig. 2. Occupants' typical clothes for (a) hot and (b) cool seasons.

minimum air speed threshold was 0.05 m/s, with resolution of 0.01 m/s. The probe registered the maximum, minimum and average values of the air speed, and also indicated the standard deviation within the 5-min 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, Fig. 3c.

2.4. 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 below.

2.4.1. Indoor climate data

Measurements were taken during morning and afternoon lectures, for at least 2 h 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 0.60 m, corresponding to the subjects' waist height inside the classrooms. The second height was 1.10 m which corresponded to the subjects' waist height while seated in the studio classrooms. The measurements recorded were averages of 5 min. 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 1 m radius and at the same work plan height. As a result, mean air velocities were recorded for each subject. The hot wire
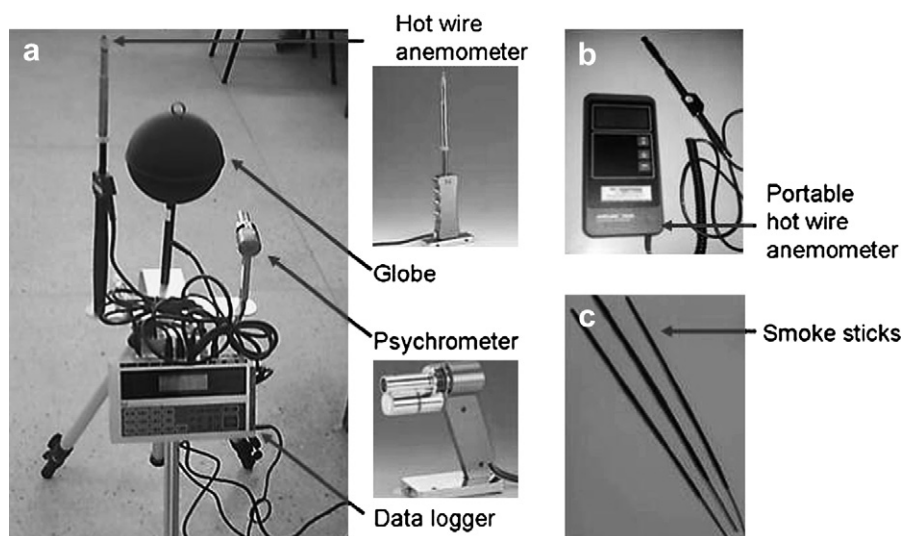
Fig. 3. (a) Microclimatic station Babuc, (b) hot wire anemometer and (c) smoke sticks.

anemometer was oriented according to the dominant flow direction indicated by the smoke sticks.

2.4.2. 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)[2]. 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 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.

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.

Table 2
Air movement acceptability scale.

−2 Unacceptable	−1	0 Acceptable	1	2 Unacceptable
Because too low air velocity	But too low air velocity	Enough air velocity	But too high air velocity	Because too high air velocity

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[2] 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.

2.5. 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.

3. 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 Fig. 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 Fig. 5). These results met the 90% acceptability goal considered as "a higher standard of thermal comfort" [12].

Fig. 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 Fig. 6. The majority of subjects were concentrated in thermal sensations of "slightly warm" and "warm" associated with a majority requesting "more air movement".

In an 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. Fig. 7 summarizes thermal preference votes. Most subjects' thermal preferences were "no change" and "cooler" (44.6% and 50.7%, respectively). Very few
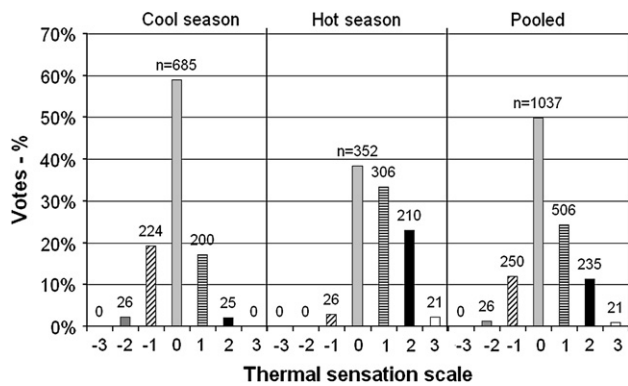
Fig. 4. Frequency distribution of thermal sensation votes (numerical values of −3, −2, −1, 0, 1, 2, and 3 indicate cold, cool, slightly cool, neutral, slightly warm, warm, and hot thermal sensations, respectively) for cool/hot season and also pooled.

Fig. 6. Overall thermal sensation and air movement preference.

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".

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*. Fig. 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"
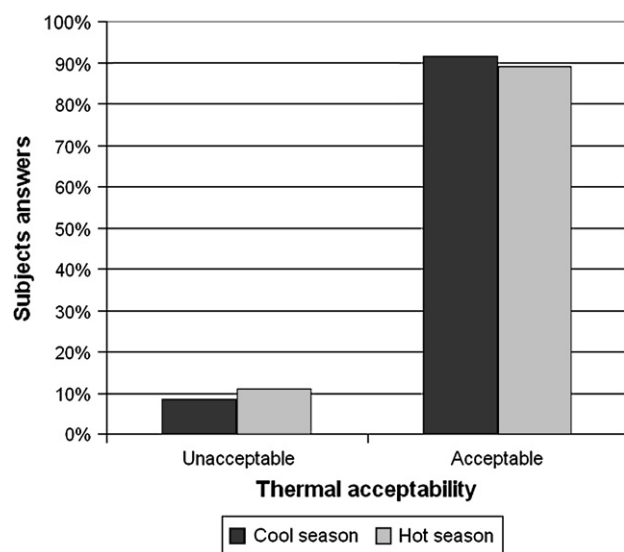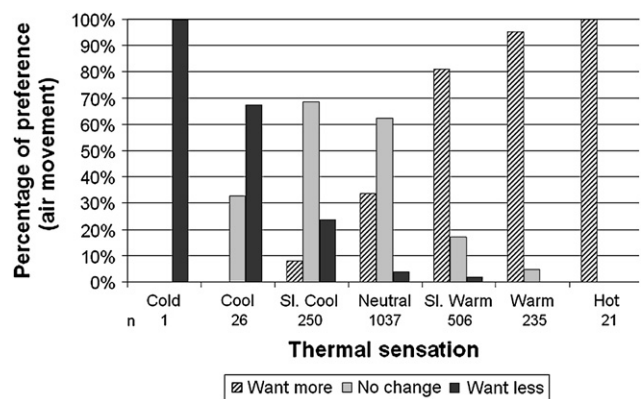
in air speed remained around 45% of subjects who were exposed to air speeds in the range 0.1–0.5 m/s, but then the percentage voting for "no change" in air speed increased at an almost linear rate as measured air speeds increased from 0.5 to 0.9 m/s. The percentage of subjects requesting "less air movement" 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 Fig. 8 to the "no change" votes described earlier (i.e. static rate of "want more" votes between 0.1 and 0.5 m/s air speeds, but then a steady decrease in the percentage of such requests as measured air speeds increased from 0.5 to 0.9 m/s).

Fig. 9 sorts the samples into those who found the air movement at the time of their questionnaire to be "acceptable" (Fig. 9a) and those who assessed it as "unacceptable" (Fig. 9b). In Fig. 9a (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 0.8 m/s which is indicated as the maximum limit in ASHRAE 55 [12].

Fig. 9b 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 0.5 m/s and minimum of 45% for 0.9 m/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 0.9 m/s.

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

Fig. 5. Overall thermal acceptability for both seasons.
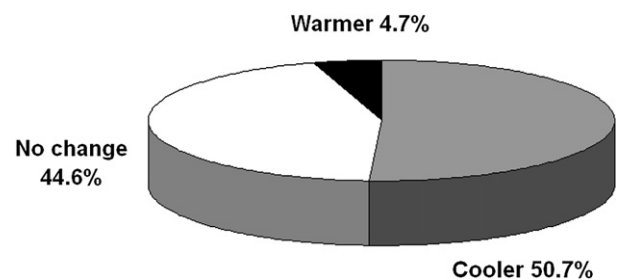
Fig. 7. Overall thermal preference.

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*

Fig. 10. Air velocity acceptability assessments within different prevailing air velocities.

Fig. 8. Overall air movement preference and air velocity range.

their acceptability as described in Table 2 previously (see Section 2). The overall air velocity acceptability votes binned according to air velocity at the same time of questionnaire is indicated in Fig. 10. It is possible to identify a majority of the sample concentrated into the three *acceptable* categories (−1, 0 and 1).

For the "acceptable but too low air velocity" (−1) answers in Fig. 10, the values were approximately 50% at an air velocity of 0.1 m/s decreasing for 22% at 0.3 m/s, 15% at 0.5 m/s and less than 8% up to 0.7 m/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 1.00 m/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 <0.2 m/s assessed it as "unacceptable because of too low air velocity". For air velocity in

the range $0.2 \leq v \leq 0.4$ m/s, this percentage decreased to 33% and decreased further to less than 15% for the air velocities up to 0.5 m/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 0.2 m/s, and another 35% were registered at velocities between 0.2 and 0.4 m/s.

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 subsamples 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 0.9 m/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 0.1 m/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 Fig. 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.
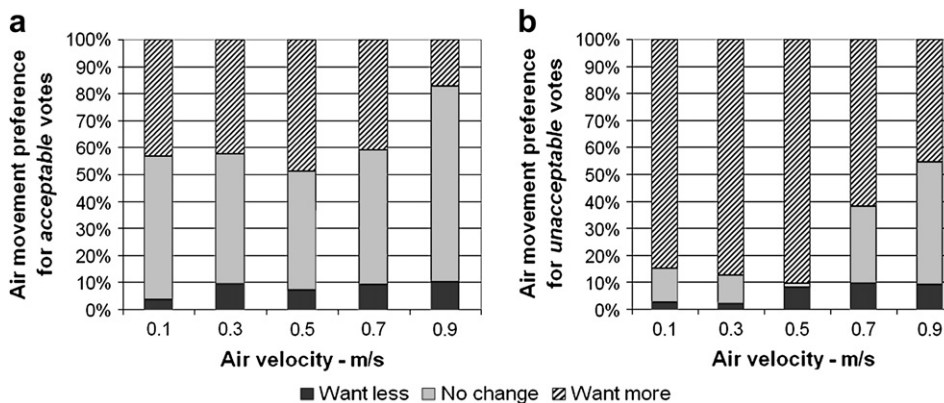
Fig. 9. Air movement preferences of those subjects for whom the air movement was (a) *acceptable* or (b) *unacceptable.*

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). Fig. 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 0.4 m/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 0.5 m/s. For operative temperatures of 29 °C and 30 °C air velocity values were slightly higher (0.6 and 0.7 m/s, respectively).

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

4. 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" preference votes.

In relation to air movement preference, most subjects requested "more air movement" even in air speeds above 0.50 m/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 0.7 m/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

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}, m/s	V_{90}, 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	–

to "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 value 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 0.4 m/s for an operative temperature of 26 °C and rising to 0.9 m/s at 30 °C. Subjects are not only preferring more air movement but also indicating minimal air velocity values close or greater than the 0.8 m/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.

5. Conclusions

Our results lead to the conclusion that air movement can be quite acceptable at speeds well above 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 velocity values obtained based on these goals were close to or above 0.8 m/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.
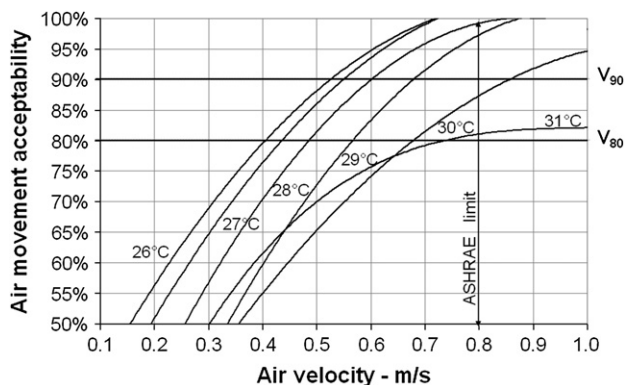

Fig. 11. Air movement acceptability and operative temperature binned by air velocity values resulted from the probit regression analysis (95% confidence levels).

Acknowledgements

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.buildenv.2009.06.005.

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

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ERA 2010 Classification: A

4.2.1 Paper Overview

This paper focuses how we can shift occupants' comfort expectations away from the static indoor climates of the past, towards the more variable thermal regimes found in naturally ventilated buildings. The main research question investigated is weather or not prior exposure to air-conditioning lead building occupants to actually prefer air-conditioning over natural ventilation.

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.

Cooling exposure in hot humid climates: are occupants 'addicted'?

Christhina Cândido[1,3]*, Richard de Dear[2], Roberto Lamberts[3] and Leonardo Bittencourt[4]
[1]Department of Environment and Geography, Faculty of Science, Macquarie University, Sydney, NSW 2109, Australia
[2]The University of Sydney, Sydney NSW, Australia
[3]Federal University of Santa Catarina, Florianópolis/SC, Brazil
[4]Federal University of Alagoas, Maceio/AL, Brazil

According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (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 ignored completely the behavioural and lifestyle dimensions of energy consumption in the buildings sector. Behavioural 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 can widen the range of opportunities available in a building to provide comfort for the 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 the following: 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 (AC)? If so, how tolerant or compliant will they be when the thermally constant conditions provided by AC are replaced by the thermally variable conditions that characterize naturally ventilated spaces? Does the frequency of prior exposure to AC 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 AC lead building occupants to actually prefer AC over natural ventilation? This article 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 analysed in relation to occupants' prior exposure to AC in their workplaces.

Keywords: Air conditioning; energy conservation; hot-humid climate; natural ventilation; thermal comfort; thermal history

INTRODUCTION

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007) highlighted the potential of the buildings sector to achieve greenhouse gas (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) reducing heating, cooling and lighting loads; (2) improving and using the thermal mass of the building; (3) increasing the efficiency of appliances and heating, ventilation and air-conditioning (HVAC) systems; and (4) increasing the efficiency of lighting systems.

Interestingly, this assessment was premised exclusively on technical (engineering) measures but completely ignored the behavioural and lifestyle dimensions of energy consumption in the buildings sector. Behavioural 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 adaptive opportunities within indoor environments as much as possible, thus reinforcing passive cooling strategies as an essential energy conservation strategy. The 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.*, 2010). This focus is re-awakening an interest in natural ventilation (Tanabe and Kimura, 1989; de Dear and Brager, 2002; Toftum, 2004; Zhang *et al.*, 2007).

*Corresponding author: *Email:* ccandido@els.mq.edu.au

Particularly in hot and humid regions, buildings should avoid external heat gains while dissipating internal ones. Shading is crucial and thermal mass is designed to maximize the storage potential for free heating and cooling while 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 (AC). 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 a 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 predicted mean vote and predicted percentage dissatisfied methodologies used internationally by HVAC engineers, allowing natural ventilation with limited acceptance penalties. Previous results suggested that occupants of air-conditioned buildings tended to prefer such buildings whereas occupants of non-air-conditioned buildings preferred not to have AC (de Dear and Auliciems, 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. AC, but does it mean that they will present differences in terms of thermal preference when the thermal constancy of AC is replaced by the thermal variability that characterizes natural ventilation? Does prior exposure to AC lead building occupants to actually prefer AC over natural ventilation? This article addresses these questions in naturally ventilated indoor environments located for the hot and humid climatic zone of Brazil (Maceio city).

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:

- microclimatic station, including globe thermometer, psychrometer for dry- and wet-bulb temperatures and a hot wire anemometer
- portable hot wire anemometer (Airflow Developments, model TA35 sensor)
- smoke sticks.

The microclimatic station was able to take measurements and store the data collected into a data logger during the experiment period; 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 used to verify the main airflow direction during measurements of individualized air velocity. The method for obtaining instantaneous thermal comfort and sensation responses as well as the indoor microclimatic measurement procedures have been detailed in an earlier article (Cândido et al., 2010).

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

Maceio city is located on the northeast coast of Brazil (latitude 9°40′ south). The climate is classified as hot and humid, with small daily and seasonal temperature fluctuations combined with a high vapour pressure. Seasons are divided into two: winter and summer. Summer is classified as a hot season and winter as a cool one.

The mean annual temperature is around 26°C and the annual thermal amplitude is 3.4°C (the highest monthly average occurs in February−26.7°C and the lowest monthly average is in July−23.7°C). Typically, the hottest days are from November to February and the coolest days are 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.

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 20 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

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	24.0	26.8	21.4
Outdoor relative humidity (%)	73.8	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

Table 2 | Biographical characteristics of the samples

Characteristic	Cooling exposition at their workplace	
	Exposed to AC systems	Without exposure to AC 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

considering concepts of personal control and the adaptive model (de Dear and Brager, 2002).

For this analysis, occupants were classified into two groups according to their responses for cooling exposure at their workplace: occupants exposed to AC systems at their work environment and those not exposed. Table 2 summarizes biographical characteristics of the sample.

Questionnaire

The questionnaire was presented in three parts. The first one corresponded to 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 the pattern of AC 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 the questionnaire. This article focuses on cooling exposition and preference questions.

The third and last part of the questionnaire related to subjects' activities (metabolism) during the measurement process. It also recorded information about the occupants' clothing by way of a garment checklist (insulation).

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 workplaces with and without AC systems. Results were analysed for thermal sensation votes, thermal preferences 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 workplace and occupants without exposure to AC systems at their workplace. 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 workplace voted for 'slightly cool' (5%) and only occupants with AC systems at their workplace voted for 'hot' (4%).

Despite the similarity of their thermal sensations votes, preferences varied depending on AC exposure. Figures 2a 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 workplace. This fact is noticeable within all operative temperature bands. Thermal preferences for 'cooler' were significantly higher for occupants who had been exposed to AC systems at their workplace compared with occupants without AC exposure.

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 AC. The overall cooling preference results were subsequently cross-tabulated with those of occupants' cooling exposure at their workplace (see Figures 3a and b).

Two thirds of occupants exposed to AC systems at their workplace preferred AC systems (65.7%), while the remaining one third (34.3%) indicated preference for natural ventilation or natural ventilation plus fans.

In contrast, the results were completely the opposite for occupants without exposure to AC systems at their workplace. In this sample, two thirds of cooling preference responses preferred natural ventilation and natural ventilation and fans whereas only one third preferred AC systems.

Figure 4 shows occupants' cooling preference votes across operative temperature bins. Once more it is clear that occupants with AC systems at their workplace indicated a preference for AC systems, and these percentages increased when the operative temperature also increased (from 50% for an operative temperature of 24.5°C increasing to 88% at 29.5°C). In contrast, the percentage of occupants preferring natural ventilation and natural ventilation and fans decreased with increasing operative temperature values from 50% at 24.5°C down to only 12% at 29.5°C.

For occupants without AC systems at their workplace, 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°C operative temperature to 60% at 29.5°C.

Table 3 shows the cross-tabulated percentages for cooling and thermal preferences 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 workplace but preferring different cooling strategies. For occupants without AC exposure at their workplace, thermal preferences were broadly similar
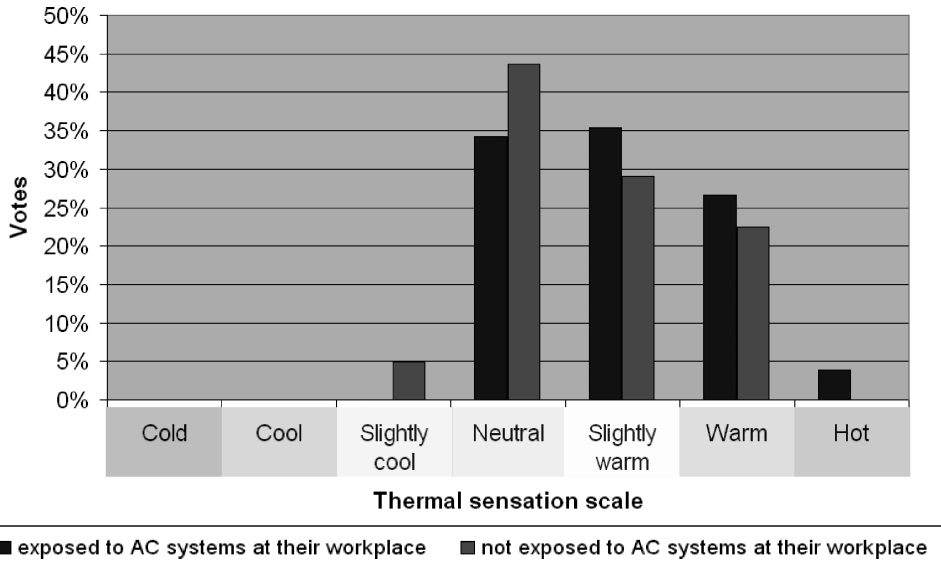
Figure 1 | Occupants' thermal sensation votes exposed to AC systems at their workplace

Figure 2 | Occupants' thermal preference votes within operative temperature values: (a) occupants exposed to AC systems at their workplace and (b) occupants without exposure to AC systems at their workplace
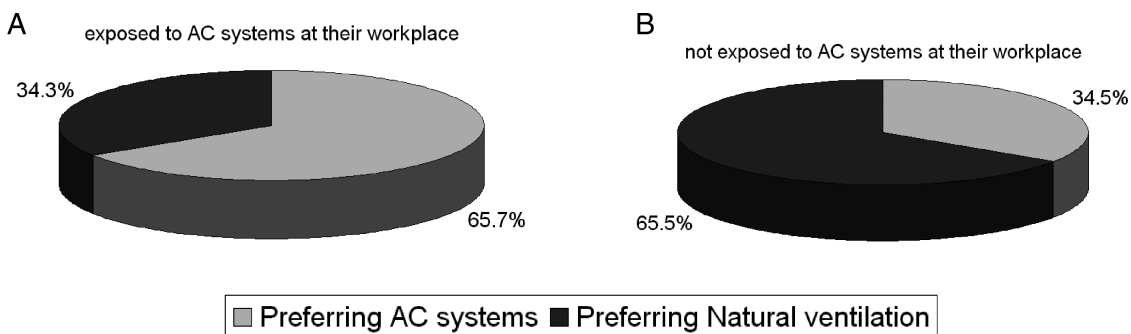
Figure 3 | Overall cooling preference votes: (a) occupants exposed to AC systems at their workplace and (b) occupants without exposure to AC systems at their workplace
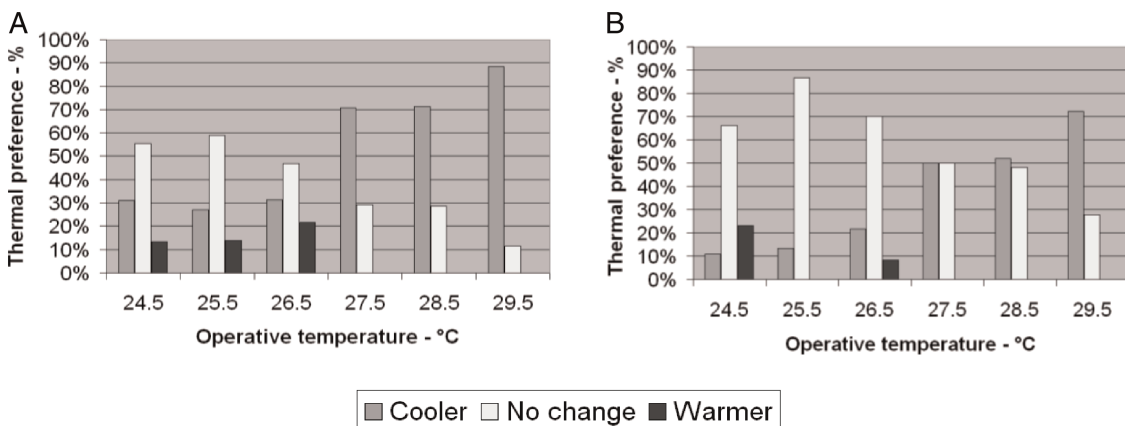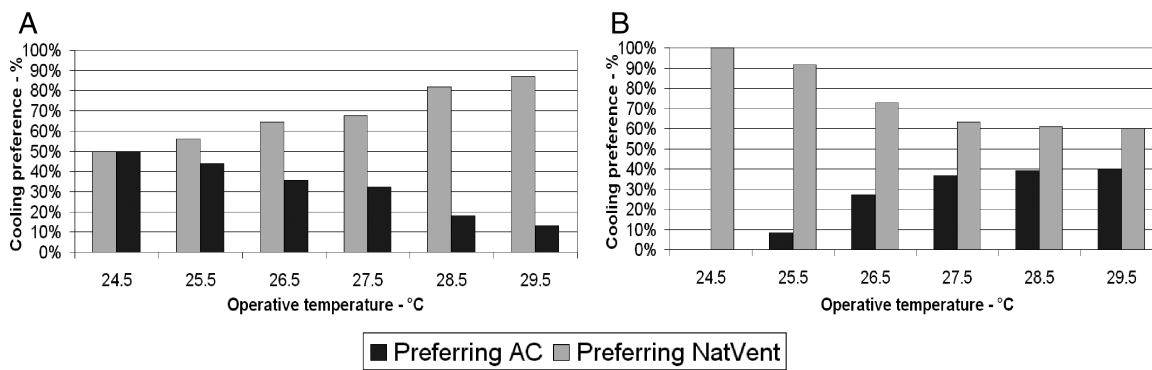
Figure 4 | Occupants' cooling preference votes within operative temperature values: (a) occupants exposed to AC systems at their workplace and (b) occupants without exposure to AC systems at their workplace

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 workplace	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 workplace	Preferring AC systems	78.3%	21.7%	0.0%
	Preferring natural ventilation	52.0%	48.0%	0.0%

regardless of AC and natural ventilation preference. For occupants with AC systems at their workplace, the results presented significant differences in their cooling preference. In this sample, occupants who preferred AC systems also indicated a preference for being 'cooler' in a majority (78.3%). However, 52% of occupants who preferred natural ventilation indicated 'want cooler' as their thermal preference.

DISCUSSION

This article investigated differences in terms of thermal sensation, heating preferences 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 and without AC at their work

environments. 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 the questionnaire as occupants who did not have prior AC exposure. The AC-exposed sample seemed to be less tolerant and less adaptable when the thermal constancy of the AC environment was replaced with the thermal 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 AC. These results suggest an 'addiction' to static thermal environments. They also indicate that occupants' thermal history directly influences their thermal perception and preferences (Chun *et al.*, 2008). Past experience and behaviour influence occupants' thermal perception of the indoor environment, and hence they should be taken into account in the design of bioclimatic architecture. It is indeed a hard mission to control what sort of environment occupants will be exposed to outside their workplace. However, when inside these indoor environments, they will bring their expectations with them.

CONCLUSIONS

This article has demonstrated the importance of 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 the 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.

Conversely, these findings raise important questions about the role that rising comfort expectations resulting from increased AC usage might play in hindering the 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 the 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 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 a daily basis.

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

4.3.1. Paper Overview

This paper focuses on thermal and air movement acceptability percentages in order to assess occupants. Almost 90% thermal acceptability was found within the prescriptions of the ASHRAE 55-2004 adaptive comfort standard and yet occupants required 'more air velocity'. Minimum air velocity values were found in order to achieve 90% of combined *thermal and air movement acceptability*. Results highlighted 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.

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

Christhina Cândido [a,c,*], Richard de Dear [b], Roberto Lamberts [c]

[a] Macquarie University of Sydney, Department of Environment Science Sydney, NSW 2109 Australia
[b] The University of Sydney, Faculty of Architecture, Design and Planning, Australia
[c] Federal University of Santa Catarina, Department of Civil Engineering, Brazil

ABSTRACT

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 0.3 m/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 0.4 m/s; from 27 to 29 °C is 0.41 −0.8 m/s, and from 29 to 31 °C is >0.81 m/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.

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1. 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 towards 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

* Corresponding author.
E-mail address: ccandido@els.mq.edu.au (C. Cândido).

climates, the maximum permissible air speed is typically quite low (i.e. 0.20 m/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 2.5 m/s [14—25].

ASHRAE 55 [2] specifies 0.80 m/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 0.80 m/s the occupants' control of air movement devices is not required, and (2) up to 1.20 m/s occupant control is required [24]. 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—25], 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 0.3 m/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*" [3,4,24].

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.

2. 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.

2.1. 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—1.3 *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

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

air velocities; architecture design studios and classrooms occupied by students carrying out drawings or building delicate scale prototypes of buildings. A total of 2075 questionnaires were completed during the two field campaigns and Table 2 summarizes the occupant samples' profiles.

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].

2.2. 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.

2.3. 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 min period following a 30 min settling-in period upon entering their studios/classrooms. Apart from permitting subjects' metabolic rates to settle down to approximately sedentary levels [26], this initial 30 min period was used to set-up the indoor climatic instruments and also to explain the questionnaire in detail to the occupants. Fig. 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 min interval throughout the entire 140 min 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 m of the subject filling in their questionnaire, and at a height of 0.60 m above the floor for

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
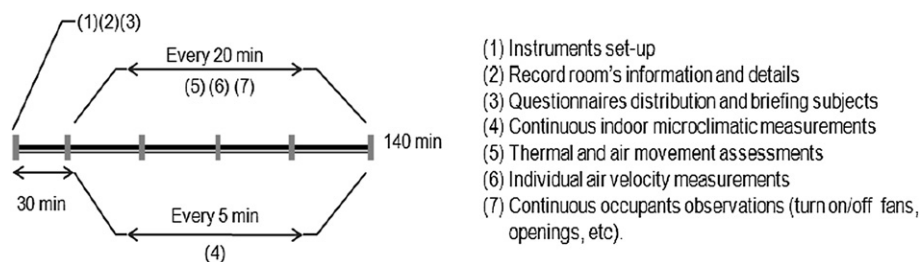
Fig. 1. Schematic representation of the measurement protocol.

classrooms and 1.10 m 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.

3. 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 [27,28]. 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.

Fig. 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.

Fig. 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 Fig. 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 [29,2,31]. 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.
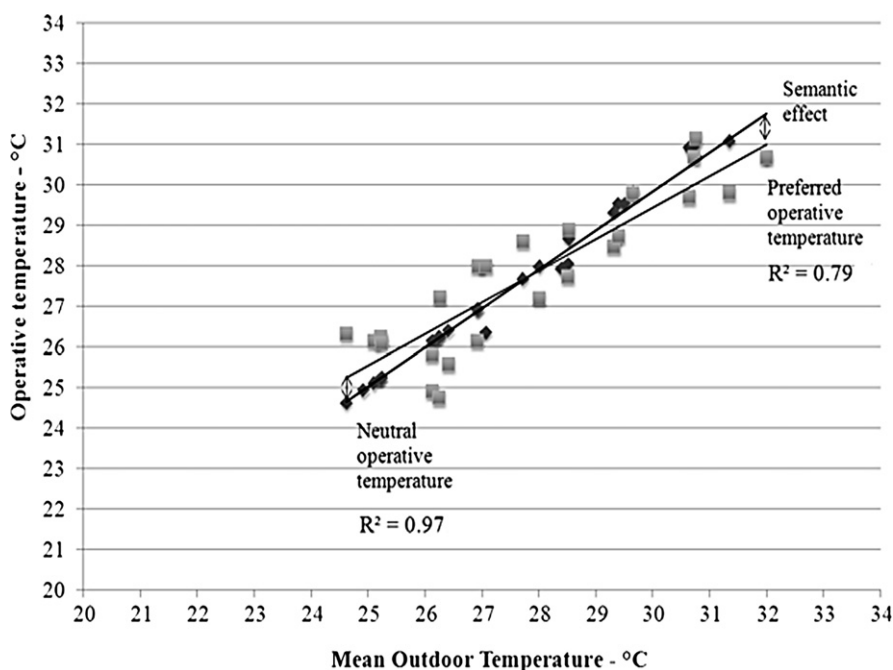
Fig. 2. Observed differences in neutral and preferred temperatures in relation to mean daily outdoor temperatures.

Fig. 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.

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 0 ± 0.50 (neutral). Because many of the original studies in the ASHRAE database did not have an acceptab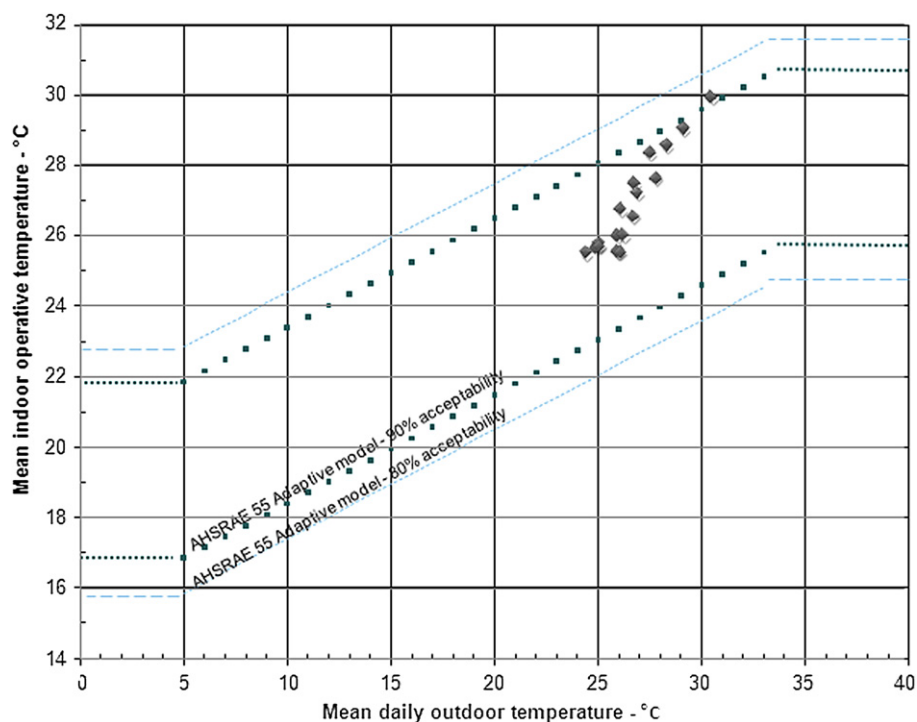ility question, so it had to be inferred from their thermal sensation data, in the same way that PPD is inferred from PPD. In the present study, however, thermal acceptability was explicit in the questionnaire, permitting a direct approach to the analysis of this item. Before the thermal acceptability analysis, the results for mean daily outdoor temperature and mean indoor operative temperature were plotted against the ASHRAE 55 [2] adaptive model. Fig. 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.

Within the sample rooms plotted in Fig. 3, thermal acceptability votes were then analyzed. Fig. 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). Fig. 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).

Even though occupants' thermal acceptability percentages were high, direct assessments of for air movement acceptability reveal another interpretation of their thermal indoor environment

indoors. Fig. 5 shows the results for air movement preference binned for 0.2 m/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 0.40 m/s, the percentage of occupants preferring "more air movement" represented 86% of dissatisfaction during the cool season and 74% for the 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 [24,29] as "being paramount to occupant's satisfaction" [31]. 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.

Fig. 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*" [32]. 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.

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
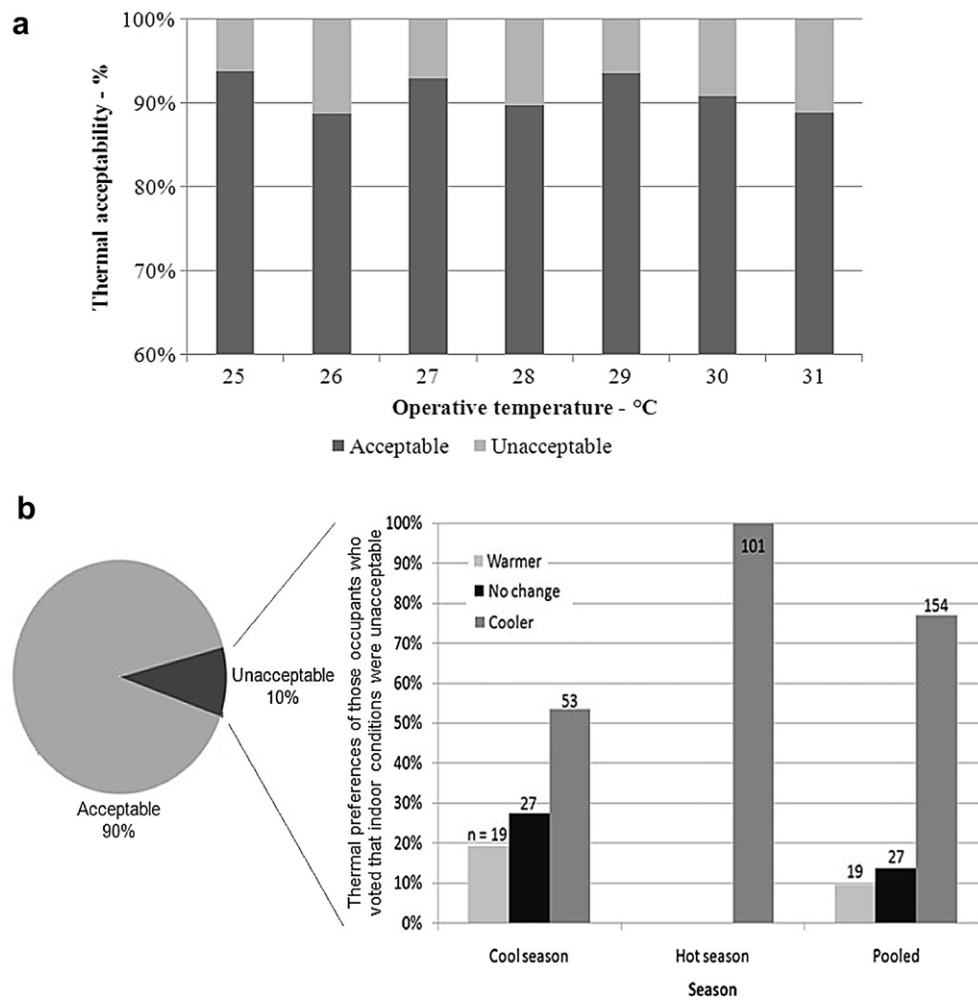
Fig. 4. (a)Thermal acceptability percentages across this study and (b) thermal preference votes separated by hot and cool seasons.
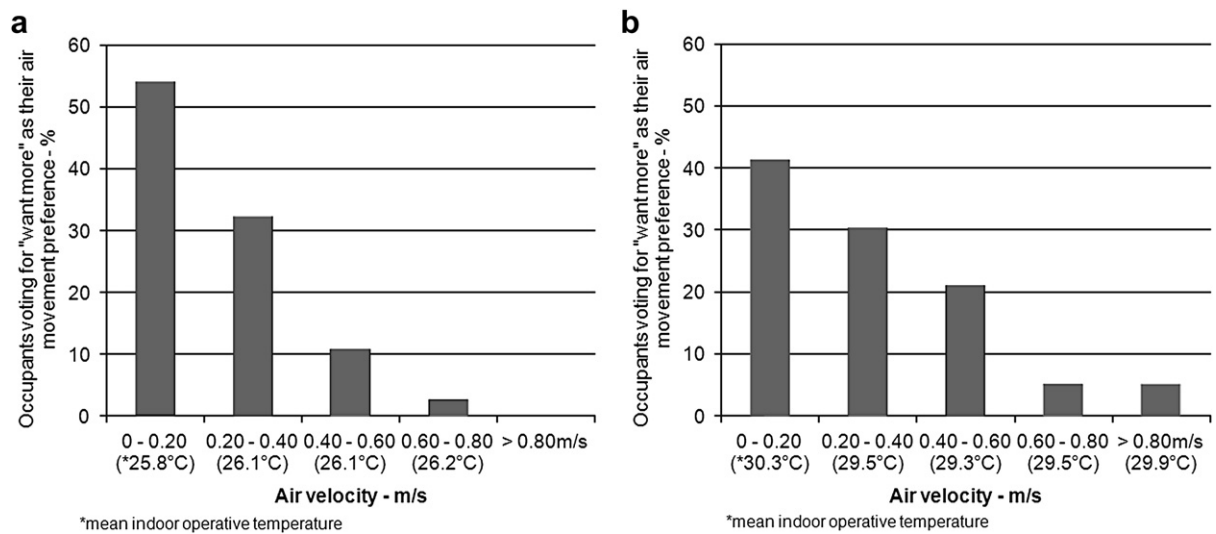
Fig. 5. Occupants voting for "want more" as their air movement preference for (a) cool and (b) hot season.

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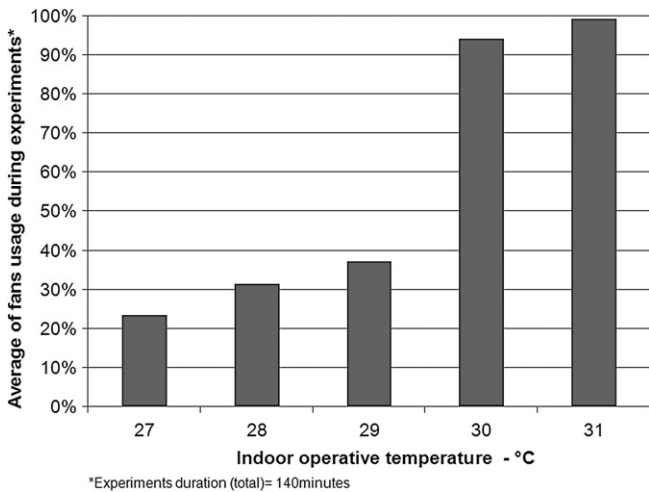
Fig. 6. Average of fans usage binned to indoor operative temperatures as an example of occupants' adaptive behavior.

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 20 s 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 Fig. 7.

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 Fig. 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 0.80 m/s prescribed as maximum acceptable limits in ASHRAE [2]. Minimal air velocity values required for these occupants varied from 0.40 m/s to up to 1 m/s and the results were organized in Fig. 7 within three categories: $v = 0.40$ m/s; 0.41 m/s $< v <$ 0.80 m/s and $v > 0.81$ m/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) [33]. 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 [34] 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.
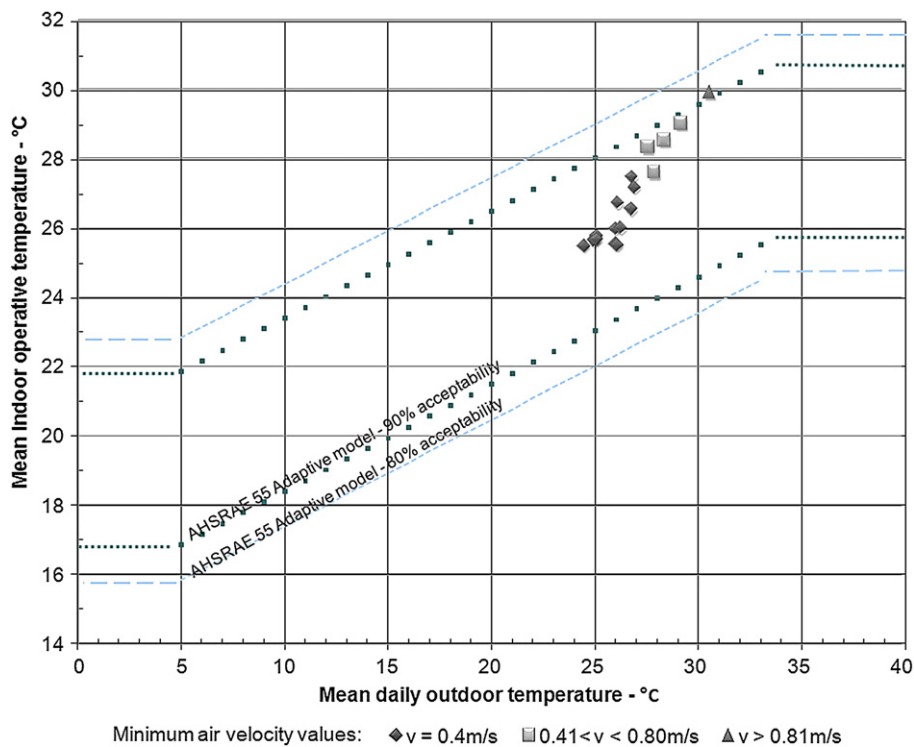
Fig. 7. Minimal air velocity values found for 90% of air movement acceptability plotted against mean daily outdoor temperatures and mean indoor operative temperatures.

4. 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 0.4 m/s; from 27 to 29 °C the minimum recommended velocity is 0.41–0.8 m/s, and from 29 to 31 °C the minimum velocity for thermal and air movement acceptability is >0.81 m/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

4.4.1. Paper Overview

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 opportunity and potential will be considered, as well as thermal and air movement acceptability goals. Permissible operative temperatures are based on the ASHRAE 55-2004 adaptive model, and *minimal* air velocity values within the occupied zone are specified. Occupants control over air movement receives attention, with specific recommendations being made.

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.

RESEARCH PAPER

Towards a Brazilian standard for naturally ventilated buildings: guidelines for thermal and air movement acceptability

Christhina Cândido[1], Roberto Lamberts[2], Richard de Dear[1], Leonardo Bittencourt[3] and Renata de Vecchi[2]

[1]Faculty of Architecture, Design and Planning, University of Sydney, Sydney, NSW 2006, Australia
E-mails: christhina.candido@sydney.edu.au and richard.dedear@sydney.edu.au

[2]Department of Civil Engineering, Federal University of Santa Catarina, Florianópolis, SC, Brazil
E-mails: lamberts@ecv.ufsc.br and renata.vecchi@labeee.usfc.br

[3]Faculty of Architecture and Urban Planning, Federal University of Alagoas, Maceió, AL, Brazil
E-mail: lsb54@hotmail.com

The Brazilian Federal Government has been recently promoting energy-conservation initiatives, most notably 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 provide information for designers based on Brazil's climate requirements, with specific advice related to lighting systems, HVAC and the thermal envelope of buildings. Nevertheless, requirements for naturally ventilated indoor environments appear as an open category without clear criteria. To address this, the paper proposes guidelines for naturally ventilated environments in which specific thermal and air movement acceptability goals must be achieved. The guidelines are based on results from field experiments in non-residential naturally ventilated buildings in different climatic zones as well as drawing on other studies. The proposed guidelines consider occupants' adaptive potential as well as thermal and air movement acceptability. Combining thermal acceptability with air movement acceptability is a key design challenge. Permissible operative temperature ranges are based on the ASHRAE 55 adaptive comfort standard, and minimum air velocity requirements within the occupied zone are specified. Considerations also included 'active' occupants and specific control over openings and fans.

Keywords: adaptive comfort, air movement acceptability, design guidelines, natural ventilation, occupants, satisficing, thermal acceptability, thermal comfort

Le Gouvernement fédéral brésilien encourage depuis peu les initiatives en faveur des économies d'énergie, et tout particulièrement les initiatives « Performances Thermiques des Immeubles – Zones Bioclimatiques Brésiliennes et Directives de Construction pour les Logements à Faible Coût » et « Réglementation Fédérale pour l'Etiquetage Volontaire des Niveaux de Rendement Energétique des Immeubles Commerciaux, Publics et de Services ». Ces réglementations nouvelles fournissent aux concepteurs des informations basées sur les exigences climatiques du Brésil, et s'accompagnent de conseils spécifiques relatifs aux systèmes d'éclairage, aux systèmes CVCA et à l'enveloppe thermique des immeubles. Néanmoins, les exigences relatives aux environnements intérieurs à ventilation naturelle apparaissent comme une catégorie ouverte sans critères clairs. Pour traiter ce problème, le présent article propose des directives pour les environnements à ventilation naturelle dans lesquels des objectifs spécifiques d'acceptabilité thermique et en matière de circulation d'air doivent être atteints. Ces directives sont basées sur les résultats d'expériences de terrain menées dans des immeubles non résidentiels à ventilation naturelle dans différentes zones climatiques, mais s'appuient également sur d'autres études. Les directives proposées prennent en considération le potentiel adaptatif des occupants aussi bien que l'acceptabilité thermique et en matière de circulation d'air. Réussir à

combiner l'acceptabilité thermique et l'acceptabilité en matière de circulation d'air pose un problème de conception essentiel. Les plages de température de service admissibles sont basées sur la norme de confort adaptatif ASHRAE 55, et les exigences minimales quant à la vitesse de l'air dans la zone occupée sont précisées. Ont également été pris en considération les occupants « actifs » et les commandes spécifiques des ouvertures et des ventilateurs.

Mots clés: confort adaptatif, acceptabilité de la circulation d'air, directives de conception, ventilation naturelle, occupants, satisficing [stratégie de prise de décision], acceptabilité thermique, confort thermique

Introduction

The potential for energy conservation and greenhouse gas mitigation from the building sector has been well documented (Intergovernmental Panel on Climate Change (IPCC), 2007). In order to achieve this, technical solutions such as insulation, cooling and heating systems, efficiency in appliances, etc. are often heralded as the main mitigation path. The ultimate success or failure, in terms of a building's long-term viability, energy use and occupant satisfaction, depends heavily upon the indoor environmental quality delivered to building occupants. With this concept in mind, designers are beginning to explore how they may widen the range of opportunities for occupant comfort, both in new-build and retrofit contexts. This has reawakened interest in natural ventilation for the provision of comfort, particularly in terms of regulations and standards worldwide (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2004; International Organization for Standardization (ISO), 2006; van der Linden *et al.*, 2006; Comité Européen de Normalisation (CEN), 2007).

In Brazil where there is a broad range of climates, the idea of a unified standard that takes into consideration both technical and behavioural issues is not an obvious choice. Much of Brazil's territory is classified as a hot, humid climate. In such regions, natural ventilation combined with solar protection are the most effective bioclimatic design strategies to improve thermal comfort passively. Despite these passive options, the number of buildings relying on active systems as the main cooling strategy continues to increase inexorably.

In 2001 Brazil experienced a major electricity crisis as a result of extreme climatic events (a lack of rain to drive hydroelectricity generation) and inadequate infrastructural investments (transmission lines and back-up generation plans). As a consequence, the consumption reduction imposed was 20% for the entire country, with some of this reduction becoming 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 efforts to provide information for designers based on Brazil's climate requirements, with specific items related to lighting systems, heating, mechanical ventilation and air-conditioning (HVAC) and the thermal envelope of buildings, but design requirements for naturally ventilated indoor environments are yet to be defined.

Revisiting Brazilian energy-efficiency initiatives

In Brazil, power generation is largely from hydroelectricity, accounting for approximately 91% of the total. Brazil's total hydroelectric power potential is 260 GW, of which approximately 22% has already been implemented (Brazil Ministério do Desenvolvimento, 2009). Of this, 40% is in the Amazon region where demand is low, while most of the potential for large developments in the southeast have already been exploited (Brazil Ministério do Desenvolvimento, 2009). Due to the lack of investments in the supply side and constant growth of demand, energy efficiency improvements have become essential.

Energy used in buildings accounts for about 48.3% of the total electrical energy consumption in Brazil (Brazil Ministério do Desenvolvimento, 2009): with 23% of this dedicated to commercial and public buildings and approximately 22% to the residential sector (Ministério das Minas e Energia, 2007). Based upon this, the Federal Government released a 'National Policy of Conservation and Rational Use of Energy' focusing on energy efficiency in buildings and equipment. Among the Brazilian Government actions on energy efficiency are two that should be highlighted: design guidelines for the residential sector and a rating 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 concern the thermal envelope, lighting and acoustics, along with minimum requirements for ventilation and openable areas. One important contribution made by this document was the definition of bioclimatic zones (Figure 1). Eight zones were defined

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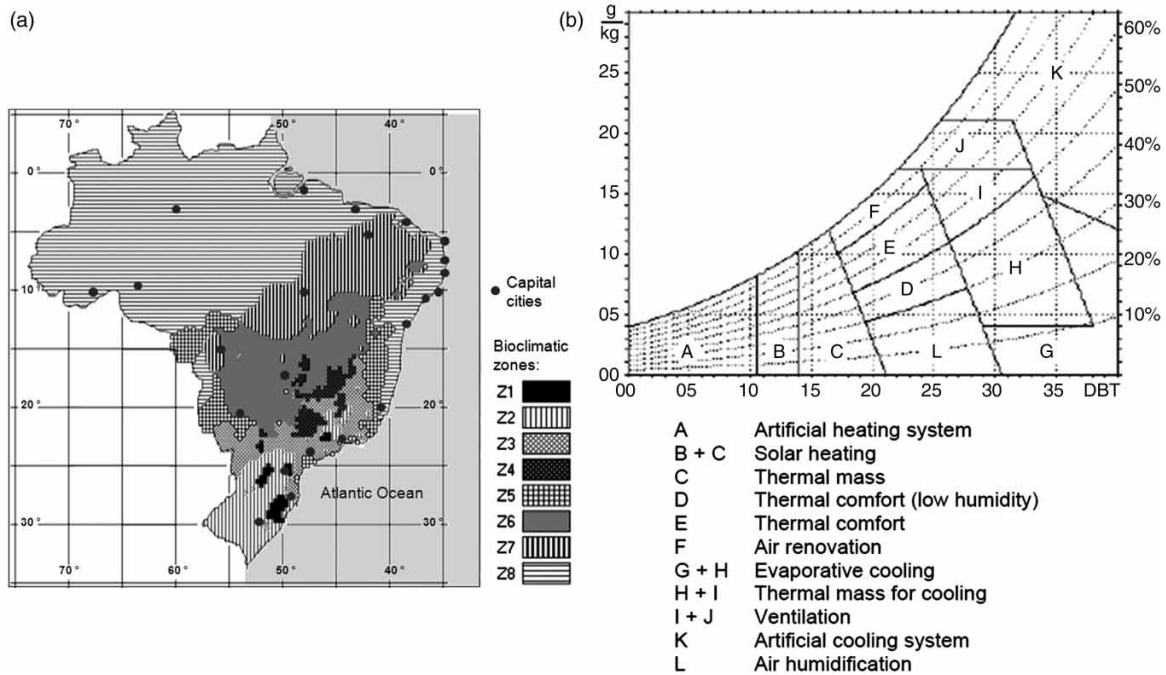
Figure 1 (a) Bioclimatic zoning in Brazil and (b) bioclimatic chart (ABNT, NBR 15220-3, 2005)

based on detailed climate data from 330 sites across Brazil. Based upon this division, a set of specific bioclimatic design strategies was developed, with particular emphasis on the early design stage.

The 'Federal Regulation for Voluntary Labeling of Energy Efficiency Levels in Commercial, Public and Service Buildings' addresses commercial and public buildings. This new regulation is based on a study focusing on Brazil's climate requirements with specific items related to lighting system, HVAC and the 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 2 shows different bioclimatic strategies and recommended ventilation patterns for Zones 1–8. The first is 'cross-ventilation', indicating necessity of airflow through the indoor environments for Zones 2, 3 and 5. The second is 'selective ventilation', applicable during warmer seasons and/or when the indoor temperature is higher than the outdoor temperature for Zones 4, 6 and 7. The final pattern is 'permanent ventilation', which is designed for 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 Zone 1, corresponding to the coldest region in Brazil.

These regulations established a consistent amount of technical information about building's thermal

envelope, but left a gap for naturally ventilated environments that needs to be addressed. Natural ventilation is frequently associated with a strong concern about airflow distribution in indoor environments, hence the recommendations related to openable areas and ventilation patterns (ABNT, NBR 15220-3, 2005). This is also the traditional reference of regional building codes across Brazil, with requirements dealing exclusively with minimum openable area without much consideration of thermal comfort criteria. These are undoubtedly a contribution to improving an occupant's thermal comfort through natural conditioning, but a more accurate comfort specification for thermal indoor environments is desirable.

Adapting a model for Brazilian occupants: evidence from previous field experiments

Given the wide range of climate conditions found in Brazil, differences in thermal acceptability are not surprising. For instance, thermal acceptability in the south of Brazil has been observed from 14 to 24°C (Xavier, 2000; Lazarotto and Santos, 2007), while in the north-east acceptability limits extend from 24.5 to 32°C without compromising occupants' thermal comfort (Araújo, 1996). Despite minor differences, the observed range of acceptable temperatures in Brazil is consistent with the ASHRAE 55 (2004) adaptive model. As identified by the Brazilian researchers, field evidence indicates adaptive opportunities to be a decisive factor in these thermal environments, particularly clothing adjustments (Lazarotto and Santos,

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Figure 2 Bioclimatic design strategies and ventilation pattern for different zones (ABNT, NBR 15220-3, 2005).
Ventilation pattern: Zone 1: Not recommended; Zone 2: Cross-ventilation; Zone 3: Cross-ventilation; Zone 4: Selective ventilation; Zone 5: Cross-ventilation; Zone 6: Selective ventilation; Zone 7: Selective ventilation; Zone 8: Permanent ventilation.

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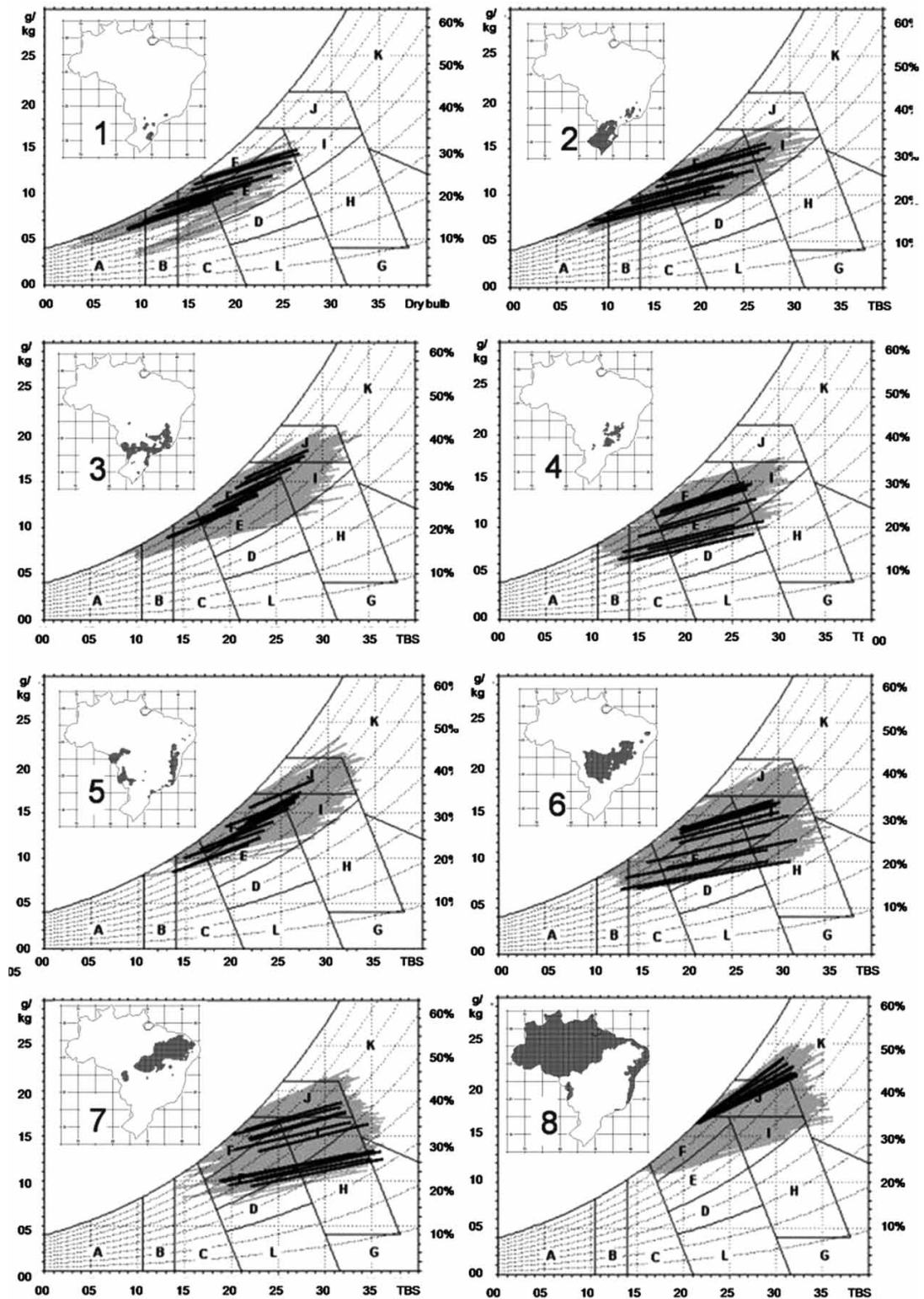2007; Andreasi *et al.*, 2010) and air movement enhancement by use of fans (Gonçalves *et al.*, 2001).

Discrepancies into occupants' adaptive opportunities, particularly in terms of clothing insulation (Ruas, 1999; Andreasi, 2001) and air movement (Araújo, 1996; Cândido *et al.*, 2010) were found. In the first case, the main complaints related to restricted degrees of freedom within the dress code (Andreasi, 2001), with occupant satisfaction being maximized by a flexible dress code (Lazarotto and Santos, 2007). In the second case, occupants' complaints stemmed from their preference for 'more air movement' (Cândido *et al.*, 2010), especially in the hot–humid zone which attracted strongest demand for higher air velocities. This demand was more pronounced at operative temperatures above 26°C (Araújo, 1996; Andreasi *et al.*, 2010; Gonçalves *et al.*, 2001). In addition to higher air velocities, occupants also appreciated having control over fans as a complementary source of ventilation, especially during weather without breeze.

Field experiments performed in Brazil's hot–humid climate zone showed almost 90% thermal acceptability within the operative temperature ranges prescribed in the ASHRAE Standard 55 on adaptive comfort (Cândido *et al.*, 2011). However, occupants required air velocities values higher than the average 0.3 m/s found within the ASHRAE RP 884 database in order to achieve air movement acceptability. In this hot, humid context, occupants' overall thermal environmental satisfaction cannot be defined simply in terms of an operative temperature range. Air movement is the main determinant of whether or not operative temperature in the high 20°Cs will be acceptable or not. Based on these results, it is clear that Brazilian occupants in naturally ventilated buildings (1) accept temperature swings during the day and year, (2) prefer higher air velocities *if* (3) control and fans are provided. These generalizations can be easily related to the three categories of responses that occupants undertake in order to re-establish thermal comfort as summarized by de Dear *et al.* (1997): behavioural, physiological and psychological adaptation.

The weight of research done so far focuses on thermal sensation, preference and acceptability in buildings where occupants wear uniforms or relatively strict dress codes prevail, and adaptive opportunities are limited (high school classrooms, army headquarters, etc.). Despite natural ventilation being one of the main bioclimatic design strategies in Brazil, more detailed field studies combining thermal comfort and air movement questionnaires with accurate indoor climatic instrumental observations are therefore necessary.

This paper summarizes a first attempt at defining guidelines for non-residential naturally ventilated environments in which thermal and air movement acceptability criteria must be achieved in addition to specific requirements for occupants' control.

Method

Results presented and discussed here are based on original field experiments performed in non-residential naturally ventilated buildings located in various different climatic zones in Brazil (9°31′S and 27°35′S). The fundamental feature of this field research design is the proximity, in time and space, of indoor climate observations with corresponding comfort questionnaire responses from the occupants. Field experiments resulted in approximately 5000 questionnaires collected during both summer and winter seasons.

When buildings were selected for inclusion in this study the following criteria were applied: (1) windows had to be easy to access and operate; (2) rooms could not have a mechanical cooling system (refrigerated air-conditioning); (3) rooms could have complementary mechanical ventilation with unconditioned air (fans); (4) the opening and closing of windows had to be the primary means of regulating thermal conditions; and (5) occupants had to be engaged in near sedentary activity (1.0–1.3 met), and permitted to adapt their clothing freely to the indoor and/or outdoor climatic conditions.

The questionnaires comprised four different and complementary parts. The first part focused on thermal sensation, preference and acceptability. The second part consisted of questions related to air movement acceptability and preference. The third part focused on exposure to air-conditioning and thermal history. The fourth and last part recorded occupants' activities and clothing.

The subjects started answering the questionnaire at least 30 minutes after they arrived in the room in order to minimize any influence from their previous activities. Each subject answered the questionnaire on five separate occasions during the same experiment period (approximately 140 minutes). Simultaneous indoor climatic observations were taken with a microclimatic station (Babuc A and SENSU), 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.

The field experiments were purposely designed to register air velocity values at exactly the same time and location as the occupants answered their questionnaires. This was because the project's focus was on the occupant's perception of air movement, and the tendency for this parameter to vary in space and time more than the other comfort parameters. The

instrument used for these observations was a portable hot-wire anemometer (Airflow Developments, model TA35 sensor) within a 1 metre radius around each occupant. Smoke sticks were used to visualize the airflow direction during each anemometer measurement. 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 comfort questionnaires.

Results and discussion

Adaptive capacity potential
Buildings can be assessed in terms of their 'adaptive capacity potential' (Kwok and Rajkovich, 2010, p. 20), which 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.

A building's design must comply 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

- opening design: location, dimension and detailed information of apertures' operability

- complementary devices for ventilation (if applicable) such as wind catchers, ventilated sills, pergolas, verandas, etc.;

- complementary mechanical devices (if applicable), *i.e.* ceiling and/or desk fans, their 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 aforementioned strategies. In this regard, buildings will be assessed in a *qualitative* sense. Buildings complying with this item will be then considered for subsequent analysis.

Acceptable thermal conditions
A combination of thermal and air movement acceptability criteria 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 Brazilian acceptable thermal conditions were derived from the ASHRAE 55 adaptive model (de Dear and Brager, 2002). Thermal acceptability goals will be set at 80% and 90%. Extensions from the neutral temperature will be $\pm 2.5°C$ for 90% of thermal acceptability and $\pm 3.5°C$ for 80% of thermal acceptability.

Air movement
Air velocity is recognized as a key parameter in an occupant's thermal comfort and has been considered in comfort standards worldwide. Typically, *maximum* limits are established in order to avoid draft. While draft might be a relevant concern in cold climates, it is largely irrelevant in warm environments (Arens *et al.*, 2002; Khedari *et al.*, 2000; Tanabe and Kimura, 1989; Zhang *et al.*, 2007). Field studies suggest 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. Previous work has 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, which are often related to preferences for 'more air movement' (Toftum, 2004; Zhang *et al.*, 2007). Revisions to air speed limits have been proposed along with 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 an 80% and 90% limit. In order to achieve these targets, indoor environments must meet *minimum* air velocity requirements according to Figure 3.

The air velocity requirements must be achieved during a building's occupied hours.

Supplementary air movement can be achieved by the use of fans, which are encouraged in order to supply airflow for occupants, especially during periods when exterior wind is absent or/and areas with low porosity (city centres, for example). Nocturnal ventilation techniques are also encouraged, but limits will not be established in terms of air velocities. Table 1 summarizes an occupant's control requirements over openings and complementary mechanical

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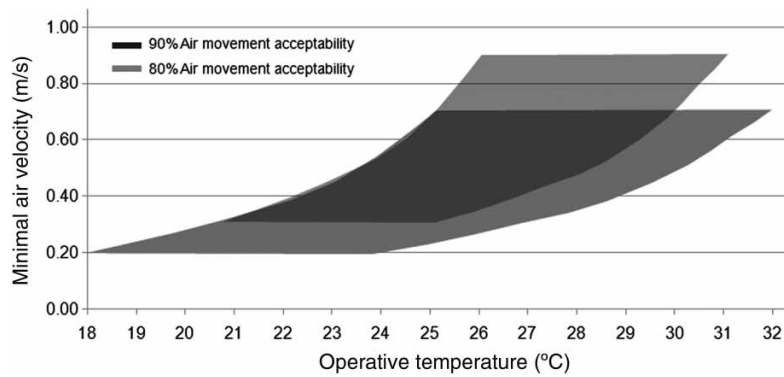
Figure 3 Minimal air velocity values required within the occupied zone, corresponding to 80% and 90% air movement acceptability

devices. Three different categories were defined for application *in combination with* the air velocities detailed above.

Labelling categories

Naturally ventilated buildings applying for a thermal comfort and energy efficiency label will be graded into three different categories. Table 2 summarizes the suggested requirements for natural ventilation. Buildings must conform to the adaptive capacity potential, and both thermal and air movement acceptability percentages must be met in order to be classified into one of the three categories. Category 1 comprises indoor environments where air movement acceptability met or exceeded 90% and received three stars for occupant control. Category 2 corresponds to buildings where air movement acceptability was 80% and received two stars for occupant control. The last category (3) applies to indoor environments with 80% air movement acceptability but received only one star for occupant control.

In order to conform 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 (2008), the following classification is suggested. The NatVent category will be combined with the percentage of hours in the comfort zone (PHC). The results for the suggested label are summarized in Table 3.

Conformity

Buildings applying for this labelling must provide proof of conformity according to the above criteria. Adaptive capacity must be demonstrated with detailed information related to the building's design strategies and their relevance to its bioclimatic zone.

Thermal and air movement acceptability must be shown by means of calculation and/or simulation

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

Category	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

Table 2 Suggested design requirements for naturally ventilated buildings

Natural ventilation category	Adaptive capacity potential	Thermal and air movement acceptability	
		Acceptability (%)	Occupant's control
1	Yes	90	☆☆☆ and ☆☆
2	Yes	80	☆☆
3	Yes	80	☆
4	Yes	–	☆

and/or wind tunnel experiments for buildings in the 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

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Table 3 Suggested labelling categories for naturally ventilated buildings

Label category	Percentage hours in the comfort zone (PHC)	Natural ventilation category
A	PHC ≥ 80	1
B	70 ≤ PHC < 80	2
C	60 ≤ PHC < 80	3
D	60 ≤ PHC < 80	4

- air velocity provided by the complementary mechanical devices and occupant's control pattern applied; within the occupied zone

- 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 control

Field experiments must be in compliance with minimal requirements specified in 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.

Conclusions

The overwhelming weight of evidence from a large number of studies indicates that increased air movement in warm environments is essential for improving occupant thermal comfort, and therefore higher air velocities are suggested for these contexts. Air movement has major significance in terms of preference and acceptance of the indoor thermal environment, and thermal (*i.e.* temperature) acceptability alone was necessary but insufficient to satisfy occupants. Combining thermal acceptability and air movement acceptability is the key challenge design in these indoor environments. Brazil's climatic context should move it towards this linkage, incorporating these separate but connected dimensions of environment, as well as specific requirements for an occupant's control into a comprehensive standard for naturally ventilated buildings.

This study proposed a set of guidelines for a future Brazilian standard focusing on naturally ventilated indoor environments, and taking into consideration thermal comfort, air movement acceptability and their interactions. 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 drawn from the ASHRAE adaptive model, overlain with minimum air velocity requirements.

This is a first attempt at combining design 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 active behaviour 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.

Acknowledgement

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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 ASHRAE Standard 55-2004 to be the threshold of draft perception inside air-conditioned buildings. For occupants possessing air velocity control, this limit can be extended to 0.8m/s in 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].

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.

Finally, 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 [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 is 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.

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 more fully it in their

design, focusing on more sustainable, energy efficient and, why not, pleasurable built environmental designs.

Finally, it was noted that some suggest the shift in terminology from 'occupant' to 'inhabitant', conceptualizing that "…the *occupant* is a passive recipient of a set of pre-determined indoor conditions while the *inhabitant* plays an active role in adapting their indoor environment" [3]. So the new mantra for 'adaptable' indoor environments requires active occupants (or inhabitants). This study shows that naturally ventilated environments would offer these 'active' conditions to its inhabitants. In Heschong's words [4] *"…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"* (page 17). 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. Limitations and Future research

The following topics are related but beyonf the scope of this thesis and it should be considered in future research:

• 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 of the previous values suggested in the literature. For natural ventilation in these climates, higher air velocities 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.

• Another item that 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.

• 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. The sample was chosen within architecture students, specially first and second year[7] in order to avoid biased results. 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.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.

• This study considered air velocity from natural ventilation and also mechanical ventilation (fans). Even though the occupants clearly preferred having air movement enhacement within those indoor environment, questions related to other related disturbance such as noise from fans was beyond the scope of this projet. More research is therefore necessary in order to understand occupants' overall indoor environmental satisfaction.

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[7] Architecture students from these universities start attending units related to indoor environmental quality and thermal comfort during their second year.

5.2. References

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Appendix

Appendix A

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Effects of artificially induced heat acclimatization on subjective assessments of indoor thermal environments. Part I: Thermal sensation, acceptability and preference

Macquarie University
SYDNEY ~ AUSTRALIA

To Editor of Indoor Air

Dear Editor,

I am submitting the paper entitled "Effects of artificially induced heat acclimatization on subjective assessments of indoor thermal environments. Part I: Thermal sensation, acceptability and preference" to this journal and I acknowledge that this original paper is in accordance with the following required items:

- With the exception of review papers, the work is original;

- The information reported in the paper is accurate according to the best knowledge of the author(s);

- The paper has not been and will not be submitted simultaneously to other journals;

- The author(s) are aware of Elsevier's policy on plagiarism and self-plagiarism.

This paper is part of a PhD project that is mainly focused in air movement issues in hot and humid climates. There is plenty of anecdotal evidence suggesting that building subjects become accustomed to levels of warmth prevailing within buildings on time scales of weeks to months. But would short-term physiological acclimatization also have an impact on subjects' perception of their indoor thermal environment? Would that take place even if subjects are constantly exposed to air-conditioned indoor environments? This paper investigates these questions, and focuses on the effects of artificially induced acclimatization to heat on subjects' thermal physiology, thermal sensation, acceptability and preferences in static indoor environments. Subjects were exposed to heat by increasing their core temperature by exercise. Results indicate that, from the psychology point of view, subjects' perceptions changed between the prior to and after acclimatization experiments. This could be inferred from their thermal sensation, preference and particularly, thermal acceptability votes. The results presented in this paper showed that it is possible to physiologically acclimatize such 'air-conditioning addicts' to warmer indoor environments without, however, compromising their thermal acceptability.

Yours sincerely,

Christhina Cândido

Phd student

Department of Environment and Geography
Faculty of Science
Macquarie University NSW 2109 Australia
Phone: +61 (0)2 9850 8427 Mobile: +61 (0)450 341695
http://www.els.mq.edu.au

Effects of artificially induced heat acclimatization on subjective assessments of indoor thermal environments.

Part I: Thermal sensation, acceptability and preference

Abstract

There is plenty of anecdotal evidence suggesting that building subjects become accustomed to levels of warmth prevailing within buildings on time scales of weeks to months. But would short-term physiological acclimatization also have an impact on subjects' perception of their indoor thermal environment? Would that take place even if subjects are constantly exposed to air-conditioned indoor environments? This paper investigates these questions, and focuses on the effects of artificially induced acclimatization to heat on subjects' thermal physiology, thermal sensation, acceptability and preferences in static indoor environments. Subjects were exposed to heat by increasing their core temperature by exercise. Results indicate that, from the psychology point of view, subjects' perceptions changed between the prior to and after acclimatization experiments. This could be inferred from their thermal sensation, preference and particularly, thermal acceptability votes. The results presented in this paper showed that it is possible to physiologically acclimatize such 'air-conditioning addicts' to warmer indoor environments without, however, compromising their thermal acceptability.

Keywords: acclimatization, perceptual adaptation, core temperature, thermal acceptability, climate chamber.

Practical implications. There is evidence that such exposure will influence in occupants' expectation of their thermal environments (i.e. thermal history). In warm and humid climates, such trend for saturation of air-conditioning exposure needs to be

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more understood. The result presented in this paper reinforce the opportunities to use higher set-points in air-conditioning buildings, contributing to significant energy consumption cut-offs within the built environment.

Introduction

Perhaps the most comprehensive definition of physiological adaptation would include all the changes in the physiological responses resulting from sustained heat loads (internally or externally imposed) which lead to a gradual diminution in the strain induced by such exposure (Brager and de Dear, 1998; Kerslake, 1972). Physiological adaptation can be divided in two groups. The first relates to the inherited genetic adaptation which was developed through time and became part of a person or group of people. The second can be related to the phenomenon derived from the systematic exposure of human subjects to hot environments, stimulating the body to trigger the sweat mechanism faster and more abundantly (Parsons, 2002).

The 'acclimatization' or 'acclimation' process can be explained and regulated by the human nervous system, and it affects the physiological set-points for thermoeffector actions (Kerslake, 1972). Plenty of studies have focused on this topic, providing information about the process of thermophysiological acclimatization (Fox et al., 1965; Fox, 1974), the onset of hidromeiosis (Candas et al.,1983; Matsumoto et al., 1993; Ogawa, 1974) or the variety of cardiovascular responses, such as reduced heart rate and an increased blood volume and peripheral blood flow (Givoni and Goldman, 1973; Andres et al., 2000). These studies provided important evidence about how the human body would adapt to heat exposure (stress and strain) (Beijir and Ramsey, 1988).

There is, however, a complementary dimension of heat acclimatization relating to psychophysics and environmental psychology and which, less is known. Studies focused on how people perceive and respond to environmental stimulus (Nadel et al., 1974; Shapiro, Y., Epsteim, Y., 1984; de Dear, R.J., Leow, K.G., Ameen, A. (a) 1991; de Dear, R.J., Leow, K.G., Ameen, A. (b), 1991). Particularly for the thermal comfort field, this psychological acclimatization carries significant implications for building subjects satisfaction within their indoor environment, and by logical extension, their demand to energy to run their building's air-conditioning system.

Thermal comfort literature refers to physiological and psychological acclimatization and the adaptive model, which elaborated the concept of habituation and expectation (de Dear and Brager, 2002). A review on adaptive model is beyond the scope of this paper, suffice to say that results showed that psychological adaptation encompasses the effects of cognitive and cultural variables, describing the extent to which habituation and expectation alter one's perception of and reaction to sensory information (Brager and de Dear, 1998). There is, however, more to be understood about psychological adaptive responses.

There is plenty of anecdotal evidence suggesting that building subjects become accustomed to levels of warmth prevailing within buildings on time scales of weeks to months. But would short-term physiological acclimatization also have an impact on subjects' perception of their indoor thermal environment? Would that take place even if subjects are constantly exposed to air-conditioned indoor environments? This paper investigates these questions, and focuses on the effects of artificially induced acclimatization on subjects' thermal physiology, thermal sensation, acceptability and preferences in static indoor environments. This study also looks at heat acclimatization effects on impact on air movement acceptability and preferences. In

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this paper, Part I of a pair, the focus is on thermal sensation, acceptability and preferences. Effects of heat acclimatization on air movement acceptability and preferences will be discussed in Part II.

Methods

Subjective thermal perception experiments were carried out in a climate chamber to evaluate temperature and air movement acceptability across a range of simulated to a simulated warm and humid condition combinations. Experiments were carried out during the winter season in Japan so that subjects, from different nationalities, could all be brought to comparable levels of heat acclimatization. This method exposes subjects to a warm and humid indoor environment forcing them to increase their core temperature by means of exercise (Fox et al., 1967; Gonzalez et al., 1974) on a daily basis.

All subjects were exposed to four different experiments: *Pilot (1 day), Acclimatization Phase 1 (3 days), Acclimatization Phase 2 (3 days) and Post-acclimatization (4 days).* Specific details about experimental procedure will be provided in item 4 "*Indoor climate data and experimental protocol*".

1. Climate chamber

The climate chamber is part of the School of Architecture and Wind Engineering at Tokyo Polytechnic University. Figure 1a shows the plan view of the chamber and Figure 2 shows its interior. The climatic chamber has dimensions of 5 m wide × 11 m long × 3 m high, and houses a laboratory (3.7 m wide × 8 m long × 2.7 m high), a pre-exposure room and a fan room. The climatic chamber was designed to uniformly deliver the following indoor climatic requirements: Temperature: 20 to 35°C ± 0.5; Humidity: 40 to 70% ± 2% and air velocity: 0.1 to 2.0 m/s.

This chamber facility is consists of a hot-water boiler and a brine chiller unit; two compact air-conditioning units (one with an air supply capacity of 3,000 m^3/h and a cooling and heating capacity of 10.5 kW, the other with an air supply capacity of 2,000 m^3/h and a cooling and heating capacity of 7.0 kW); and an electrically-heated vaporizing humidifier (10.0 kg/h). Figure 1b shows the airflow generator installed in the fan room. It is comprised of 48 plug fans driven by 280-W DC motors. It aims to reproduce the long-frequency fluctuations of the natural crosswind by controlling the revolution speeds of each motor from a desktop computer.

Figure 1 – Climate chamber plan view (a) and interior (b).

2. *Subjects and physiological data*

A total of 12 male adults were used as subjects and they participated in all experimental conditions, and during the same time of the day, to account for circadian rhythm. Subjects were volunteers from Tokyo Polytechnic University and received payment for undertaking the experiments. These subjects develop their daily activities in air-conditioned office indoor environments. Table 1 summarizes subject's anthropometric information.

Table 1 – Subject's anthropometric information.

Subjects wore clothing ensembles simulating typical summer conditions, i.e. short-sleeve shirt, trousers, underwear, socks, slippers and their own underwear. The clo insulation values were estimated in 0.54 *clo,* according to ASHRAE (2004) garment check list.

Subject's height and weight was registered with laboratory precision instruments. Skin temperatures on the left chest, left underarm and forehead were recorded every 5 seconds throughout the experiment using thermocouples affixed with medical tape. Subjects and their clothes were weighed before and after the exposure and water intake were recorded every 30 minutes. Tympanic temperature was recorded with tympanic digital thermometer while core temperature and skin wettednes were estimated using the two-node model as programmed in the ASHRAE software called WinComf® (Fountain and Huizenga, 1996), considering subjects' anthropometric information, chamber indoor conditions and exposure time.

3. Questionnaires

The questionnaire aims to characterize whole-body thermal comfort and also to identify the subject's air movement acceptability, on the basis of a "right-now" assessment. The questionnaire is organized into four parts. The first corresponds to the subject's demographic and anthropometric characteristics such as age, height, weight and gender. The second part corresponds to thermal comfort assessments relating to thermal sensation, preference and acceptability. The third part comprises questions related to the subject's prior cooling exposure, preference and control preference. The last part includes questions associated with air movement acceptability and preference.

4. Indoor climate data and experimental protocol

Experiments were carried out during the morning and afternoon and three subjects were exposed at the same time. Throughout the experiments, the indoor microclimate was controlled for design air temperatures, air speed and humidity. Measured values of air temperature, relative humidity and air velocity were recorded

and they are listed in Table 2. Air velocity was changed randomly, at 20 minutes intervals, to remove the effects of increased familiarity and over-familiarity (boredom).

Air temperature and humidity were recorded at three different heights in ten positions distributed within the chamber. Wall and ceiling temperatures were monitored with thermocouples in 12 points symmetrically distributed inside the chamber. Air velocity was recorded in two different ways. Firstly, a 3-D ultra-sonic anemometer was situated at the middle point in front of the subject's occupied zone. The second one corresponds to two thermistors located at two different heights (0.60 and 1.10m), aligned to subjects' occupied zone.

- *Pilot experiments*

Subjects were put trough to one day of pilot experiments in order to (1) identify the optimum metabolic rate for the acclimatization exposures and (2) brief subjects about the overall experimental procedure. For this experiment, subjects were requested to perform different activities at varying activities, which included walking, running or jumping on the same spot. While performing these activities, skin and tympanic temperature as well as metabolic rate were recorded. Water intake was also registered based on individual water bottles provided by the researchers.

- *Acclimatization Phase 1*

The acclimatization experiments were organized into two phases, during six consecutive days: (1) subjects performed the work-in-heat activity to achieve acclimatization to heat during the first three days (Acclimatization Phase 1); and (2) thermal and air movement assessments were carried out during three more days

(Acclimatization Phase 2). Figure 2 shows the experimental procedure adopted for this experiment.

During the first phase of these experiments, subjects were required to walk or run at the same spot, considering that after 15 to 20 minutes of constant activity subjects would achieve a steady-state (Goto et al., 2006). While performing these activities, skin and tympanic temperature and metabolic rate where recorded. Water intake was also registered based on individual water bottles provided by the researchers.

Figure 2 – Experimental procedure during Acclimatization Phase 1.

- ***Thermal and air movement assessments - Acclimatization Phase 2 and Post-acclimatization experiments***

During these experiments, subjects assessed the chamber's thermal and air movement assessments. The subjects' activities were typical to an office environment. They were allowed to write, read and/or type during the experiments. Subjects were also asked to assess their thermal indoor environment by using the questionnaire, four times during each experiment, within 30 minutes interval. Figure 3 shows the experimental procedure adopted for these experiments.

Subjects were exposed to two different air temperatures: 28 and 30°C and four different air speed values: 0.20, 0.40, 0.80 and 1.20m/s. Air velocity was changed every 30 minutes. Relative humidity was kept constant at 70% throughout all experiments. Water intake and tympanic temperature were also registered every 30 minutes and skin temperature was monitored with thermocouples affixed with medical tapes.

Figure 3 – Experimental procedure during thermal and air movement assessments (Acclimatization Phase 2 and Post-acclimatization period).

Results and discussion

1. Acclimatization – Phase 1

According to earlier research carried out by Fox et al. (1976) and Gonzales et al. (1974), it is possible to induce acclimatization to warm/hot environments if core temperature is elevated to approximately 38.3°C. The effects of heat acclimatization to heat were evident, such as sweat production, on the first day of exposure and progressed rapidly to full development by the third or fourth day (Givoni et al., 1972; Griefahn, 1997). This is different for acclimatization in cold climates, when longer sequences of successive cold exposure are required, as is the case for 'passive' exposures to heat in the course of normal day-to-day sedentary activity (Wyndham, 1969; Kampman, 2008). Based on this evidence, subjects in the present study were increased their core temperature by exercising in hot and humid environment.

During the experiments, subject's core temperature increased from to 37.5 to 38.9°C, on average. Figure 4 shows results for core temperature variation, according to exposure time during the 120 minutes Acclimatization Phase 1. Based on this graph, subjects on average maintained their core temperatures for 30 minutes above the critical temperature of 38.3°C identified as artificial heat acclimatization.

Figure 4 – Mean core temperature variation, according to exposure time, during the Acclimatization Phase 1.

2. Acclimatization Phase 2 and Post-acclimatization

In order to consider subject's expectation related to indoor environment, the second part of acclimatization phase was dedicated to thermal and air movement assessments. These experiments aimed to provide comparative analysis about subjects' thermal perception; and, in particular, temperature and air movement assessments before and after the Acclimatization Phase 1.

- *Thermal sensation*

Thermal assessments were inferred directly from questionnaires and it aimed to characterize subject's thermal and air movement assessments prior and post forced acclimatization to heat. Thermal sensation votes were analysed separately according to Standard Effective Temperature - SET*. This thermo-physiological model is based on ASHRAE's extended research and practice and it is defined as the equivalent dry bulb temperature of an isothermal environment at 50% RH in which a subject, while wearing clothing standardized for activity concerned, would have the same heat stress (skin temperature) and thermo-regulatory strain (skin wettedness) as in the actual test environment" (Gagge, Fobelets and Berglund, 1986).

Figure 5 a and b shows the overall distribution of thermal sensation votes during acclimatization and post-acclimatization experiments. As an overall trend, the majority of subjects classified their thermal sensation as 'neutral' or 'slightly warm' prior and after acclimatization period. Approximately half of the subjects rated their thermal sensation as 'slightly warm' during the acclimatization phase. In the post-acclimatization phase, the percentage of 'slightly warm' sensation decreased in comparison to the acclimatization phase.

The main effect of acclimatization appears in Figure 5. A significant difference occurred for subjects voting for 'slightly cool' prior and after acclimatization. Prior

acclimatization, none of the subjects classified their thermal sensation and 'slightly cool'. Thermal sensation votes of 'warm' only occurred during the acclimatization period. During the post-acclimatization experiments, subjects did not vote for 'warm' despite the effective temperatures being up to 31°C.

In contrast, Figure 5 also indicates that approximately 15%, 10% and 5% of subjects exposed to SET* equals to 15, 27 and 29°C actually voted 'slightly cool' as their thermal sensation during the Post-acclimatization period. When exposed to SET* equals to 31°C, 100% of subjects classified their thermal sensation as 'warm' while, post-acclimatization, subjects voted as 'slightly warm' and 'neutral'. As an overall trend, it is possible to infer that subjects were sensitive to temperature changes in which they were being exposed before and after acclimatization.

Figure 5 – Overall thermal sensation votes during (a) Acclimatization Phase 2 and (b) Post-acclimatization experiments.

- *Thermal acceptability and preferences*

Figure 6 a and b shows results for subjects' overall thermal acceptability. The total percentage of subjects who found their indoor thermal environment 'acceptable' doubled from only 39% during acclimatization experiments to approximately 80% post-acclimatization. Thermal acceptability was also analyzed according SET* and these results were depicted in Figure 7 a and b. Non-acclimatized subjects voting for 'acceptable' was about 65% when exposed to SET* equals to 25°C and this percentage decreased to 41% and only 10% when SET* increased to 27°C and 29°C, respectively. When exposed to an indoor environment with SET* equals to 31°C, 100% of subjects classified it as 'unacceptable'. After acclimatization, these values

changed significantly. Thermal acceptability values decreased from 100% when SET* was 25°C to about 40% when SET* as 31°C.

Figure 6 – Overall thermal acceptability votes during Acclimatization Phase 2 (a) and Post-acclimatization (b) experiments.

Figure 7 – Subjects' thermal acceptability votes during (a) Acclimatization Phase 2 and (b) Post-acclimatization experiments.

In attempt to identify subjects' overall thermal satisfaction with their thermal environment, they were asked to indicate their thermal preference votes and these results were depicted in Figure 8. During acclimatization, approximately 68% of subjects preferred to be 'cooler' and 32% voted for 'no change'. After being exposed to acclimatization, subjects' votes changed significantly. Post acclimatization votes for 'cooler' decreased to 45% while 52% of the subjects voted for 'no change'. Only 3% of subjects voted for 'warmer'.

Figure 8 – Overall thermal preference votes during acclimatization (a) and post-acclimatization (b) experiments.

Figure 9 a and b presents the result for thermal preference votes depicted for SET* bins. Based on these results, it is possible to infer the impact of acclimatization in subject's thermal preference. As an overall trend, subjects indicating preference for "cooler" increased according to elevation in SET* values. However, the percentages of subjects voting for "cooler" decreased in number from acclimatization to post-acclimatization experiments, particularly when SET* was above 29°C. The number of subjects voting for "no change" as their thermal preference was significantly higher

after acclimatization in comparison to prior-acclimatization. These results reinforce the fact that subjects were more tolerant to higher temperatures after being acclimatized.

Figure 9 - Subjects' thermal preference votes during (a) Acclimatization Phase 2 and (b) Post-acclimatization experiments.

Conclusions

The physiological monitoring of subjects in these experiments established that core temperature was increased through exercise in heat and subjects' response to this procedure was consistent with previous results obtained by Fox et al. (1967) and Gonzalez et al. (1974). The increment in core temperature by three consecutive days appeared to be an effective short acclimatization procedure, as demonstrated by the diminution in thermal sensation, improved thermal acceptability and thermal preferences during exposure to warm thermal environments (SET* varying from 25 to 31°C).

A similar experiment carried-out in Singapore, results showed statistically insignificant differences, suggesting that humans cannot be naturally adapted to prefer warmer ambient temperatures (de Dear, Leon and Ameen, 1993 a, de Dear, Leon and Ameen, 1993 b). However, occupants were passively acclimatized to heat. The results from this current study showed that, acclimatization had indeed (1) a major impact in subjects' assessments of their thermal environment and (2) it provided evidence that the experimental procedure of acclimatization to heat applied was successful. These results corroborate the concept of *perceptual adaptation* and the results for thermal acceptability highlighted that subjects' reaction to temperature will strongly depend

on expectations and that psychological adaptation will be play an essential role. These results align to previous studies focusing on *perceptual adaptation* and the notion of expectation earlier pointed-out by McIntyre (1980).

As a world trend, occupants are indeed expending almost 90% of their daily activities indoors and, quite often, in air-conditioned indoor environments. There is evidence that such exposure will influence in occupants' expectation of their thermal environments (i.e. thermal history). In warm and humid climates, such trend for saturation of air-conditioning exposure needs to be more understood. The results presented in this paper showed that it is possible to physiologically acclimatize such 'air-conditioning addicts' to warmer indoor environments without, however, compromising their thermal acceptability. These results reinforces the opportunities to higher set-points in air-conditioning buildings, contributing to significant energy consumption cut-offs within the built environment.

Acknowledgements

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Figures

a)   b)
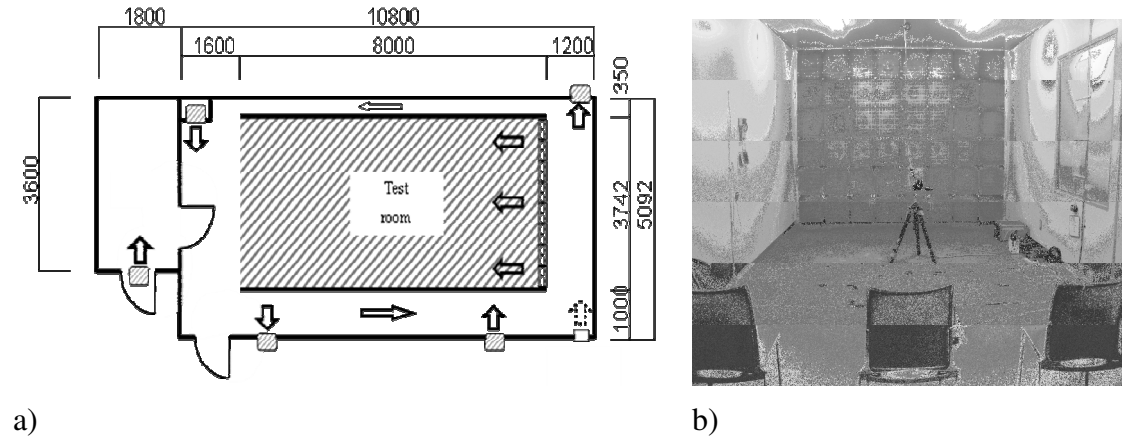
Figure 1 – Climate chamber plan view (a) and interior (b).
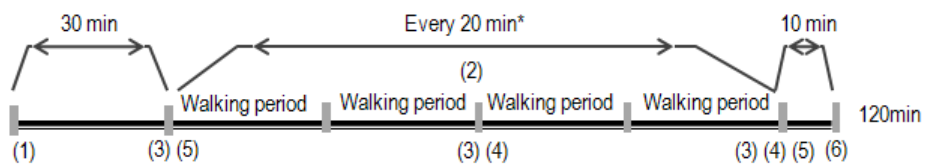
(1) Subjects' arrival and clothing adjustments in the preparation room
(2) Continuous indoor microclimatic and skin temperature measurements
(3) Tympanic temperature measurements
(4) Water intake
(5) Subject weighing
(6) Clothing weighing

*Excluding 5min required in order to change air velocity and allow the subjects to rest

Figure 2 – Experimental procedure during Acclimatization Phase 1.
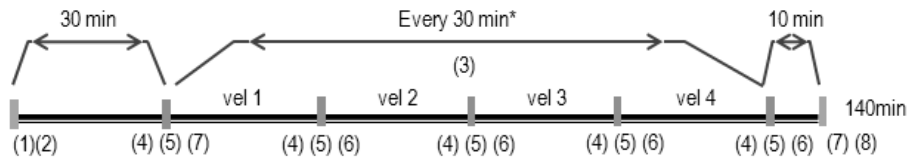
(1) Subjects arrival and clothing adjustments into preparation room
(2) Questionnaires distribution
(3) Continuous indoor microclimatic and skin temperature measurements
(4) Thermal and air movement assessments
(5) Tympanic temperature measurements
(6) Water intake
(7) Subject weighing
(8) Clothing weighing

*Excluding 5min required in order to change air velocity and allow the subjects to rest

Figure 3 – Experimental procedure during thermal and air movement assessments (Acclimatization Phase 2 and Post-acclimatization period).

Figure 4 – Mean core temperature variation, according to exposure time, during the Acclimatization Phase 1.

Figure 5 – Overall thermal sensation votes during (a) Acclimatization Phase 2 and (b) Post-acclimatization experiments.
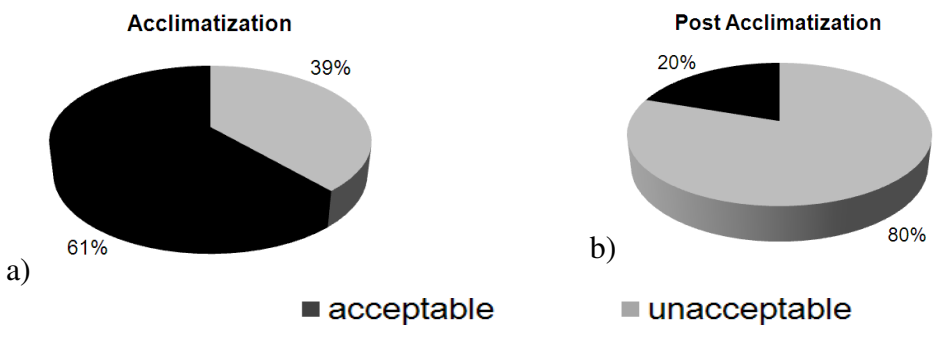
Figure 6 – Overall thermal acceptability votes during Acclimatization Phase 2 (a) and Post-acclimatization (b) experiments.

Figure 7 – Subjects' thermal acceptability votes during (a) Acclimatization Phase 2 and (b) Post-acclimatization experiments.

Figure 8 – Overall thermal preference votes during acclimatization (a) and post-acclimatization (b) experiments.
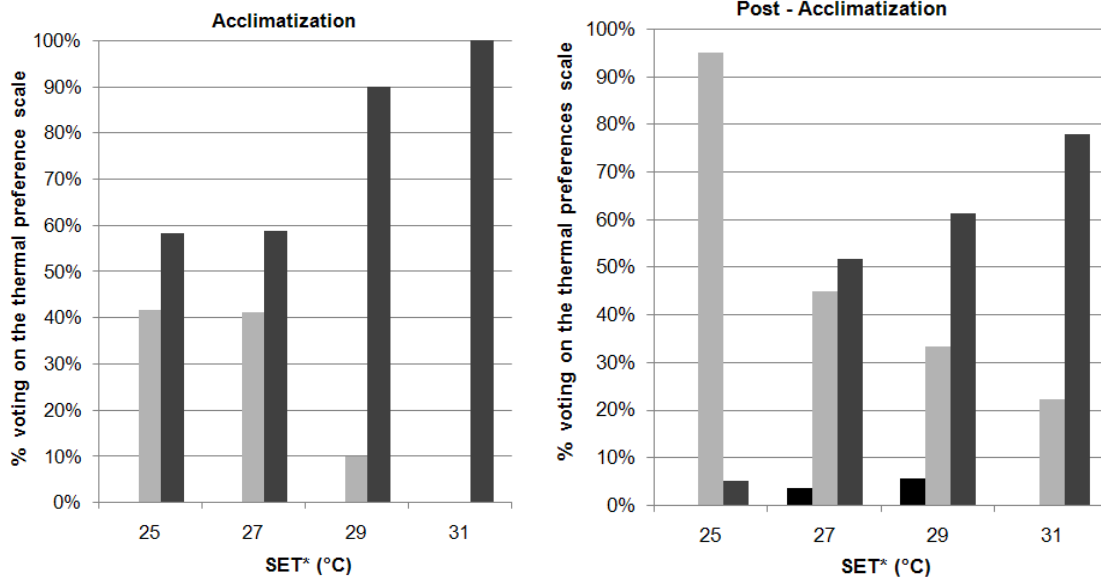
Figure 9 - Subjects' thermal preference votes during (a) Acclimatization Phase 2 and (b) Post-acclimatization experiments.

Tables

Table 1 – Subject's anthropometric information.

Sample size n = 176 questionnaires	Min	Max	Mean	SD
Weight (cm)	45.6	82.1	64.1	11.0
Height (kg)	150.8	180.5	170.2	7.7
Age (years)	25.0	44.0	30.7	4.9

Table 2 - Experimental conditions and measured thermal environment values.

Experiment	Total exposure (days)	Daily exposure (minutes)	Met	Clo	Clo +chair	Air temperature (°C)	Relative humidity (%)	Air velocity (m/s)	SET* (°C)
Pilot	1	60	2.0 - 2.6	0.54	0.54	32	70	0.40	35
Acclimatization Phase 1 *Forced acclimatization to heat*	3	120	2.6	0.54	0.54	32	70	0.40	35.4
Acclimatization Phase 2 *Thermal and air movement assessments*	3	140	1.0	0.54	0.69	28	70	0.20* 0.40 0.80 1.20	28.7* 27.3 26.2 25.7
				0.54	0.69	30	70	0.20* 0.40 0.80 1.20	31.3* 29.9 28.7 28.1
Post-acclimatization *Thermal and air movement assessments*	4	140	1.0	0.54	0.69	28	70	0.20* 0.40 0.80 1.20	28.7* 27.3 26.2 25.7
				0.54	0.69	30	70	0.20* 0.40 0.80 1.20	31.3* 29.9 28.7 28.1

*Air velocity was changed randomly.

Appendix B

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 purposes in hot-humid climates).

Aplicabilidade dos limites da velocidade do ar para efeito de conforto térmico em climas quentes e úmidos

The relevance of air velocity limits for thermal comfort purposes in hot-humid climates

Christhina Candido
Roberto Lamberts
Leonardo Bittencourt
Richard de Dear

Resumo

Este trabalho discute os limites dados para a velocidade do ar pelas normas ASHRAE 55 (2004) e ISO 7730 (2005). Para tal, realizou-se uma análise comparativa entre os valores-limite para a velocidade do ar definidos por essas normas e as respostas dos usuários em relação à preferência e aceitabilidade do movimento do ar obtidas em experimentos de campo realizados em Maceió/AL. Resultados indicam que ambas as normas especificam valores para a velocidade do ar inferiores aos desejados pelos usuários. Os resultados da preferência do movimento do ar indicam que significativa percentagem dos usuários demanda "maior movimento do ar". Quando associada às respostas da aceitabilidade do movimento do ar, a insatisfação dos usuários ficou mais evidente, assim como a demanda por maior velocidade do ar. O mesmo movimento de ar, considerado como inaceitável em climas frios e temperados, é desejado pelos usuários em climas úmidos. Nesse contexto, a aplicabilidade de limites máximos para a velocidade do ar provenientes de estudos com características climáticas diferentes deve ser evitada. Tais limites devem vir de resultados de experimentos de campo em ambientes naturalmente ventilados, onde os usuários possam utilizar de oportunidades adaptativas para reestabelecer o conforto térmico. Futuras normas brasileiras devem focar em tais questões, visando limites de velocidade que correspondam à expectativa dos usuários em climas quentes e úmidos.

Palavras-chave: Velocidade do ar. Conforto térmico. Normas.

Christhina Candido
Faculty of Architecture, Design and Planning
University of Sydney
Sydney – Australia
NSW, 2006
Tel.: (612) 9351-3206
E-mail: chrismcandido@yahoo.com

Roberto Lamberts
Centro Tecnológico, Departamento de Engenharia Civil
Universidade Federal de Santa Catarina
Campus Universitário, Trindade, Caixa Postal 476
Florianópolis – SC – Brasil
CEP 88040-900
Tel.: (48) 3721-7090
E-mail: lamberts@ecv.ufsc.br

Leonardo Bittencourt
Centro de Tecnologia, Departamento de Arquitetura e Urbanismo
Universidade Federal de Alagoas
Campus A. C. Simões, BR 104 Norte, KM 97, Cidade Universitária
Maceió – Al - Brasil
CEP 57072-970
Tel.: (82) 3214-1290
E-mail: lsb54@hotmail.com

Richard de Dear
Faculty of Architecture, Design and Planning
University of Sydney
Sydney – Australia
NSW, 2006
Tel.: (612) 9351-2801
E-mail: r.dedear@usyd.edu.au

Abstract

This article discusses the air velocity limits established by ASHRAE 55 (2004) and ISO 7730 (2005). A comparative analysis was developed between those air velocity limits and users' answers for air movement preferences and acceptability, obtained in field experiments carried out in the city of Maceio, Alagoas, Brazil. The results suggest that the air velocity limits specified by those standards are lower than those required by users. The results indicate that a significant percentage of users demand "more air movement". When those results were combined with the answers on air movement acceptability, the number of unsatisfied users increased, as well as the demand for higher air velocity levels. The same air movement that is considered unacceptable in cold or temperate climates is desirable in hot-humid climates. Therefore the application of maximum air velocity limits from studies carried out in a climate that has different characteristics should be avoided. Air velocity limits should be defined based on field experiments in naturally ventilated indoor environments where adaptive opportunities are available in order to re-establish users' thermal comfort. Future standards in Brazil should consider these issues, in order to establish air velocity limits that can meet users expectations in hot-humid climates.

Keywords: Air velocity. Thermal comfort. Standards.

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Introdução

Um dos principais argumentos associados aos limites máximos para a velocidade do ar em ambientes internos advém do conceito de que desconforto pode ocorrer pelo incremento do movimento do ar, ou o chamado desconforto por correntes de ar (i.e. *draft)*. A intensidade de tal fenômeno é intrinsecamente relacionada à combinação da temperatura e da velocidade do ar e também a fatores complementares, tais como a intensidade de turbulência e a área do corpo do usuário exposta (MCINTYRE, 1978). Tais constatações advêm de experimentos realizados em câmaras climáticas, com usuários desenvolvendo atividades sedentárias, utilizando vestimenta leve e sem oportunidades adaptativas (FANGER; PEDERSEN, 1977; FANGER; CHRISTENSEN, 1986).

A equação resultante é utilizada para estimar o percentual de usuários insatisfeitos com o movimento de ar e serve como referência para os limites considerados como máximos para a ASHRAE 55 (2004) e ISO 7730 (2005). A Equação 1 mostra as variáveis utilizadas para tal cálculo. O percentual de insatisfação dos usuários preditos pela Equação 1 é válido para condições cuja temperatura do ar varia entre 20 °C e 26 °C, com velocidade média entre 0,05 e 0,40 m/s e intensidade da turbulência inferior a 70%. A aplicabilidade de tais valores é estritamente limitada às condições laboratoriais onde foram encontrados (ambientes com ar-condicionado) e/ou climas com características semelhantes.

$$DR = (34 - t_a) \times (\bar{v} - 0.05)^{0.62} \times (0.37 \times \bar{v} \times Tu + 3.14)(\%) \quad \text{Eq. 1.}$$

Onde:

DR = percentual de usuários sentindo desconforto causado pelo movimento do ar;

$\bar{v}$ = velocidade média do ar [m/s];

t_a = temperatura do ar [°C]; e

Tu = intensidade de turbulência [%].

Normas internacionais oferecem, além da Equação 1, gráficos complementares para se obterem os valores de velocidade do ar nos ambientes internos. Na ASHRAE 55 (2004), os limites para a velocidade do ar podem ser obtidos de duas formas. A primeira utiliza a Equação 1 como referência, sendo aplicável para os ambientes de forma geral. A norma ainda considera o desconforto por correntes de ar como um dos itens relacionados ao desconforto térmico localizado, que, por sua vez, também é relacionado à determinação das condições de aceitabilidade térmica do ambiente. De acordo com esse item, o valor máximo de usuários insatisfeitos devido ao desconforto provocado por correntes deverá ser de 20%.

A segunda forma de obtenção dos valores máximos para a velocidade do ar é tratada especificamente para os casos cujo incremento do movimento do ar é desejado e quando os usuários têm o controle dos mecanismos de ventilação. Nesse caso, o valor máximo pode ser obtido pelo cruzamento dos valores do incremento da temperatura do ar com os valores da diferença entre a temperatura radiante e a temperatura do ar, conforme a Figura 1a. Apesar de a escala apresentar valores entre 0 e 1,50 m/s, a norma explicita claramente que a velocidade não deverá exceder 0,80 m/s e que o ajuste permitido aos usuários não deve ser superior a 0,15 m/s.

Na ISO 7730 (2005), os valores máximos para a velocidade do ar também se baseiam na Equação 1. De forma complementar, essa norma apresenta o gráfico da Figura 1b, que informa o limite da velocidade do ar em função dos valores da temperatura do ar e da intensidade de turbulência. Como resultado, pode-se obter valores para um máximo de 15% de insatisfação dos usuários. Os valores da velocidade do ar variam entre 0 e 0,40 m/s, para temperaturas do ar entre 18 °C e 26 °C e turbulência oscilando entre 0% e 60% (Figura 1b).
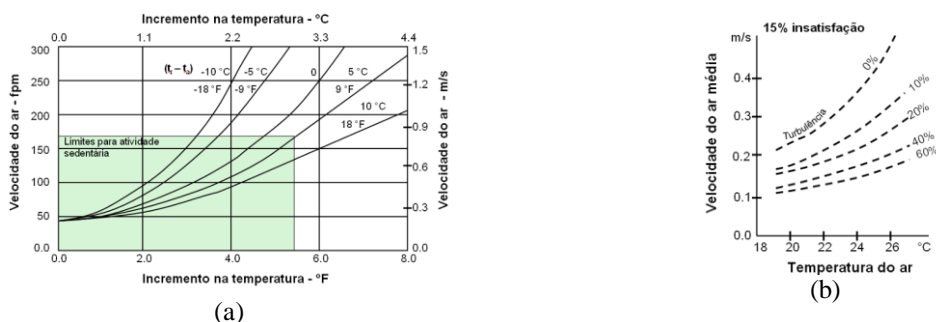

(a)

(b)

Figura 1 – **Determinação dos valores da velocidade do ar de acordo com a (a) ASHRAE 55 (2004) e (b) ISO 7730 (2005), livremente adaptados e traduzidos dos originais**

Em climas quentes, ou moderadamente quentes, no entanto, o mesmo movimento do ar que é considerado como desconfortável em climas frios e temperados, pode ser tido como extremamente bem-vindo pelos usuários para fins de conforto térmico. A aplicabilidade de limites máximos para a velocidade do ar advindos de experimentos laboratoriais vem sendo cada vez mais questionada, principalmente quando se trata de ambientes reais, com usuários utilizando oportunidades adaptativas (ARENS *et al.,* 1998, YANG; ZHANG, 2008; ZHANG *et al.,* 2007a). Do ponto de vista fisiológico, o mesmo incremento do movimento do ar em climas frios e em climas quentes é percebido de maneira diferente pelos usuários, podendo o mesmo insuflamento de ar ser considerado uma incômoda corrente de ar ou uma agradável brisa. Tal percepção pode ser explicada fisiologicamente pelo fato de os termorreceptores para frio estarem localizados mais superficialmente na pele que os de calor (DEAR, 2009). Nessa abordagem, a diferença na percepção do mesmo movimento do ar pode ser explicada pelo conceito de alliesthesia (CABANAC, 1971). Segundo esse conceito, o estímulo causado no ambiente pode ser positivo ou negativo, dependendo de como ele auxilia ou dificulta o restabelecimento (alliesthesia positiva) ou afastamento (alliesthesia negativa) do conforto do usuário (DEAR, 2009). Dessa forma, os ambientes que utilizam a ventilação natural como estratégia de condicionamento oferecem esse estímulo positivo, e as flutuações do movimento e velocidade do ar podem ser não só bem-aceitas, mas até desejadas pelos usuários.

Resultados de uma ampla análise realizada no banco de dados do RP-884 da ASHRAE mostram que, do ponto de vista de preferência e expectativa, em ambientes onde a ventilação natural é utilizada como a principal forma de condicionamento os usuários tendem a indicar frequentemente preferência por "maior movimento do ar" (ZHANG *et al.,* 2007b). Nesse banco de dados, a velocidade média foi de 0,30 m/s, estando,

portanto, dentro dos limites utilizados na ASHRAE 55, por exemplo. Com base em tais evidências, Arens *et al.* (2009) sugerem uma revisão dos valores de velocidade do ar permitidos em ambientes internos da ASHRAE 55 (2004). Tal proposta amplia os limites máximos da velocidade do ar, de acordo com o tipo de controle dos usuários em relação a janelas e ventiladores. De acordo com os autores, é possível ampliar a velocidade do ar de 0,80 m/s para até 1,20 m/s, se o controle local estiver disponível para grupos de até 6 usuários. Tais limites são, sem dúvida, um avanço em estimar o uso de valores mais elevados para a velocidade do ar.

É sabido que a extrapolação e o uso de limites para velocidade do ar oriundos de estudos com realidades climáticas diferentes podem resultar em significativa disparidade em termos de aceitabilidade térmica em geral e em preferência do movimento do ar. No entanto, pouco foi desenvolvido no intuito de se aprofundar o entendimento de aspectos subjetivos da relação do usuário com a intensidade do movimento do ar. Nesse sentido, estudos que comparam tais valores máximos da velocidade do ar com os resultados da preferência e aceitabilidade do movimento de ar dos usuários se constituem em importante contribuição para essa área do conhecimento. Este trabalho sugere analisar os usuários em termos de aceitabilidade do movimento do ar e tem como objetivo comparar os limites estabelecidos para a velocidade do ar, pelas normas ASHRAE 55 (2004) e ISO 7730 (2005), com base em experimentos de campo realizados no clima quente e úmido de Maceió - AL.

Método

Este trabalho baseia-se numa análise comparativa entre os valores definidos como velocidade do ar pelas normas ASHRAE 55 e ISO 7730, com os resultados obtidos em experimentos de campo em relação à preferência e aceitabilidade do movimento do ar.
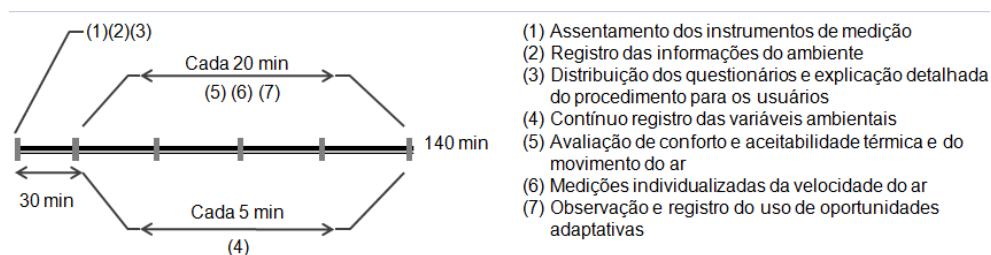
Figura 2 – **Esquema do procedimento adotado para os experimentos de campo**

(1) Assentamento dos instrumentos de medição
(2) Registro das informações do ambiente
(3) Distribuição dos questionários e explicação detalhada do procedimento para os usuários
(4) Contínuo registro das variáveis ambientais
(5) Avaliação de conforto e aceitabilidade térmica e do movimento do ar
(6) Medições individualizadas da velocidade do ar
(7) Observação e registro do uso de oportunidades adaptativas

Os experimentos de campo[1] foram desenvolvidos em salas de aula e ateliês de desenho do Curso de Arquitetura e Urbanismo da Universidade Federal de Alagoas e do Centro de Estudos Superiores de Maceió. Os ambientes utilizam a ventilação natural como estratégia principal de condicionamento térmico, sendo esta complementada pelo uso de ventiladores de teto. O estudo foi conduzido durante duas semanas, nos meses de verão e inverno, nos períodos da manhã, tarde e noite, resultando em 2.075 questionários respondidos pelos ocupantes de tais ambientes. Um esquema do procedimento adotado para tais experimentos pode ser visto na Figura 2.

A idade dos usuários variou entre 18 e 25 anos, e a maioria dos entrevistados foi do sexo feminino (cerca de 66%). As atividades desenvolvidas foram sedentárias e variavam entre 70 W/m² e 93 W/m², visto que os usuários encontravam-se sentados escrevendo ou desenhando, ou desenhando em pé. A vestimenta utilizada foi, em média, leve, considerando-se os valores de 0,30 clo para o verão e de 0,70 clo para o inverno, conforme classificação da ASHRAE 55 (2004). As atividades dos alunos não foram interrompidas durante os experimentos, visando caracterizar a utilização real dos ambientes, incluídas as oportunidades adaptativas dos usuários. Da mesma forma, permitiu-se o uso de ventiladores de teto, acionamento de lâmpadas e controle das aberturas (fechar ou abrir portas e janelas) e ajustes desejados para as vestimentas.

As variáveis ambientais foram registradas com o confortímetro Babuc A, localizado no centro das salas. Tal instrumento serviu para registrar os valores da temperatura do ar, temperatura de globo, umidade e velocidade do ar do ambiente. Com base em tais valores, pode-se calcular as variáveis derivadas (temperatura operativa, temperatura radiante média, etc.). Sendo a velocidade do ar o foco central deste trabalho, ela foi registrada de forma individualizada e simultânea ao preenchimento dos questionários de aceitabilidade térmica e ambiental pelos usuários. Para tal, utilizou-se um termoanemômetro portátil e bastões de fumaça para o registro da velocidade do ar e direção predominante do fluxo de ar respectivamente. O controle de abertura de janelas e portas bem como o acionamento de ventiladores foram realizados livremente pelos usuários, sem nenhuma interferência dos pesquisadores. Tais mudanças foram registradas pelos pesquisadores, em separado, juntamente com a hora em que foram observadas, no formulário de controle de observação dos ambientes internos, servindo como indicação do uso efetivo das oportunidades adaptativas.

O questionário utilizado baseia-se no modelo de Dear e Brager (2002)[2] e foi adaptado para o desenvolvimento deste trabalho, de acordo com as necessidades específicas dele. O questionário de aceitabilidade térmica e ambiental inclui questões relativas ao conforto térmico dos usuários, aceitabilidade e preferência térmica, preferência e aceitabilidade do movimento do ar, assim como informações dos usuários (altura, idade, vestimenta, atividade). Os questionários foram associados com a posição específica do usuário no ambiente, no momento do preenchimento, facilitando a posterior análise individualizada dos resultados.

Todas as informações relacionadas ao experimento, tais como os ambientes, usuários, respostas dos usuários, variáveis ambientais, derivadas e calculadas, foram agrupadas em um banco de dados. Posterior tratamento estatístico aplicado foi desenvolvido com o software SAS©, o que permitiu o refinamento das análises dos dados.

Resultados

A análise dos resultados foi dividida em duas partes. Primeiramente, encontraram-se os valores máximos para a velocidade do ar, de acordo com as normas, tendo como referência o gráfico da Figura 1a e 1b, apresentadas anteriormente. Tais resultados são apresentados na Tabela 1. Para viabilizar uma análise comparativa, os dados obtidos nos experimentos foram organizados de acordo com as especificações e limitações de cada norma para os valores das variáveis utilizadas, tais como temperatura do ar, temperatura operativa e intensidade de turbulência. Tendo com referência o gráfico da ASHRAE, os valores para a velocidade do ar variaram entre 0,30 m/s e 1,20 m/s. No entanto, nessa norma, a velocidade de 0,80 m/s é considerada como sendo o limite máximo aceitável. Por esse motivo, embora o valor de 1,20 m/s conste do gráfico da Figura 1, o valor máximo adotado para a velocidade do ar foi de 0,80 m/s. Considerando as especificações da ISO 7730, os valores resultantes para a velocidade do ar variaram entre 0,15 m/s e 0,20 m/s.

A segunda parte foi dedicada à análise das repostas dos usuários para preferência e aceitabilidade do ar, dentro dos valores máximos da velocidade que

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[1] Mais detalhes sobre essa metodologia podem ser vistos em Cândido *et al.* (2010).

[2] O questionário se baseia no modelo utilizado por de Dear e Brager (2002), no desenvolvimento do projeto da ASHRAE RP 884 (*Adaptive model*).

foram obtidos graficamente nas normas e sumarizados na Tabela 1. Essa análise é apresentada no capítulo a seguir.

Preferência do movimento do ar

A Figura 1a sumariza a distribuição de frequência para os resultados da preferência do movimento do ar, tendo como referência as especificações da ASHRAE. Os usuários classificaram a preferência do movimento do ar de acordo com três possíveis respostas: "maior movimento do ar", "assim mesmo" ou "menor movimento do ar". De forma geral, as respostas se concentraram nas opções "assim mesmo" e "maior movimento do ar".

Os resultados foram separados em duas categorias, dependendo do valor resultante da diferença entre a temperatura radiante e a do ar (Figura 1a). Quando essa diferença foi de 1 ℃, o percentual de usuários requisitando "maior movimento do ar" variou de 30% e 5% para velocidade do ar de 0,30 m/s e 0,80 m/s respectivamente. Nesse mesmo grupo (tr-ta = 1 ℃), a significativa maioria dos usuários indicou "assim mesmo" como preferência do movimento do ar, correspondendo a 68%, 69% e 83% para os respectivos valores da velocidade do ar 0,30 m/s, 0,60 m/s e 0,80 m/s.

Quando a diferença entre temperatura radiante e do ar foi anulada (tr-ta = 0 ℃), o percentual de usuários pedindo "maior movimento do ar" variou entre 68% e 42% para as velocidades de 0,30 m/s e 0,80 m/s. Nesse caso, o percentual de usuários indicando "assim mesmo" como preferência para o movimento do ar aumentou em função do incremento da velocidade do ar, variando entre 22% e 58%. Nota-se que o percentual máximo de usuários indicando preferência por "menor movimento do ar" foi significativamente inferior às outras duas opções, não ultrapassando 10% das respostas em todos os casos.

A Figura 3b sumariza os resultados para a preferência do movimento de ar tendo como referência a ISO 7730. Neste caso, os dados que delinearam a identificação dos valores da velocidade do ar incluem a temperatura do ar e a intensidade da turbulência (Tu). Cruzando tais dados com os obtidos nos experimentos, a análise incluiu as ocorrências cuja temperatura do ar situava-se entre 24 ℃ e 26 ℃ e os valores da intensidade de turbulência de 40% e 60%. Para a temperatura do ar de 24 ℃, o percentual de usuários demandando "maior movimento do ar" foi de 22% para turbulência de 40%, e de 25% para turbulência de 60%. No restante da amostra, os usuários indicaram "assim mesmo" como preferência do movimento do ar em 78% e 75% dos casos (para Tu = 40% e 60% respectivamente). Para a temperatura do ar de 24 ℃, nota-se um incremento dos usuários demandando "maior movimento do ar" de 32% para Tu = 40% e de 37% para Tu = 60%. Por outro lado, 12% dos usuários demandaram "menor movimento do ar" para Tu = 40%, e apenas 4% para Tu = 60%. Considerando a demanda por "menor movimento do ar" como usuários insatisfeitos por correntes de ar, o percentual foi significativamente inferior aos 20% indicados como valor máximo pela norma.

As duas normas especificam valores-referência para o percentual de insatisfação dos usuários relativo ao movimento do ar excessivo. A ASHRAE considera 20% como o valor máximo para a insatisfação dos usuários decorrente do excessivo movimento de ar (ou draft). Já na ISO 7730, o percentual de insatisfação dos usuários é inferior, de 15%. Considerando-se os usuários que votaram por "maior movimento do ar" ou "menor movimento do ar" como insatisfeitos, nota-se que as normas definem velocidades do ar inferiores às desejadas pelos usuários. Ao analisar a distribuição das preferências do movimento do ar, observa-se que o maior percentual de insatisfação dos usuários foi relacionado à necessidade de maior movimento do ar e que os usuários demandando menor movimento do ar foram significativamente inferiores.

ASHRAE 55			ISO 7730		
Temp. radiante – temp. ar (°C)	Incremento na temp. ar (°C)	Vel. ar (m/s)	Temp. ar (°C)	Turbulência (%)	Vel. ar (m/s)
tr-ta = 1	1,10	0,30	24	40	0,20
	2,20	0,60		60	0,20
	3,30	0,80			
tr-ta = 0	1,10	0,30	26	40	0,15
	2,20	0,60		60	0,20
	3,30	0,80			

Tabela 1 – **Valores da velocidade do ar obtidos de acordo com as especificações da ASHRAE 55 (2004) e ISO 7730 (2005)**
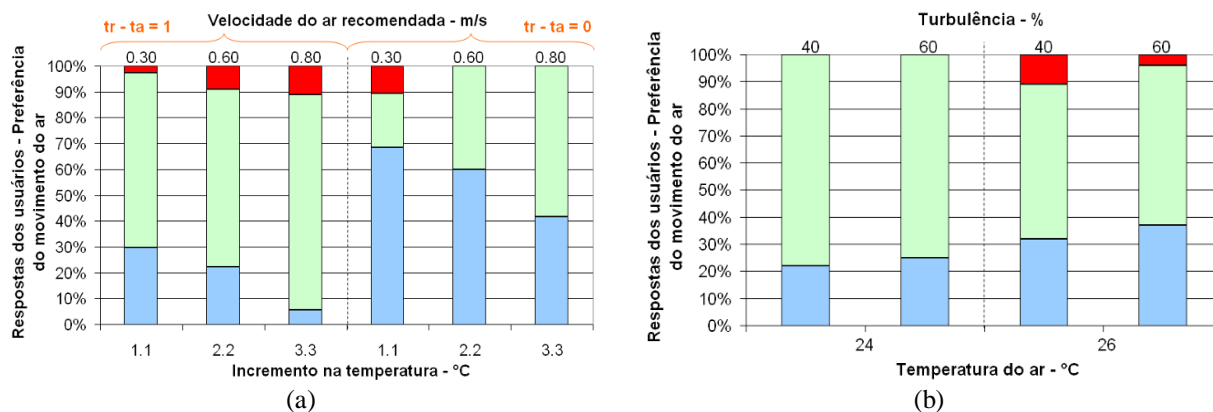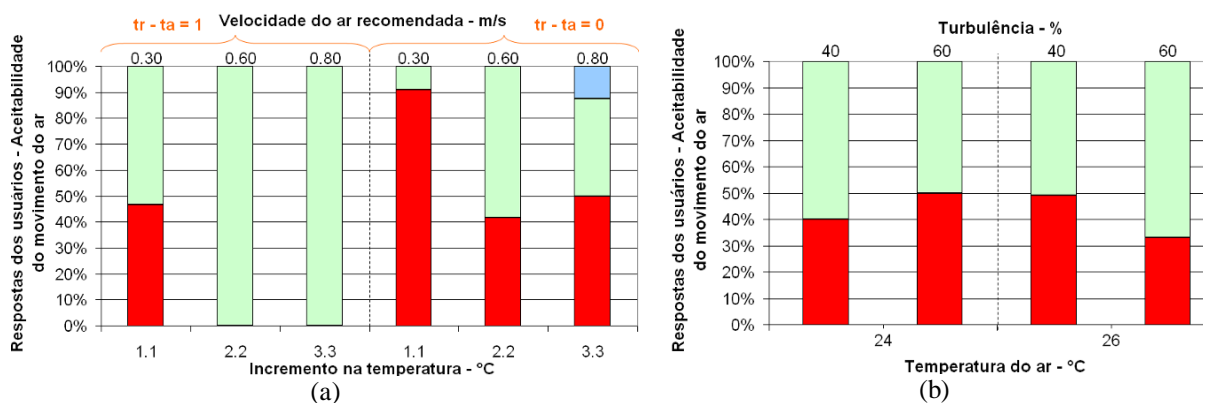
Figura 3 – **Gráfico da preferência do movimento do ar tendo como referência as especificações da ASHRAE 55 (b) e ISO 7730 (a)**

Inaceitável	Aceitável			Inaceitável
devido à baixa velocidade do ar	mas com baixa velocidade do ar	velocidade do ar suficiente	mas com alta velocidade do ar	devido à alta velocidade do ar

Tabela 2 – **Escala para a aceitabilidade do movimento de ar**

Figura 4 – **Gráfico da aceitabilidade do movimento do ar tendo como referência as especificações da ASHRAE 55 (a) e ISO 7730 (b)**

Aceitabilidade do movimento do ar

Ao se combinar a análise de preferência com a aceitabilidade do movimento de ar, os resultados são ainda mais expressivos. Os usuários entrevistados podiam classificar o movimento do ar como aceitável ou inaceitável e depois fornecer informações específicas sobre a velocidade do ar. As respostas foram agrupadas em uma escala que varia entre aceitável e inaceitável, e que pode ser vista na Tabela 2. Para esta análise, consideraram-se as três respostas dos usuários para o movimento do ar *aceitável,* visto que não foram registrados votos para as duas categorias de *inaceitável* nas

faixas limítrofes para a temperatura e turbulência utilizadas por ambas as normas

As Figuras 4a e 4b sumarizam os resultados para as três diferentes respostas dos usuários que consideraram a velocidade do ar aceitável. Assim como para a preferência do movimento do ar, os resultados foram separados em duas categorias, dependendo do valor resultante da diferença entre a temperatura radiante e a do ar. Quando essa diferença foi de 1 ºC e a velocidade do ar de 0,30 m/s, 47% dos usuários classificaram o movimento como "aceitável, mas com baixa velocidade do ar", e os 53% restantes indicaram movimento do ar "aceitável, com velocidade suficiente". Nas duas

demais faixas de velocidade do ar, de 0,60 m/s e de 0,80 m/s, as respostas foram para "velocidade do ar suficiente". Em nenhuma das faixas de velocidade os usuários indicaram movimento do ar "aceitável, mas com alta velocidade".

Quando a diferença entre a temperatura radiante e a temperatura do ar foi nula, aproximadamente 90% dos usuários responderam "aceitável, mas com baixa velocidade do ar" para a velocidade de 0,30 m/s. Com o incremento da velocidade do ar para 0,60 m/s e 0,80 m/s, o percentual de usuários indicando tal resposta diminuiu para 42% e 50% respectivamente. Nota-se que para velocidades de 0,80 m/s apenas 11% dos usuários indicaram movimento do ar "aceitável, mas com alta velocidade do ar".

Utilizando o gráfico da ISO 7730 como referência, os valores para a aceitabilidade foram no mínimo de 32% e no máximo de 50% para respostas de "movimento do ar aceitável, mas com baixa velocidade do ar". O restante das respostas foi para movimento do ar "aceitável e velocidade do ar suficiente", e não houve registro de respostas para movimento do ar "aceitável, mas com alta velocidade do ar".

Aplicabilidade de limites mínimos para a velocidade do ar

Com base em análise Probit, valores mínimos da velocidade do ar foram encontrados, focando-se em 80% e 90% de aceitabilidade do movimento do ar. O gráfico da Figura 5 sumariza os valores encontrados para velocidades máximas de acordo com a ISO 7730, ASHRAE 44 e Arens *et al.* (2009), e comparação com os valores mínimos

para aceitabilidade do movimento do ar de 80% e 90%.

A Figura 5 mostra que a velocidade mínima necessária para atingir 80% e 90% de aceitabilidade do movimento do ar é superior aos valores especificados pelas normas ASHRAE 55 e ISO 7730, em comparação com os valores indicados pelo estudo de Arens *et al.* (2009). Nota-se que os valores mínimos encontram-se na área onde o controle local não é necessário e entre o limite inferior e o superior dessa zona. Em termos de valores máximos, ocupantes consideraram 1,60 m/s ainda aceitável, e valores similares a este foram encontrados por Tanabe e Kimura (1987) em câmaras climáticas no Japão. O valor de 1,60 m/s é acima da linha limítrofe de 1,20 m/s, em que o controle local começa a ser necessário (a cada 6 ocupantes) por Arens *et al.* (2009).

Tais resultados sugerem que a utilização de valores mínimos se constitui em diferente abordagem e difere da utilizada em normas, cuja preocupação está voltada para valores máximos. No entanto, quando os usuários têm acesso e controle, a inserção de valores mínimos de velocidade do ar para fins de conforto ambiental parece ser mais relevante. Outro fator é a possibilidade de acionamento de ventiladores para compensar períodos de calmaria. A Figura 6 sumariza resultados para o uso de ventiladores distribuídos por temperaturas operativas. Nos ambientes aqui estudados, o controle das janelas e, principalmente, o acionamento dos ventiladores ocorreram em grupo, média de 1 ventilador para aproximadamente cada 6 ocupantes, número este similar à recomendação de Arens *et al.* (2009) para o chamado controle local.
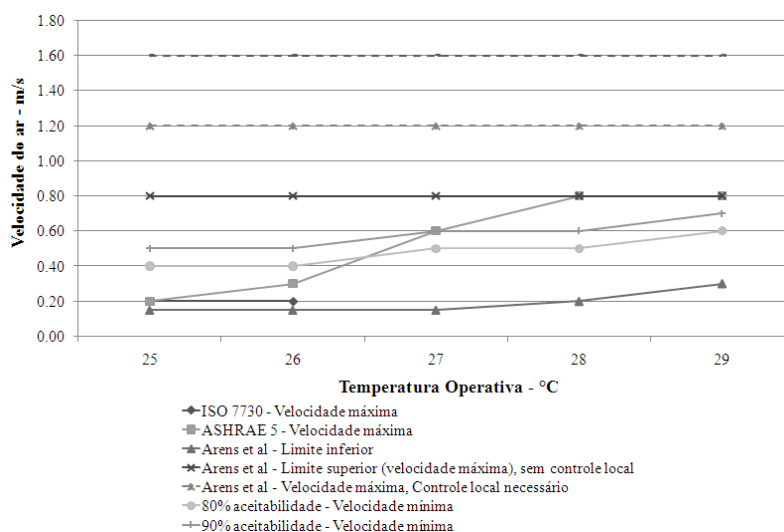

Figura 5 – **Gráfico dos valores encontrados para velocidades *máximas* de acordo com a ISO 7730, ASHRAE 44 e Arens *et al*. (2009) e comparação com os valores *mínimos* para aceitabilidade do movimento do ar de 80% e 90%**
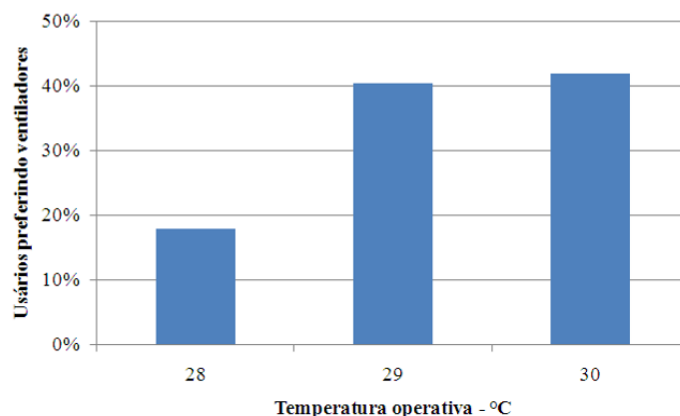
Figura 6 – **Preferência de ventiladores para temperaturas operativas acima de 28 °C**

A Figura 5 mostra a preferência por ventiladores para valores de temperatura operativa acima de 28 °C. É possível notar que o número de ocupantes que demandam por ventiladores aumenta de acordo com o incremento da temperatura operativa, indicando a preferência dessa oportunidade adaptativa para restabelecer o conforto térmico. No entanto, estudos anteriores ressaltam uma relação direta entre o histórico de exposição prévia dos ocupantes (CHUN *et al.,* 2008) e a preferência pelo uso de ventiladores e de ambientes naturalmente ventilados (OLESEN, 2004), revelando uma espécie de "vício". Quanto mais expostos a ambientes condicionados naturalmente, ocupantes tendem a preferir ventilação natural e ventiladores. Por sua vez, quanto mais expostos a ambientes com ar-condicionado, mais os ocupantes preferem esse tipo de condicionamento (CÂNDIDO *et al.,* 2010).

Sugestões de indicadores para normas brasileiras

Utilizando os dados aqui apresentados, os seguintes itens são sugeridos para normas brasileiras:

(a) capacidade adaptativa[3];

(b) o conceito de capacidade adaptativa engloba desde a preocupação com a orientação do sítio até o controle local dos usuários. A adoção de oportunidades adaptativas demonstrou ser de grande utilidade para incrementar o movimento do ar para fins de conforto térmico. As edificações aqui investigadas oferecem grande porosidade ao fluxo de ar e dispositivos complementares para a ventilação (ventiladores de teto), além de flexibilidade do vestuário e controle/acesso dos dispositivos de incremento da ventilação (janelas e

ventiladores). Tais itens, quando combinados, parecem contribuir para o restabelecimento do conforto dos usuários e para a aceitabilidade de velocidades mais elevadas;

(c) limites *mínimos* de velocidade do ar;

(d) a adoção de valores mínimos, ao invés de máximos, parece ser uma mudança de enfoque necessária para o contexto climático aqui investigado. Os limites mínimos encontrados visaram estabelecer 80% e 90% de aceitabilidade do movimento do ar e ficaram claramente acima dos estabelecidos por normas internacionais. Valores acima de 0,80 m/s e até 1,60 m/s foram aceitos pelos usuários e, por sua vez, deveriam ser adotados em climas quentes e úmidos. A aplicabilidade dos limites mínimos aqui encontrados, no entanto, necessitam ser comparados com outros experimentos de campo em contextos climáticos diferenciados;

(e) adoção de ventiladores como dispositivos complementares da velocidade do ar; e

(f) a preferência pela adoção de ventiladores foi clara acima de temperatura operativa de 28 °C, e aqui, mais uma vez, os usuários fizeram uso dessa oportunidade adaptativa. O uso de ventiladores pode ser bastante útil para incrementar a velocidade mínima necessária para o conforto dos usuários, principalmente em períodos de calmaria. Requerimentos específicos podem ser identificados, especialmente no que concerne ao controle dos usuários.

Conclusões

Este artigo teve como objetivo investigar a aplicabilidade dos limites dados para a velocidade do ar pelas normas ASHRAE 55 (2004) e ISO 7730 (2005) com os resultados de preferência e aceitabilidade do movimento do ar obtidos em

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[3] Termo livremente traduzido de "adaptive capacity" (KWONG; RAJKOVICH, 2010).

experimentos de campo no clima quente e úmido de Maceió/AL.

Resultados indicam que ambas as normas especificam valores para a velocidade do ar inferiores aos desejados pelos usuários dos ambientes aqui investigados. Os resultados para a preferência do movimento do ar indicam que significativa percentagem dos usuários demanda "maior movimento do ar", sendo os valores para "menor velocidade do ar" bastante inferiores. Quando associada às respostas da aceitabilidade do movimento do ar, a insatisfação dos usuários ficou mais evidente, indicando a demanda por "maior velocidade do ar". Os limites estabelecidos pelas normas tendem a superestimar a insatisfação dos usuários pelo incremento do movimento do ar. Os usuários, por sua vez, aceitam e preferem valores de velocidade do ar mais elevados como forma de restabelecimento do conforto térmico.

Do ponto de vista da percepção e expectativa, os conceitos de preferência e de aceitabilidade do movimento do ar parecem estar fortemente relacionados a questões subjetivas dos usuários, principalmente à adaptação às flutuações de tais valores, assim como ocorre para a temperatura do ar. O estímulo causado pelas flutuações do movimento do ar parece ser desejado pelo usuário por questões subjetivas e essencialmente individuais. Os valores máximos dados pelas normas aqui utilizadas como referência não contemplam tais questões, permitindo maiores percentuais de insatisfação pelo movimento do ar insuficiente, e não o excessivo. Já do ponto de vista fisiológico, o incremento do movimento do ar demandado pelos usuários pode ser associado ao estímulo ou alliesthesia positiva, auxiliando no restabelecimento do conforto do usuário (DEAR, 2009). As flutuações do movimento e velocidade do ar, quando associadas à temperatura, podem ser não só bem-aceitas como também desejadas pelos usuários.

Outro ponto de relevância identificado foi a importância de dispositivos complementares para o incremento do movimento do ar. A preferência pelo uso de ventiladores foi significativa para temperaturas acima de 28 ºC e indica o uso de oportunidades adaptativas pelos usuários. É importante destacar que os usuários possuíam o controle dos mecanismos de incremento do movimento do ar, tais como janelas e ventiladores, sendo este um item de essencial importância no processo de intensificação do movimento do ar nos ambientes.

Por fim, três itens foram sugeridos como indicadores para normas brasileiras: capacidade adaptativa, limites mínimos para a velocidade do

ar e adoção de ventiladores. No entanto, mais experimentos de campos são indubitavelmente necessários visando a um maior entendimento da aplicabilidade e das limitações dos valores aqui encontrados em diferentes contextos climáticos. Os dados apresentados neste trabalho indicam que draft não parece ser um risco, nem, portanto, uma limitação, para o incremento do movimento do ar nos ambientes investigados.

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Appendix C

Toward a Brazilian standard for naturally ventilated buildings: guidelines for thermal and air movement acceptability.

Conference Paper: 2010 Windsor Conference - Adapting to Change: New Thinking on Comfort.

Towards a Brazilian standard for naturally ventilated buildings: guidelines for thermal and air movement acceptability.

Christhina Cândido[1, 2], Roberto Lamberts[1], Richard de Dear[3] and Leonardo Bittencourt[4]

[1] Federal University of Santa Catarina, Florianópolis – Brazil
[2] Macquarie University of Sydney, Sydney – Australia
[3] The University of Sydney, Sydney – Australia
[4] Federal University of Alagoas, Maceió/AL – Brazil

[*]*Corresponding author's email: ccandido@els.mq.edu.au*

Abstract

In 2001, Brazil suffered an electricity energy crisis as a result of meteorological conditions and poor strategic investments. One of the most important outcomes was the establishment of the energy efficiency law by the Federal Government, after long ten years of politic process. After this landmark event, the Brazilian Government has been promoting energy conservation initiatives including the Thermal Performance in Buildings – Brazilian Bioclimatic Zones and Building Guidelines for Low-Cost Houses (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. Yet requirements for naturally ventilated indoor environments appear as an open category. This paper summarizes a first attempt in order to define guidelines for naturally ventilated environments in which specifications for thermal and air movement acceptability goals must be achieved.

Keywords: thermal acceptability, air movement acceptability, standard, natural ventilation, thermal comfort, energy conservation.

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. Behavioral change, however can deliver faster and long-lasting results. 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 Liden, 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 are the most effective building bioclimatic design strategy in order to improve thermal comfort by passive means. Despite these favourable conditions, the number of buildings relaying in active systems as the main cooling design strategy continues increasing inexorably.

In 2001, Brazil suffered an 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 all country and some of this reduction became permanent as a result of government actions and population engagement (Lamberts, 2008). One of the most important outcomes was the establishment of the energy efficiency law by the Federal Government, after long ten years of politic process.

After this landmark event, the Brazilian Government has been promoting energy conservation initiatives including the Thermal Performance in Buildings – Brazilian Bioclimatic Zones and Building Guidelines for Low-Cost Houses (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. Yet requirements for naturally ventilated indoor environments appear as an open category. This paper summarizes a first attempt in order to define guidelines for naturally ventilated environments in which specifications for thermal and air movement acceptability goals must be achieved.

Revisiting Brazilian energy efficiency initiatives

The energy matrix in Brazil is based manly on hydroelectricity but there was a considerable increase in coal usage during the recent years (Ministério das Minas e Energia, 2007). Investments in a more sustainable energy matrix are essential for a developing country like Brazil, however it is important to bear in mind that there are other areas needing scarce financial resources such as educational and health programs. Therefore investments cannot be wasted and there ample opportunities for energy conservation.

Based upon this, the Federal Government released a *National Policy of Conversation and Rational Use of Energy* focusing on energy efficient buildings and equipment. Despite de fact that these actions were mainly focused on electricity use, its impact was undoubtedly significant considering that 23% of the hydroelectricity is dedicated to commercial and public buildings and approximately 22% to residential sector (Ministério das Minas e Energia, 2007). 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 Houses" (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. Currently the energy efficiency labeling for residential buildings is in progress and it will be made public later in 2010. One important contribution of this document was the definition of bioclimatic zones and Figure 1 shows their definitions. Eight zones were defined according to its 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 a newly released "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 for designers in general 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. Currently it is voluntary but it will become mandatory in 2013 with scheduled reviews every 5 five years (Carlo and Lamberts, 2008).
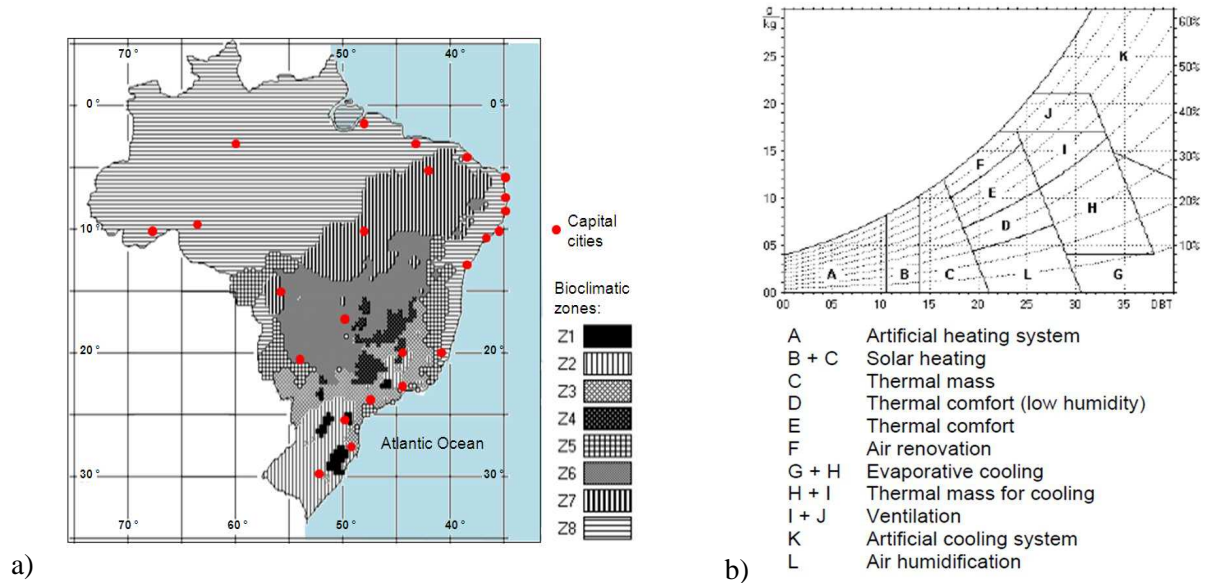

A	Artificial heating system
B + C	Solar heating
C	Thermal mass
D	Thermal comfort (low humidity)
E	Thermal comfort
F	Air renovation
G + H	Evaporative cooling
H + I	Thermal mass for cooling
I + J	Ventilation
K	Artificial cooling system
L	Air humidification

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 during warmer seasons and/or when the indoor temperature is superior to 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.
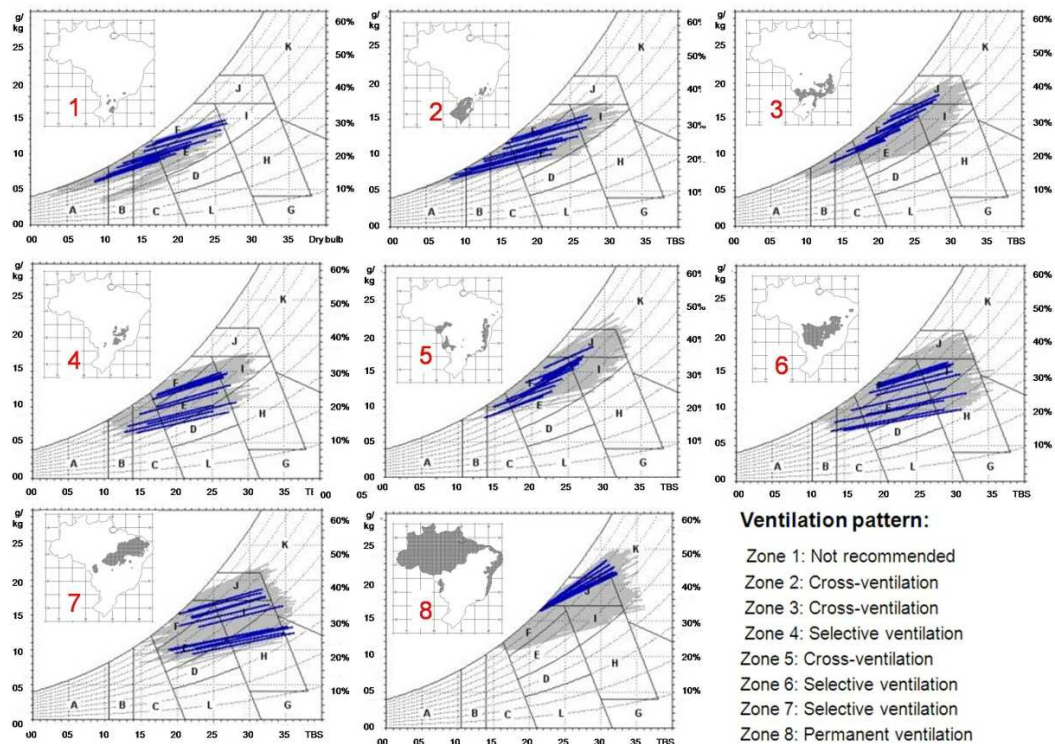
Figure 2. Bioclimatic design strategies and ventilation pattern for different zones (ABNT, NBR 15220-3, 2005).

These two regulations were an important contribution for energy efficiency in buildings and it will be possible to quantify this within the next years. 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. Naturally ventilated buildings receive high incentives as far as it is proved that they provide thermal comfort to the occupants. 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. These requirements are undoubtedly a contribution to occupant's thermal comfort but a more accurate relationship with thermal indoor environments is necessary. 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 standards that focuses on air movement enhancement in combination to thermal comfort is therefore necessary.

Adapting a model for Brazilian occupants

1. Field experiments' evidence

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 in which occupants would consider 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).

Figure 3 shows results from different field experiments. The red dots represent results from the experiments and it is possible to see minor discrepancies in relation to the model. 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). It is noticeable that the range of temperatures that were found as acceptable for occupants felt in similar range predicted by the adaptive model (de Dear and Brager, 1998).
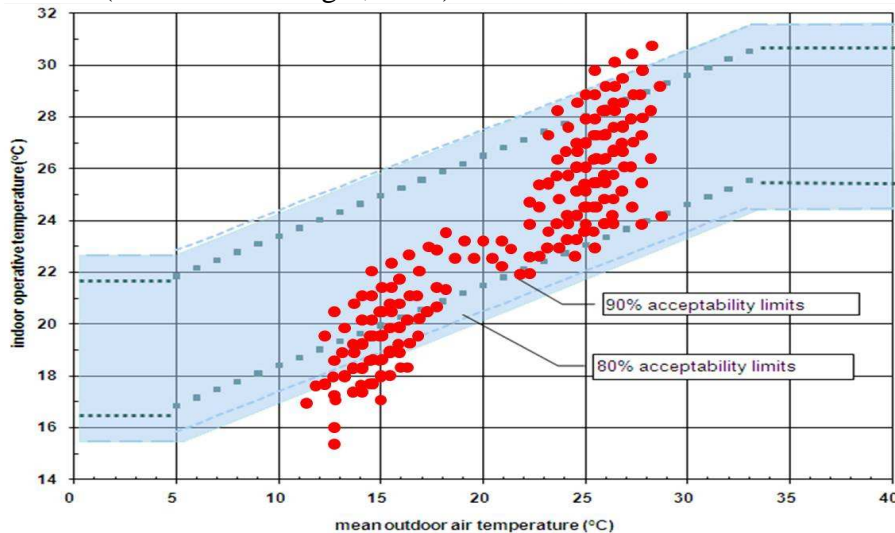

Figure 3. Thermal acceptability for naturally ventilated buildings (after de Dear and Brager, 1998).

Interestingly, discrepancies were found also related to occupant's adaptive opportunities, again here 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). 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, where there is 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 values, 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).

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.

2. General requirements

The general 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. This is a first attempt in order to provide indicators and start a discussion about future standard for naturally ventilated buildings in Brazil.

General requirements are related to 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 fans in order enhance air velocity. In addition, specific requirements will be determined in terms of number of occupants and their access to control of fans.

i. Adaptive capacity potential

Into this section, 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 daylighting; 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 items will be assessed as minimal design requirements in order to be in accordance to the adaptive capacity potential:

- Orientation;
- Site planning;
- Bioclimatic design strategies applied according to specific zone;
- Openings design: location, dimension and detailed information of its operability
- Complementary devices for ventilation enhancement: wind catchers, ventilated sills, pergolas, verandahs, etc) *in combination* with daylighting and shading systems;
- Complementary mechanical devices i.e. ceiling and/or desk fans and its distribution inside indoor environment and occupants control (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 thermal environments. Buildings complying with this item will be considered for subsequent analysis regarding acceptable indoor conditions.

ii. 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.

a. Indoor operative temperatures

The acceptable thermal conditions applied will be established according to the adaptive model (de Dear and Brager, 1998). Allowable indoor operative temperatures will be presented as a variation of mean monthly outdoor temperatures and it was based on field experiments carried out in different regions in Brazil presented before in Figure 2. 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.

Specific air movement requirements will be necessary for operative temperatures higher than 26°C. Minimal air velocity values will be required and complementary mechanical cooling devices will be requested. These complementary requirements aim to enhance adaptive opportunities for the occupants into these environments.

b. 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). 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 this Brazilian standard, air movement acceptability must be considered and the target values will be for 80 and 90%. In order achieve these targets indoor environments must fulfil *minimal* air velocity requirements according to Figure 4. The air velocity requirements must be achieved during the occupied period. For operative temperatures higher than 26°C, complementary ventilation will be required.
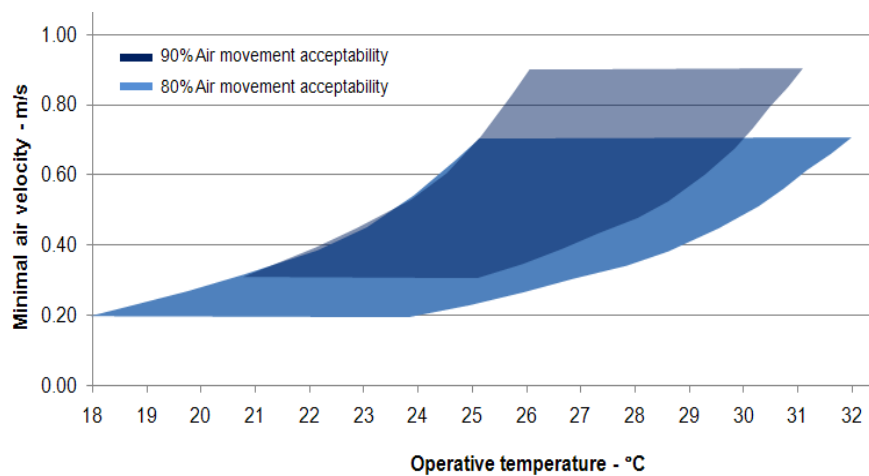

Figure 4. Minimal values for air velocity corresponding to 80 and 90% air movement acceptability.

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 conjunction* with air velocity values above detailed.

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

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

3. 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 *1* 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.

Table 2. Suggested requirements for natural ventilation.

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

In order to be in conformity to the existing Federal Regulation for Voluntary Labelling of Energy Efficiency Levels in Commercial, Public and Service Buildings, the following classification is suggested. The NatVent category that the building was classified will be combined to the percentage of hours into the comfort zone (PHC). The results for the suggested label were summarized into Table 3. The EqNumV column corresponds to the numerical values that are necessary for the complete building's energy evaluation presented in more detail in Carlo and Lamberts (2009) and it comprises lighting and cooling systems and thermal envelope.

Table 3. Suggested labelling categories for naturally ventilated buildings.

Label Category	% Hours into the comfort zone (PHC)	NatVent Category	EqNumV
A	PHC ≥ 80%	1	5
B	70% ≤ PHC < 80%	2	4
C	60% ≤ PHC < 80%	2	3
D	50% ≤ PHC < 70%	3	2
E	PHC < 50%	-	1

4. Conformity

Buildings willing to receive this labelling must provide proof of conformity according to the above requirements. Adaptive capacity must be showed by detailed information related to building's design strategies, according to its specific bioclimatic zone. Qualitative analysis are acceptable but quantitative area preferable in order to provide detailed information about this components/strategies and its performance.

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;
- 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 the minimal requirements specified into the measurement protocol detailed in this guideline. 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.

Conclusions

This paper presented guidelines for a Brazilian standard for naturally ventilated buildings. The main variables 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 adaptive model and minimal air velocity requirements were also determined. Specific occupant's control over openings and fans were also considered. Finally, an energy conservation labelling system was proposed.

This is a first attempt to combine 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.

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Appendix D

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).

Conference Paper: X Encontro Nacional e VI Encontro Latino Americano de Conforto no Ambiente Construído – ENCAC 2008.

APLICABILIDADE DOS LIMITES DA VELOCIDADE DO AR PARA EFEITO DE CONFORTO TÉRMICO EM CLIMAS QUENTES E ÚMIDOS

Christhina Cândido (1); Roberto Lamberts (2), Leonardo Bittencourt (3) e Richard de Dear (4)

(1) Arquiteta, Doutoranda do PPGEC/UFSC e Macquarie University, christhina@labeee.ufsc.br
(2) PhD, Professor do Departamento de Engenharia Civil, lamberts@ecv.ufsc.br
(3) PhD, Professor do Departamento de Arquitetura e Urbanismo, lsb@ctec.ufal.br
(4) PhD, Professor Department of Architecture, Design and Planning, r.dedear@arch.usyd.edu.au
(1), (2), Universidade Federal de Santa Catarina, Departamento de Engenharia Civil, Laboratório de Eficiência Energética em Edificações, Caixa Postal 476, Florianópolis - SC, 88040-900; (3) Universidade Federal de Alagoas, Maceió/AL; (4) The University of Sydney, Sydney, Austrália

RESUMO

Um dos principais argumentos utilizados para a adoção de limites para a velocidade do ar nos ambientes construídos advém do conceito de que a ocorrência de "correntes de ar" (*draft*) seria desagradável para os usuários desses espaços. Esse desconforto sentido pelo usuário seria decorrente da velocidade do ar e serve como referência para estabelecer os limites máximos da velocidade do ar na ASHRAE 55 (2004) e ISO 7730 (2005). O mesmo incremento do movimento do ar é percebido de maneira diferente pelos usuários em climas frios e em climas quentes, podendo ser classificado como incômodo ou uma agradável brisa. Este trabalho discute os limites dados para a velocidade do ar pelas normas ASHRAE 55 (2004) e ISO 7730 (2005). Para tal, foi realizada uma análise comparativa entre os valores limites para a velocidade do ar definidos por essas normas e as respostas dos usuários em relação à preferência e aceitabilidade do movimento do ar obtidas em experimentos de campo realizados em Maceió/AL. Resultados indicam que ambas as normas especificam valores para a velocidade do ar *inferiores* aos desejados pelos usuários. Os resultados da preferência do movimento do ar indicam que significativa percentagem dos usuários demanda "maior movimento do ar". Quando associada às respostas da aceitabilidade do movimento do ar, a insatisfação dos usuários ficou mais evidente, assim como a demanda por maior velocidade do ar. O desconforto por correntes de ar não se apresenta como desconforto para os usuários destes ambientes. Valores mais elevados para a avelocidade do ar são desejáveis para para o conforto térmico dos usuários.

Palavras-chave: velocidade do ar, *draft*, conforto térmico.

ABSTRACT

One of the main arguments applied in order to establish air velocity limits inside buildings is related to the draft concept, which means an unpleasant air movement into indoor environments. This concept is considered as reference in order to identify maximum air velocity values into broadly used standards such as ASHRAE 55 (2004) and ISO 7730 (2005). However, air movement improvement inside buildings can be noticed in different perspectives from subjects in cold and warm climates and, therefore, the same air velocity can be classified as unpleasant (draft) or pleasant breeze. This paper discusses the air velocity limits specified into ASHRAE 55 (2004) and ISO 7730 (2005). A comparative analysis was developed between these standardized air velocity limits and subjects' answers for air movement preferences and acceptability from field experiments carried out in Maceio city. Results suggest that air velocity limits into standards are lower than those required from the subjects. Results indicate that a significant percentage of the subjects demand for "more air movement". When those results were combined with air movement acceptability, the number of unsatisfied subjects increased, as well as the demand for higher air velocity levels. Draft is not a risk inside these environments. Therefore higher air velocity levels are desirable in order to improve subjects' thermal comfort conditions.

Keywords: air velocity, draft risk, thermal comfort.

1. INTRODUÇÃO

Um dos principais argumentos utilizados para a adoção de limites para a velocidade do ar nos ambientes construídos advém do conceito de que a ocorrência de 'correntes de ar' provocaria um certo incômodo nos usuários desses espaços. Essas 'correntes de ar' (*draft*) seriam a causa do desconforto sentido pelo usuário em decorrência do aumento do movimento do ar (ASHRAE, 2004); sendo intrinsicamente relacionado à temperatura e velocidade do ar, mas também por fatores complementares, tais como a intensidade de turbulência e à área do corpo que está exposta (MCINTYRE, 1978). Tal conceito foi desenvolvido baseado em experimentos realizados em câmaras climáticas, com usuários engajados em atividades sedentárias e utilizando vestimenta leve. A equação resultante é utilizada para estimar o percentual de usuários insatisfeitos devido à existência de *draft* e serve como referência para os limites considerados como máximos para a ASHRAE 55 (2004) e ISO 7730 (2005), ver [Equação 1. O percentual de insatisfação dos usuários preditos pela [Equação 1 são válidos para condições onde a temperatura do ar varie entre 20 e 26°C, com velocidade média entre 0.05 e 0.40m/s e intensidade da turbulência menores que 70%.

$$DR = (34 - t_a) \times (\bar{v} - 0.05)^{0.62} \times (0.37 \times \bar{v} \times Tu + 3.14)(\%) \qquad \text{[Equação 1]}$$
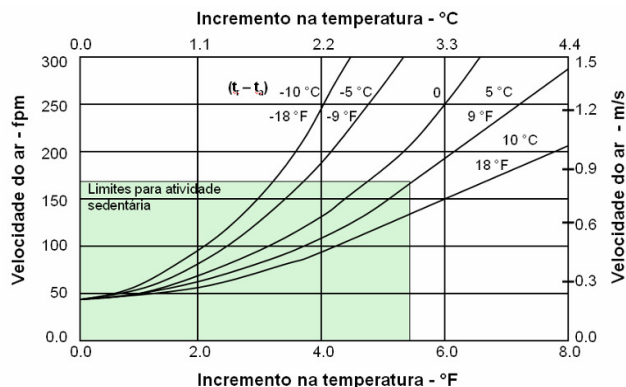
Onde:

$\bar{v}$ velocidade do ar média [m/s]

t_a temperatura do ar [°C]

Tu intensidade de turbulência [%]

Na ASHRAE 55 (2004), os limites para a velocidade do ar podem ser obtidos de duas formas. A primeira utiliza a [Equação 1 como referência para os limites da velocidade do ar, sendo aplicável para os ambientes de forma geral. A norma ainda considera o desconforto por correntes de ar como um dos itens relacionados ao desconforto térmico local que, por sua vez, também é relacionado à determinação das condições de aceitabilidade térmica do ambiente. De acordo com este item, o percentual de usuários insatisfeitos devido ao desconforto provocado por correntes de ar não poderá ser maior que 20%. A segunda forma de obtenção dos valores máximos para a velocidade do ar é tratada especificamente para os casos onde o incremento da do movimento do ar é desejado e quando os usuários têm o controle dos mecanismos de ventilação. Neste caso, o limite máximo para a velocidade do ar é obtida pelo cruzamento dos valores do incremento da temperatura do ar e os valores da diferença entre a temperatura radiante e a temperatura do ar, ver Figura 1A. Apesar da escala apresentar valores entre 0 e 1.50m/s, a norma explicita que a velocidade não deverá exceder 0.80m/s e que o ajuste permitido aos usuários não deve ser superior à 0.15m/s.

Na ISO 7730 (2005), os limites máximos para a velocidade do ar também se baseiam na [Equação 1. De forma complementar, essa norma apresenta o gráfico da Figura 1B que informa o limite da velocidade do ar em função dos valores da temperatura do ar e da intensidade de turbulência. Como resultado, pode-se obter valores para a velocidade do ar considerando um máximo de 15% de insatisfação dos usuários. Os valores da velocidade do ar variam entre 0 e 0.4m/s, para temperaturas do ar entre 18 e 26°C e turbulência oscilando entre 0 e 60%.

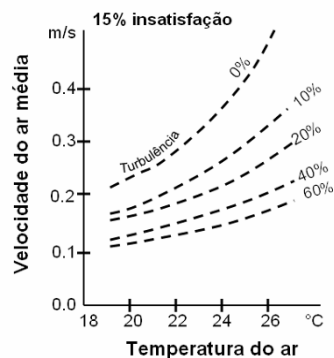(A)   (B)

Figura 1 – Gráficos para determinação dos valores da velocidade do ar de acordo com a (A) ASHRAE 55 (2004) e (B) ISO 7730 (2005).

A aplicabilidade de tais limites, no entanto, vêm sendo questionada por experimentos desenvolvidos em ambientes reais, onde os usuários têm o controle dos mecanismos de ventilação (ARENS et al, 1998, YANG e ZHANG, 2008, ZHANG et al, 2007 a). Resultados indicam que, em ambientes onde a ventilação natural é utilizada como a principal forma de condicionamento ambiental (ou até mesmo quando esta é combinada com sistemas de condicionamento artificial, como é o caso de edifícios híbridos), os usuários tendem a indicar frequentemente preferência por "maior movimento do ar" (ZHANG et al, 2007 b).

O mesmo incremento do movimento do ar em climas frios e em climas quentes é percebido de maneira diferente pelos usuários, podendo ser uma incômoda corrente de ar (*draft*) ou uma agradável brisa. Tal percepção pode ser explicada fisiologicamente pelo fato dos termoreceptores para frio estarem localizados mais superficialmente na pele que os de calor (de DEAR, 2009). Neste mesmo ponto de vista fisiológico, a diferença na percepção do mesmo movimento do ar pode ser explicada pelo conceito de *alliesthesia* (CABANAC, 1971). Segundo esse conceito, o estímulo causado no ambiente pode ser positivo ou negativo, dependendo de como o mesmo auxilia ou dificulta no reestabelecimento (*alliesthesia positiva)* ou afastamento (*alliesthesia negativa)* do conforto do usuário (de DEAR, 2009). Desta forma, os ambientes que utilizam a ventilação natural como estratégia de condicionamento oferecem este estímulo positivo e as flutuações do movimento e velocidade do ar podem ser não só bem aceitas, mas desejadas pelos usuários. Em climas quentes e úmidos, o uso de limites para velocidade do ar baseados em estudos com realidades climáticas diferentes pode resultar em significativa disparidade na *aceitabilidade e preferência* dos usuários no que se refere à intensidade do movimento do ar. Nesse sentido, estudos que comparem tais valores máximos da velocidade do ar com os resultados da preferência e aceitabilidade do movimento de ar dos usuários se constituem em importante contribuição para essa área de conhecimento.

2. OBJETIVO

Este trabalho tem como objetivo comparar os limites estabelecidos para a velocidade do ar, pelas normas ASHRAE 55 (2004) e ISO 7730 (2005), com os resultados de preferência e aceitabilidade do movimento do ar obtidos em experimentos de campo no clima quente e úmido de Maceió/AL.

3. MÉTODO

Este trabalho desenvolve uma análise comparativa entre os valores definidos como velocidade do ar pelas normas ASHRAE 55 e ISO 7730, com os resultados obtidos em experimentos de campo em relação à preferência e aceitabilidade do movimento do ar.

Os experimentos de campo foram desenvolvidos em salas de aula e ateliês de desenho do curso de arquitetura e urbanismo da Universidade Federal de Alagoas e do Centro de Estudos Superiores de Maceió. Os ambientes utilizam a ventilação natural como estratégia principal de condicionamento térmico, sendo esta complementada pelo uso de ventiladores de teto. O estudo foi conduzido durante duas semanas nos meses de verão e inverno nos períodos da manhã, tarde e noite, resultando em 2075 questionários respondidos pelos ocupantes de tais ambientes.

A faixa etária dos usuários oscilou entre 18 e 25 anos e a maioria dos entrevistados do sexo feminino (66%). As atividades desenvolvidas foram sedentárias e variavam entre 70 e 93W/m², visto que os usuários encontravam-se sentados escrevendo ou desenhando, ou em pé e desenhando. A vestimenta utilizada foi como leve, em média, considerando-se os valores de 0,30 clo, para o verão, e 0,70 clo, para o inverno, conforme classificação da ASHRAE Standard 55 (2004). As atividades dos alunos não foram interrompidas, visando caracterizar a utilização real dos ambientes. Da mesma forma, foi permitido o uso de ventiladores de teto, acionamento de lâmpadas e controle das aberturas (fechar ou abrir portas e janelas).

As variáveis ambientais foram registradas com o confortímetro Babuc A, localizado no centro das salas, seguindo as especificações da ISO. Tal equipamento serviu para registrar os valores da temperatura do ar, umidade e velocidade do ar. Baseado em tais valores, pode-se calcular as variáveis derivadas (temperatura operativa, temperatura radiante média, etc) assim como índices como *draft risk*, *PS model*, etc. Para o cálculo das variáveis que compunham esses índices, foi utilizado o programa WinComf[©] (Fountain and Huizenga, 1996), sendo possível obter os valores para a temperatura efetiva (ET), nova temperatura efetiva (SET), *two-node temperature sensation index* (TSENS), *two-node discomfort index* (DISC), voto estimado médio (PMV) e percentual de pessoas insatisfeitas (PPD).

Sendo a velocidade do ar o foco central deste trabalho, esta foi registrada de forma individualizada e simultânea ao preenchimento dos questionários de aceitabilidade térmica e ambiental pelos usuários. Para tal, foi utilizado um termoanemômetro portátil e bastões de fumaça para o registro da velocidade do ar e direção predominante do fluxo de ar, respectivamente.

O questionário baseia-se no modelo adotado por de Dear e Brager (2002)[1] e foi adaptado para o desenvolvimento deste trabalho de acordo com as necessidades do mesmo. O questionário de aceitabilidade térmica e ambiental incluiu questões relativas ao conforto térmico dos usuários, aceitabilidade e preferência térmica, a preferência e a aceitabilidade do movimento do ar, assim como informações dos usuários (tais como altura, idade, vestimenta, atividade). Os questionários foram associados com a posição específica do usuário no ambiente (próximo às janelas ou no fundo da sala, por exemplo) no momento do seu preenchimento facilitando a posterior análise individualizada dos resultados.

Todas as informações relacionadas ao experimento, tais como os ambientes, usuários, respostas dos usuários, variáveis ambientais, derivadas e calculadas foram agrupadas em um banco de dados. Posterior tratamento estatístico aplicado foi desenvolvido com o software SAS©, permitindo o refinamento das análises dos dados obtidos.

4. ANÁLISE DE RESULTADOS

Os valores da velocidade do ar foram obtidos graficamente, tendo como referência as Figura 1A e 1B. Para viabilizar uma análise comparativa, os dados obtidos nos experimentos foram organizados de acordo com as especificações e limitações de cada norma para os valores das variáveis utilizadas, tais como temperatura do ar, temperatura operativa e intensidade de turbulência. A Tabela 1 sumariza os resultados obtidos para os valores da velocidade do ar de acordo com as especificações das duas normas. Tendo como referência os valores da velocidade do ar, foram analisadas as respostas dadas pelos usuários para a preferência e aceitablidade do movimento do ar.

Tendo com referência o gráfico da ASHRAE, os valores para a velocidade do ar variaram entre 0.30 e 1.20m/s. No entanto, nessa norma, a velocidade de 0.80 m/s é considerada como sendo o limite máximo aceitável. Por esse motivo, embora o valor de 1.20 m/s conste do gráfico da Figura 1, o valor máximo adotado para a velocidade do foi de 0.80m/s. Considerando as especificações da ISO 7730, os valores resultantes para a velocidade do ar variaram entre 0.15 e 0.20m/s.

Tabela 1 – Valores da velocidade do ar obtidos de acordo com as especificações da ASHRAE 55 (2004) e ISO 7730 (2005).

	Temperatura radiante – temperatura do ar (°C)	Incremento na temperatura (°C)	Velocidade do ar recomendada (m/s)
ASHRAE 55	tr-ta = 1	1.1	0.3
		2.2	0.6
		3.3	0.80
	tr-ta = 0	1.1	0.3
		2.2	0.6
		3.3	0.80
	Temperatura do ar (°C)	**Turbulência (%)**	**Velocidade do ar recomendada (m/s)**
ISO 7730	24	40	0.2
		60	0.2
	26	40	0.2
		60	0.15

A Figura 2 A sumariza a distribuição de freqüência para os resultados da preferência do movimento do ar, tendo como referência as especificações da ASHRAE. Os usuários classificaram a preferência do movimento do ar de acordo com três possíveis respostas: "maior movimento do ar", "assim mesmo" ou "menor movimento do ar". De forma geral, as respostas se concentraram nas opções "assim mesmo" e "maior movimento do ar".

Os resultados foram separados em duas categorias dependendo do valor resultante da diferença entre a temperatura radiante e a do ar (ver Figura 1A). Quando esta diferença foi de 1°C, o percentual de usuários requisitando "maior movimento do ar, variou de 30 e 5% para velocidade do ar de 0.30 e 0.80m/s, respectivamente. Neste mesmo grupo (tr - ta = 1°C), a significativa maioria dos usuários indicou "assim mesmo" como preferência do movimento do ar, correspondendo a 68, 69 e 83%, para os respectivos valores da velocidade do ar: 0.30, 0.60 e 0.80m/s.

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[1] O questionário se baseia no modelo utilizado por deDear e Brager (1998) no desenvolvimento do projeto da ASHRAE (Adaptive comfort project - model ASHRAE Project RP 884).

Quando a diferença entre temperatura radiante e do ar foi anulada (tr - ta = 0°C), o percentual de usuários pedindo "maior movimento do ar" variou entre 78 e 42%, para as velocidades de 0.30 e 0.80m/s. Neste caso, o percentual de usuários indicando "assim mesmo" como preferência para o movimento do ar aumentou em função do incremento da velocidade do ar, variando entre 20 e 58%. Nota-se que o percentual máximo de usuários indicando preferência por "menor movimento do ar" foi significativamente inferior às outras duas opções, não ultrapassando 10% das respostas em todos os casos.

A Figura 2B sumariza os resultados para a preferência do movimento de ar tendo como referência a ISO 7730. Neste caso os dados que delinearam a identificação dos valores da velocidade do ar incluem a temperatura do ar e a intensidade da turbulência (Tu). Cruzando tais dados com os obtidos nos experimentos, a análise incluiu as ocorrências onde a temperatura do ar situava-se entre 24 e 26°C e os valores da turbulência de 40 e 60%.

Para a temperatura de ar de 24°C, o percentual de usuários demandando "maior movimento do ar" foi de 20% para turbulência de 40% e de 25% para turbulência de 60%. No restante da amostra os usuários indicaram "assim mesmo" como preferência do movimento do ar em 80% e 75% dos casos (para Tu = 40% e 60%, respectivamente).
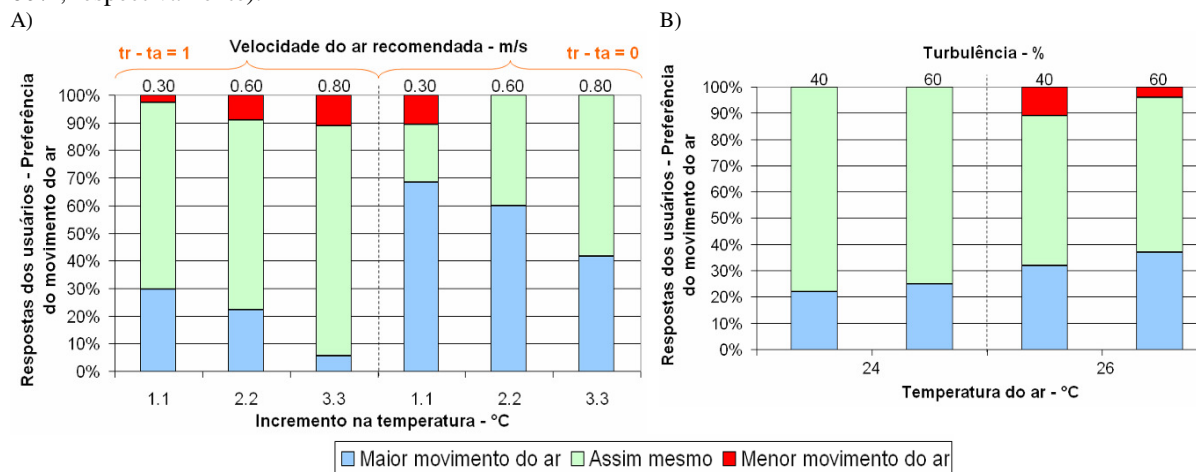

Figura 2 – Preferência do movimento do ar tendo como referência as especificações da ASHRAE 55 (A) e ISO 7730 (B).

As duas normas especificam valores referência para o percentual de insatisfação dos usuários relativo ao movimento do ar. A ASHRAE considera 20% como o valor máximo para a insatisfação dos usuários decorrente do excessivo movimento de ar (ou *draft*). Já na ISO 7730 o percentual de insatisfação dos usuários é levemente inferior, de 15%. Assumindo-se que os usuários que declaram preferência por "maior ou menor movimento do ar" como insatisfeitos, nota-se que as normas definem velocidades do ar inferiores aos desejados pelos usuários. Ao analisar a distribuição das preferências do movimento do ar, observa-se que o maior percentual de insatisfação dos usuários foi relacionado à necessidade de maior movimento do ar e que os usuários demandando menor movimento do ar foi significativamente inferior.

Ao se combinar esta análise de preferência com a *aceitabilidade* do movimento de ar, os resultados são ainda mais expressivos. Os usuários entrevistados podiam classificar o movimento do ar como aceitável ou inaceitável e depois fornecer informações específicas sobre a velocidade do ar. As respostas foram agrupadas em uma escala que varia entre -1 e 1 e pode ser vista na Tabela 2. Para esta análise, foram consideradas as três respostas dos usuários para o movimento do ar *aceitável,* visto que não foram registrados votos para as duas categorias de *inaceitável* nas faixas limítrofes para a temperatura e turbulência utilizadas por ambas as normas.

Tabela 2 – Escala para a aceitabilidade do movimento de ar.

-2	-1	0	1	2
Inaceitável	Aceitável			Inaceitável
devido à baixa velocidade do ar	mas com baixa velocidade do ar	velocidade do ar suficiente	mas com alta velocidade do ar	devido à alta velocidade do ar

As Figura 3A e 4B sumarizam os resultados para as três diferentes respostas dos usuários que consideraram a velocidade do ar aceitável. Assim como para a preferência do movimento do ar, os resultados

foram separados em duas categorias dependendo do valor resultante da diferença entre a temperatura radiante e a do ar. Quando esta diferença foi de 1°C, e velocidade do ar de 0.30m/s, 47% dos usuários indicaram movimento aceitável, mas com baixa velocidade do ar e os 53% restantes indicaram movimento do ar aceitável, com velocidade suficiente. Nas duas demais faixas de velocidade do ar, de 0.60 e 0.80m/s, as respostas foram para velocidade do ar suficiente. Em nenhuma das faixas de velocidade os usuários indicaram movimento do ar aceitável, mas com alta velocidade.

Quando a diferença entre a temperatura radiante e a temperatura do ar foi nula, aproximadamente 90% dos usuários indicaram velocidade do ar aceitável, mas com baixa velocidade do ar, para a velocidade de 0.30m/s. Com o incremento da velocidade do ar para 0.60m/s e 0.80m/s, o percentual de usuários indicando tal resposta diminuiu para 42% e 50%, respectivamente. Nota-se que para velocidades de 0.80m/s apenas 11% dos usuários indicaram movimento do ar aceitável, mas com alta velocidade do ar .

Utilizando o gráfico da ISO 7730 como referência, os valores para a aceitabilidade foram de no mínimo de 30% e máximo de 50% para movimento do ar aceitável, mas com baixa velocidade do ar. O restante das respostas foi para movimento do ar aceitável e velocidade do ar suficiente e não houve registro de respostas para movimento do ar aceitável, mas com alta velocidade do ar.
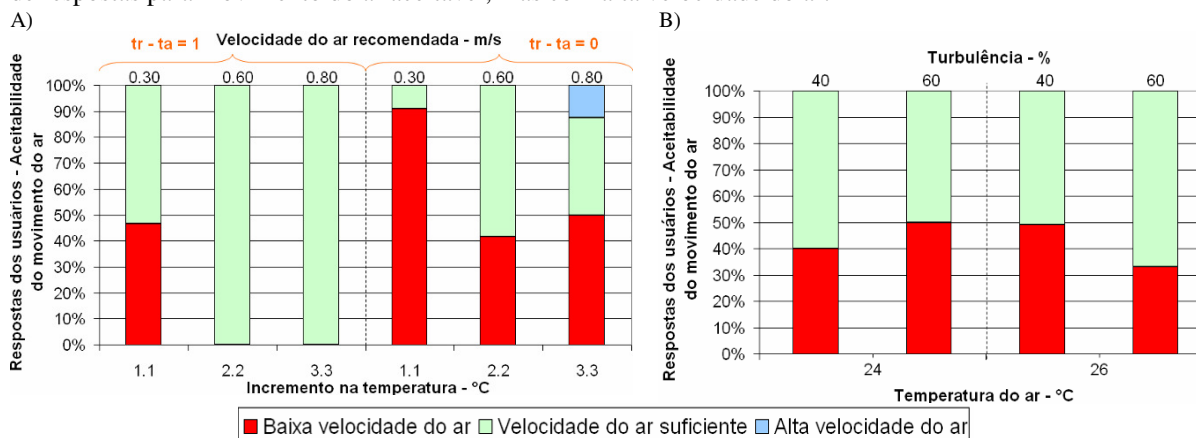

Figura 3 – Aceitabilidade do movimento do ar tendo como referência as especificações da ASHRAE 55 (A) e ISO 7730 (B).

5. CONCLUSÕES

Este artigo teve como objetivo investigar a aplicabilidade dos limites dados para a velocidade do ar pelas normas ASHRAE 55 (2004) e ISO 7730 (2005) com os resultados de preferência e aceitabilidade do movimento do ar obtidos em experimentos de campo no clima quente e úmido de Maceió/AL.

Resultados indicam que ambas as normas especificam valores para a velocidade do ar inferiores aos desejados pelos usuários dos ambientes aqui investigados. Os resultados para a preferência do movimento do ar indicam que significativa percentagem dos usuários demanda "maior movimento do ar", sendo os valores para "menor velocidade do ar" bastante inferiores. Considerando-se que em ambos os cenários das normas os usuários estão na zona de conforto, a demanda por maior velocidade do ar sugere uma dependência dessa estratégia que pode ir além do re-estabelecimento do balanço térmico em si. Quando associada às respostas da aceitabilidade do movimento do ar, a insatisfação dos usuários ficou mais evidente, indicando a demanda por maior velocidade do ar do que a especificada pelas normas.

Os limites dados por estas normas, quando comparados com experimentos desenvolvimentos tendem a superestimar a insatisfação dos usuários dada pelo incremento do movimento do ar no interior dos ambientes construído. Tal fato se deve, em parte, à *aceitabilidade* de valores de velocidade do ar pelos usuários mais elevados que os especificados por tais normas. Os conceitos de preferência e de aceitabilidade do movimento do ar, no entanto, são fortemente relacionados às questões subjetivas dos usuários, principalmente à tolerância de valores mais altos e da adaptação às flutuações de tais valores, assim como ocorre para a temperatura do ar. O incremento do movimento do ar demandado pelos usuários pode ser associado ao estímulo ou *alliesthesia positiva*, auxiliando no restabelecimento do conforto do usuário. É importante destacar que os usuários possuíam o controle dos mecanismos de incremento do movimento do ar, tais como janelas e ventiladores, sendo este um item de essencial importância no processo de intensificação do movimento do ar nos ambientes.

O estímulo causado pelas flutuações do movimento do ar parece ser desejado pelo usuário por questões subjetivas e essencialmente individuais. Os valores máximos dados pelas normas aqui utilizadas

como referência não contemplam tais questões, permitindo maiores percentuais de insatisfação pelo movimento do ar *insuficiente* e não o *excessivo*. Futuras normas para contexto brasileiro devem considerar tais aspectos e mais experimentos de campos são indubitavelmente necessários para tal. *Draft* não parece ser um risco nem, portanto, uma limitação, para o incremento do movimento do ar nos ambientes aqui investigados.

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Appendix E

Natural ventilation and thermal comfort: air movement acceptability inside naturally ventilated buildings in Brazilian hot humid zone.

Conference Paper: 2008 Windsor Conference - Air Conditioning and the Low Carbon Cooling Challenge.

Natural ventilation and thermal comfort: air movement acceptability inside naturally ventilated buildings in Brazilian hot humid zone

Christhina Cândido[1,2*], Richard de Dear[2], Roberto Lamberts[1] and Leonardo Bittencourt[3]

[1]Federal University of Santa Catarina, Florianópolis/SC -Brasil
[2]Macquarie University, Sydney - Australia
[3]Federal University of Alagoas, Maceió/AL - Brasil

[*]*Corresponding email:* chrismcandido@yahoo.com

Summary

The literature on thermal comfort indicates that acceptable indoor air speed in warm climates should range from 0.2 to 1.50 m/s; yet 0.2 m/s has been deemed in ASHRAE Standard 55 to be the threshold of draft perception (i.e. not acceptable) inside air-conditioned buildings where occupants have no direct control over their environment. However, these air velocity ranges have not explicitly addressed air movement *acceptability*, but have focused mainly on overall thermal sensation and comfort. A large percentage of Brazil is classified as having a hot and humid climate. In such regions, natural ventilation combined with solar protection, is the most efficient building design strategy to achieve thermal comfort without resorting to mechanical cooling. The present research project aims to investigate the relation between air movement acceptability and thermal comfort inside buildings in the north-east of Brazil. The investigation has been developed using university buildings in Maceio city. Questionnaires relating to thermal acceptability were given whilst measurements (air velocity, air temperature, radiant air temperature and humidity), were simultaneously taken inside classrooms. Results indicated that at operative temperatures above 24°C, building occupants preferred mean air speeds up to 1m/s. It was also observed that complaints of draft did not occur in significant numbers until air speeds exceeded 1m/s.

Keywords
Air movement acceptability, air velocity, natural ventilation, thermal comfort, hot humid climate.

Introduction
Human perception of air movement depends on environmental factors such as air velocity, air velocity fluctuations, air temperature, and personal factors such as overall thermal sensation, clothing insulation and physical activity level (metabolic rate) (Toftum, 2004). Air velocity affects both convective and evaporative heat losses from the human body, and thus determines thermal comfort conditions (Tanabe, 1988; Mallick, 1996).

If we agree that thermal environments that are slightly warmer then preferred or neutral, can be still acceptable to building occupants (as the adaptive comfort model suggests (deDear, Brager, 2002; Nicol, 2004), 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, so body temperatures will be restored to their

comfort set-points. This hypothesis can be deduced from the physiological principle of *alliesthesia* (Cabanac, 1971).

In hot and humid climates, elevated indoor air velocity increases the indoor temperature that building occupants find most comfortable. Nevertheless, the distribution of air velocities measured during these field studies was skewed towards rather low values. Many previous studies have attempted to define when and where air movement is either desirable or not desirable (i.e. draft) (Mallick, 1996; Santamouris, 2003). 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 to be the threshold upper limit of draft perception allowed inside air-conditioned buildings where occupants have no direct control over their environment (de Dear, 2004) The new standard 55 is based on Fanger's (1988) draft risk formula, which has an even lower limit in practice than 0.2 m/s. None of the previous research explicitly addressed air movement acceptability, instead focusing mostly on overall thermal sensation and comfort (Toftum, 2004).

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. This research is focused on the relationship between air movement acceptability and thermal comfort, inside naturally ventilated buildings in the north-east of Brazil (Maceió city). The research aims to explore the reasons behind occupants' air movement preferences and assessment of acceptability.

Method
The method adopted for this work is based on the analysis of the relationship between air movement acceptability and thermal comfort inside naturally ventilated buildings located in the north-east of Brazil. The rooms chosen for the measurement are part of the Federal University of Alagoas-UFAL and the Center of Superior Studies of Alagoas-CESMAC. The research field was developed during the winter period.

1.   Climate characteristics – Maceió city
Maceió is located on the north-east sea coast of Brazil (latitude 9º40' to the south of the Equator and longitude 35º42' to the west of the meridian 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 (Cabús, 2005). As a consequence, Maceió constitutes an example of thermal constancy typical of the north-east coast of Brazil. It presents small daily temperature amplitude and also small annual temperature variations. The seasons are divided into just two: winter and summer, although the "winter" remains warmer than many mid-latitude climate zone's summers. The summer season is characterized by high air temperatures and little rainfall, despite the persistently high humidity. The winter season is characterized by high rainfall and low temperatures. The annual average 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 coldest days occur from June to August (CABÚS, 2005).

The relative humidity average is around 78% during Summer and 84% during winter. However, it is possible to encounter a saturation point (100%) during colder, rainier periods. The annual average rainfall is around 1654 mm and the typical rain season occurs from April to July. Maceió is under the influence of the south-east and north-east trade winds. The south-east winds have a moderate main speed and occur in most months of the year (March to

December). The north-east winds present relatively higher speeds and occur during the hot season (mainly January, February and March.

2. *Measurement rooms*
The following criteria for the research measurements were used, when choosing the indoor environments for this study: windows had to be easy to access and operate; rooms could not have a mechanical cooling system (refrigerated air-conditioning); rooms could have mechanical ventilation with unconditioned air (fans); 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 able to freely adapt their clothing to the indoor and/or outdoor thermal conditions.

The buildings of the Federal University of Alagoas – UFAL and the Center of Superior Studies of Alagoas – CESMAC fitted these selection criteria. The monitored rooms were classrooms which were also used for drawing activities (design studies), Figure 1. In addition, the buildings presented large open spaces and natural ventilation was intentionally the main cooling strategy. In both buildings, the open spaces were easily controlled collectively by the occupants and ceiling fans provided supplemental air movement inside the rooms.
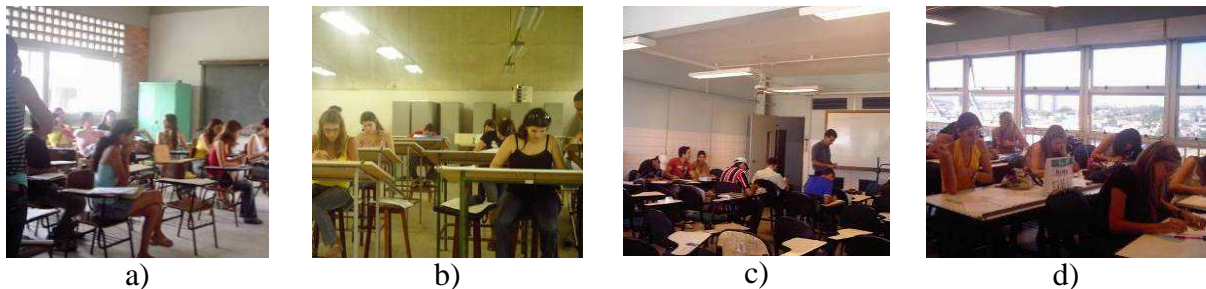

| a) | b) | c) | d) |

Figure 1 – Classrooms (a), design rooms (b) at Federal University of Alagoas (a,b) and – UFAL at Centre of Superior Studies of Alagoas (c, d).

3. *Subjects*
The field research included 232 subjects during the winter survey in August and September, 2007, and that period corresponds to the first phase of this work. A second phase was developed during February and March, 2008 but the results will not be reported in this paper.

The data were organized in order to understand the subjects' profiles including individual characteristics such as gender, age, weight and height. As a consequence, it is possible to identify a non uniform distribution between the number of female and male subjects (66% and 34%, respectively), Figure 2. In relation to the subjects' ages, a variation between the ages of 17 and 27 years was noted.
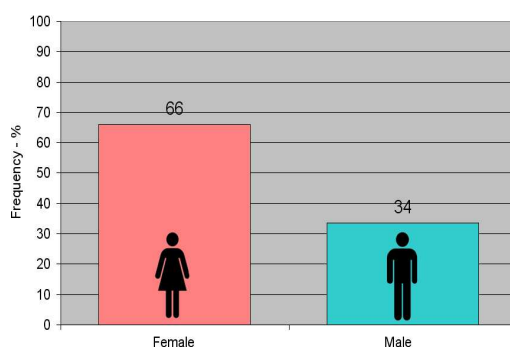

Figure 2 – Subjects' gender distribution.

Figure 3 – Subjects' age distribution.

The 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, Figure 4 a and b. The clothes were light - around 0,30clo for summer and 0,70clo for winter, Figure 4 c and d, as estimated from clothing garment check-lists in ASHRAE Standard 55 (2004).

| a) | b) | c) | d) |

Figure 4– Subjects' activities: classroom (a) and design room (b) and Subjects' typical clothes: "winter"season (c) and "summer"season (d).

4.   *Measurement equipment*

In order to measure the ambient variables, this research used specific instruments such as a microclimatic station (Babuc), hot wire anemometer and a superficial 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, the psychrometer (dry and wet-bulb temperatures) and the hot wire anemometer, Figure 5 a.
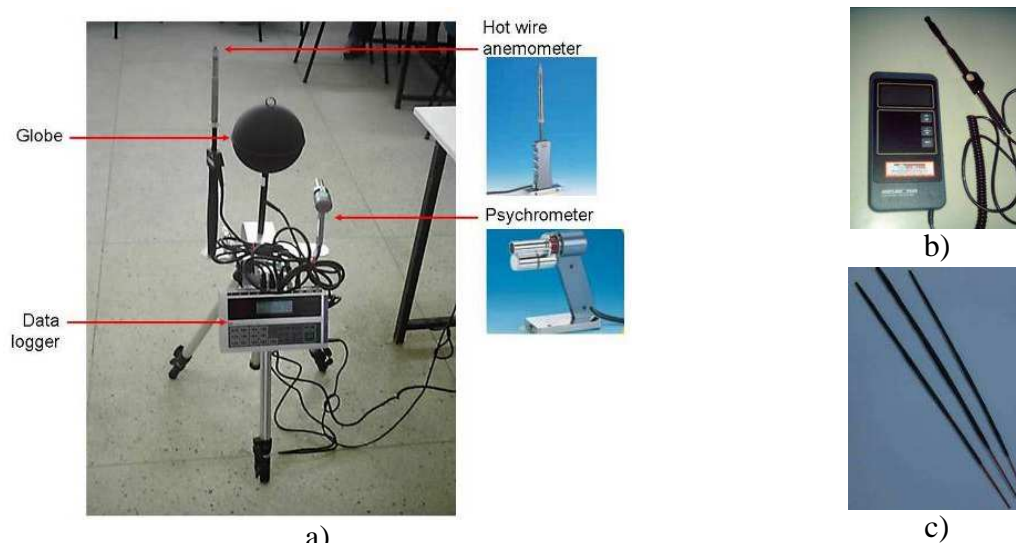

Figure 5 – Microclimatic station – Babuc (a), Hotwire anemometer (b) and Smoke stick (c)

In order to register more details related to the room, some portable equipment was used such an infra-red radiometer, hot wire anemometer and smoke sticks. For the measurements of the air speed around the participants hot wire anemometers were used. The equipment was portable, and had hot wire sensor (Airflow Developments, model TA35), Figure 5 b. The measurement band 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. The portable hot wire anemometer was a unidirectional type, so smoke sticks were used to discern the predominant airflow before the anemometer was positioned measurement position, Figure 5 c.

5. Measurement procedures

The method adopted for this research combined the indoor climate data with simultaneous questionnaires filled in by occupants of naturally ventilated spaces. In order to achieve this, indoor microclimatic measurements and questionnaires focused on thermal comfort and thermal acceptability were used inside the buildings.

a. Indoor climate

Measurements included the morning and afternoon periods, for at least two hours in each period. The subjects' activities were not interrupted in order to characterize the typical use of rooms, and they were also allowed to 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 it was 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 inside the project rooms. The measurements recorded were average of at five minutes for air speed also for the other variables (globe temperature, air temperature and humidity).

The measurement of the air speed which was in close proximity to the subjects occurred simultaneously whilst they filled out the questionnaire. For each user, the hot wire anemometer was located near to them and at the same work plan height. The hot wire anemometer was oriented according to the dominant flow direction indicated by the smoke sticks. Based on the air velocity's standard deviation it was possible to analyze the turbulence intensity.

b. Questionnaire

The questionnaire[1] aims to characterize the thermal comfort answers and also to identify the subjects' air speed and air movement acceptability. The questionnaire was presented in three parts.

The first part corresponded to the subjects' personal information such as age, height, weight and gender. The second part included questions relating to thermal comfort, air movement acceptability and also the pattern of their air-conditioning usage. In the thermal comfort part, the subjects are asked about their own thermal comfort situation, their personal preferences and also about the room itself. The air movement part was essential in order to identify the subjects' air movement acceptability and preferences. In that case, they had to indicate their air movement acceptability as it related to the air velocity and constancy. In addition, they had to indicate their preferences for a more or less dynamic air movement in order to understand their relationship with air fluctuations inside the room. The third, and last part, related to the subjects' activities that were performed during the measurement process. This part also included the information about the subjects' clothing. The subjects started answering the questionnaire at least half hour after had they arrived in the room in order to avoid any influence of their previous activities. Each subject was questionnaired on five separate occasions.

Results

The percentage of subjects who indicated that they were "neutral" represented more than 45% for all registered operative temperatures. At least 18% of users reported that they were "slightly cool" and "slightly warm" for 10% of the cases, *Figure 6*. Only 3% all subjects

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[1] The questionnaire is based on that used by deDear & Brager(1998), for the development of the ASHRAE adaptive comfort project (model ASHRAE Project RP 884).

indicated that they were "cold" or "hot". In addition, the subjects who wanted to be "cooler" represented between 18 and 32%, and an even smaller group of subjects preferred to be "warmer" (10%), Figure 7.
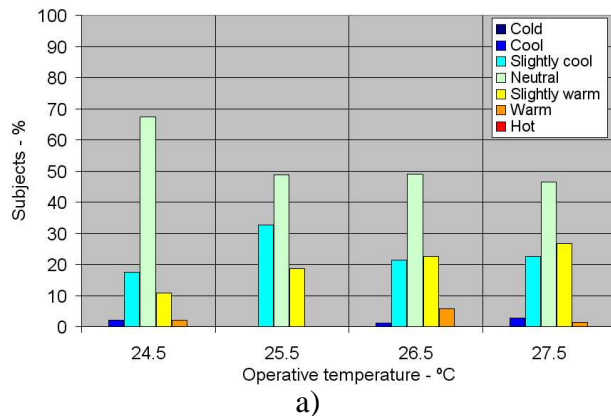

a)

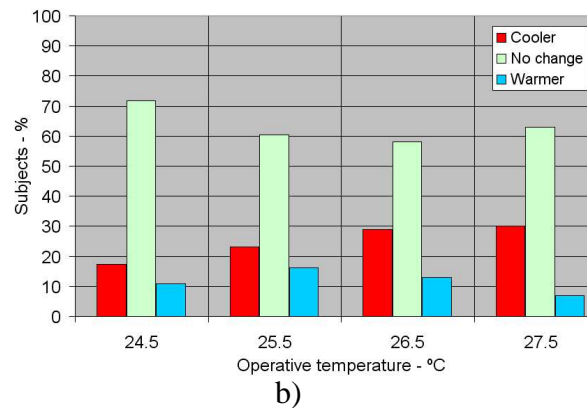*Figure 6 – Subjects' answers for thermal sensation and operative temperature.*

b)

Figure 7 – Subjects' answers for thermal preference and operative temperature.

For all operative temperatures and for the air speed average of up to 0.25 m/s, at least 22% of the subjects indicated that they preferred "more air movement" whilst another 40% of the subjects preferred "no change" while only 5% of the subjects indicated that they preferred "less air movement", *Figure 8*a. The higher demand for "more air movement" appeared for the operative temperature of 25.5° C while the minimal register occurred for the operative temperature of 27.5° C. This result relates to the design activity development inside the rooms (operative temperature 27.5° C).

For air speeds ranging between 0.25 m/s and 0,50m/s and all operative temperatures, 8% of the subjects indicated that they preferred "more air movement" while 60% preferred "no change" and 8% of the subjects indicated that they preferred "less air movement", Figure 8 b. There is a higher occurrence of preference for "more air movement" for the operative temperature of 26.5 °C and 27.5°C. In addition, it is possible to identify the preference for less air movement only for operative temperatures of 25.5 ° C and 27.5 ° C. For the operative temperature of 27.5°C, the demand for "less air movement" can be explained by the range of design activities especially when futher increasing air speed would cause paper to fly around the rooms. Moreover, it was observed that this problem could be controlled by the constant regulation of fans and the closing/opening of the windows, depending on the subjects' desire for more or less air movement.
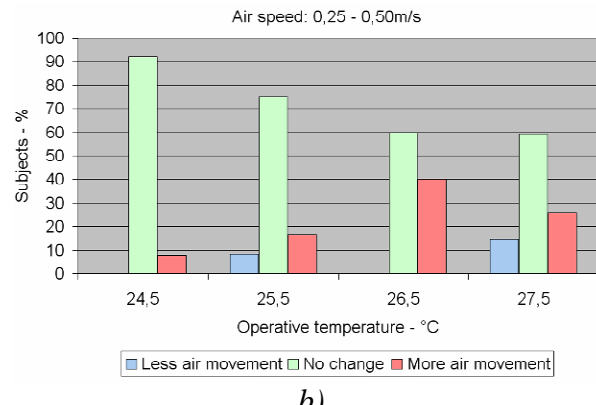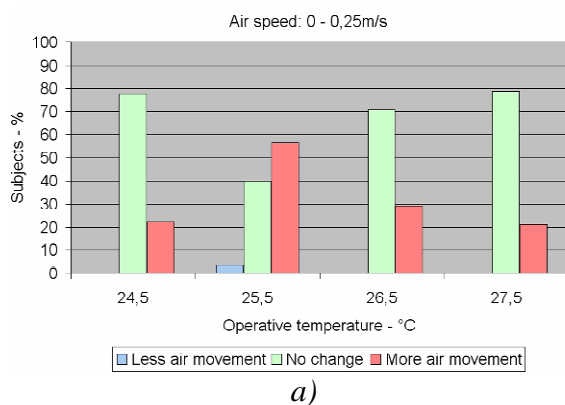

a)

b)

Figure 8 – Subjects' answers for air movement preference and operative temperature: air velocity range: (a) 0 -0.25m/s and (b) 0.25 – 0.50m/s.

For air speeds ranging between 0.50 and 1.00 m/s, indicated that 18% of the subjects preferred "more air movement for an operative temperature of 26.5°C, *Figure 9* a. In addition, for the other operative temperatures, the subjects preferred "no change" for at least 48% of the answers. For air speed above 1.50m/s (recorded only for the operative temperature of 25.5°C), at least 80% of the subjects indicated that they preferred "no change" for the air movement, *Figure 9* b. For 20% of the subjects preferred "less air movement" and none of the subjects required "more air movement".

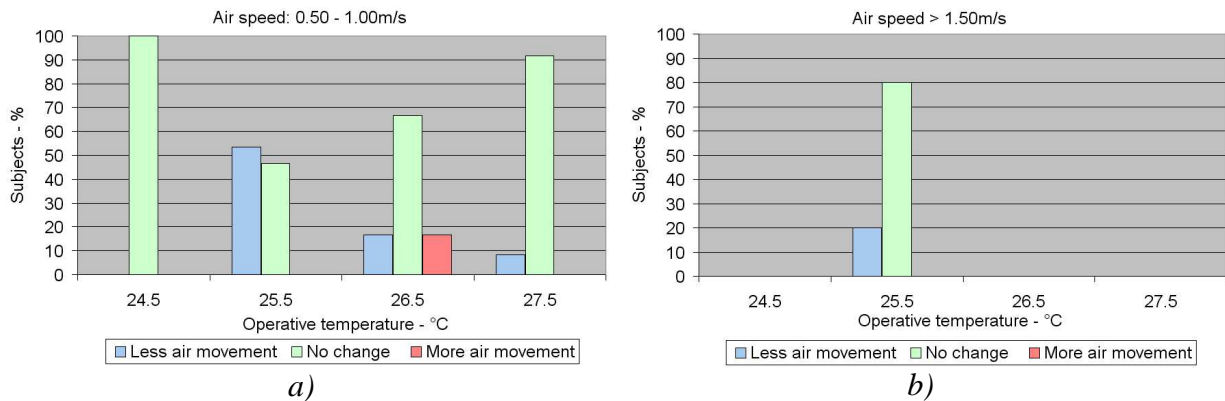*Figure 9 – Subjects' answers for air movement preference and operative temperature: air velocity range: (a) 0.50 – 1.00m/s and (b) above 1.50m/s.*

Discussion

According to the results, the subjects' answers relating to thermal comfort preferences were concentrated in the "neutral" range. Moreover, this may have been influenced by the regional climatic characteristics, where the operative temperature and humidity values for this period presented low daily amplitude and also a less operative temperature value than other periods of the year. Thus, it is particularly important to consider the other period with higher operative temperatures in order to characterize the overall condition.

In relation to air movement acceptability, it remains very high even at air speeds above the recommended comfort standards, of 0.25 m / s. Regardless of the thermal preference it is possible to identify that the majority of the responses state a maintenance of 'no change'. In addition, there was a significant correlation between requests for less air movement and those subjects who indicated that they were "cold" or "slightly cool".

In addition, it is possible to identify a significant tolerance for an air speeds ranging between 0,50 and 1,50 m / s. The subjects' responses suggested that air movement and also air velocity were acceptable for the most part. In addition, it is possible to identify that for a few cases, the air movement was unacceptable and that was related to those subjects who indicated the room felt "cool" or "slightly cool".

On the other hand, for at least 15% of the responses, the subjects indicated that their air movement perception was "acceptable", yet they would prefer "higher air speed". In these cases, it is possible to assume that these subjects would prefer more air movement or even more dynamic air movement. In addition, the subjects' answers relating to "unacceptable air movement" because of the "high air speed" corresponded to 60% of the answers. However, it is difficult to identify what is the real reason behind this complaint. This observation suggests that the questionnaire should include aspects related to specific characteristics of the air movement perception.

Conclusions

According to the results presented in this paper, it is possible to conclude that air movement can be quite acceptable at speeds well excess of the previous values suggested in the literature. For natural ventilation in hot and humid climates, higher air speeds are desirable in order to improve the subjects' thermal comfort. In addition, it is important that the occupants should be able to control the airflow inside the buildings according to their preferences. This dispels the notion of draft in hot and humid climates and is consistent with that broader theory of *alliesthesia* and the physiological role of pleasure.

In relation to air movement acceptability subjects demanded "more air movement" even in air speeds above 0.50m/s. On the other hand, the number of subjects who requested "less air movement" was few in number. These two observations combined suggest that the subjects prefer higher air speed values in order to improve their thermal comfort condition. Draft risk is definitely not the main complaint relating to the subjects' activities for a hot, humid climate such as Maceió city. (Fanger et al, 1988; Toftum, Zhou, Melikov, 1997).

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Appendix F

Aceitabilidade do movimento do ar e conforto térmico em edificações naturalmente ventiladas em Maceió/AL (Air movement acceptability in naturally ventilated buildings in Maceio).

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ACEITABILIDADE DO MOVIMENTO DO AR E CONFORTO TÉRMICO EM EDIFICAÇÕES NATURALMENTE VENTILADAS EM MACEIÓ/AL

Christhina Cândido (1,2); Roberto Lamberts (2); Leonardo Bittencourt (3); Richard deDear (4)

(1) Departamento de Engenharia Civil – Laboratório de Eficiência Energética em Edificações/ Labeee – Universidade Federal de Santa Catarina, Brasil – e-mail: christhina@labeee.ufsc.br
(2) Departamento de Engenharia Civil – Laboratório de Eficiência Energética em Edificações/ Labeee – Universidade Federal de Santa Catarina, Brasil – e-mail: lamberts@ecv.ufsc.br
(3) Departamento de Arquitetura e Urbanismo, Grupo de Estudos em Conforto Ambiental/ GECA – Universidade Federal de Alagoas, Brasil – lsb@ctec.ufal.br
(4) Division of Environmental & Life Sciences, Macquarie University, Australia - rdedear@laurel.ocs.mq.edu.au

RESUMO

Proposta: Em climas quentes e úmidos, a ventilação natural se constitui na principal estratégia de conforto térmico por meios passivos. Estudos indicam que a velocidade do ar, neste tipo de clima, deve ser ajustada entre 0.2 - 1.50 m/s. Contudo, a *aceitabilidade* em relação ao movimento do ar parece carecer de maior aprofundamento, principalmente no que concerne a associação do conforto térmico com diferentes faixas de velocidade do ar. Este trabalho investiga a relação entre a aceitabilidade do movimento e velocidade do ar e o conforto térmico de usuários de edificações naturalmente ventiladas no nordeste brasileiro (Maceió/AL). Método de pesquisa/Abordagens: Questionários de aceitabilidade térmica foram associados a medições das variáveis ambientais (temperatura de globo, temperatura do ar, umidade e velocidade do ar), bem como medições individualizadas da velocidade ar. Resultados: Para temperaturas acima de 24°C os usuários dos ambientes indicaram preferir valores de velocidade do ar acima de 1,00m/s, em média. Observa-se a concentração de respostas de desconforto por parte dos usuários, para velocidades do ar abaixo de 0,25m/s. Para estas velocidades, 70% dos usuários relataram estar levemente com calor ou com calor. Para velocidades do ar acima de 1,00m/s, observou-se uma significativa tolerância ao movimento do ar. Contribuições/Originalidade: Medições em ambientes reais sugerem faixas da velocidade do ar mais elevadas que as relatadas em ambientes laboratoriais.

Palavras-chave: aceitabilidade do movimento de ar, ventilação natural, clima quente e úmido.

ABSTRACT

Proposal: In hot and humid climates, natural ventilation is the main strategy in order to improve the thermal comfort for passive means. Thermal comfort literature indicates that indoor air speed in hot climates should be set between 0.2 - 1.50 m/s. None of the previous research explicitly addressed air movement acceptability, but focused mostly on overall thermal sensation and comfort. This research focuses on the relationship between air movement acceptability and thermal comfort inside naturally ventilated buildings in Northeast of Brazil (Maceio city). Methods: Questionnaires assessing thermal acceptability were administered simultaneously with Findings: At temperatures above 24°C it was found that building occupants preferred mean air speeds up to 1m/s. In addition, it was also observed that at least 70% of subjects' answers for these velocities range were slightly warm or warm. It was also observed that complaints of draft do not occur in significant numbers until air speed exceeds 1m/s and significant air movement acceptability. Originality/value: Measurements inside naturally ventilated spaces suggests that the air velocity values indicated to the subjects are above to similar experiments at climatic chambers.

Keywords: air movement acceptability, natural ventilation, hot humid climate

1 INTRODUÇÃO

Em climas quentes e úmidos a ventilação natural, associada à proteção solar se constitui na principal estratégia para incrementar o conforto térmico dos usuários, por meios passivos, no interior dos ambientes. Neste tipo de clima, estudos indicam que o aumento da velocidade do ar incrementa, sensivelmente, a sensação de conforto dos usuários visto que intensifica as trocas de calor por evaporação e convecção (MALLICK, 1996).

Estudos têm sido desenvolvidos para identificar as faixas de velocidade do ar mais bem aceitas pelos usuários (TANABE, 1988, TOFTUM, ZHOU, MELIKOV, 1997, NICOL, 2004) e observa-se uma significativa diferença entre eles. Kukreja (1978) sugere que a velocidade do ar para climas quentes deve ser entre 1 e 1,50m/s e outros autores ampliam essa faixa para valores entre 0,50 e 2,50 m/s (NICOL, 2004). Já os resultados de outra investigação sugerem que velocidades do ar acima de 2,50 m/s podem ser muito bem aceitas (ZHANG *et al*, 2007). Observa-se que tais limites estão, muitas vezes, baseados em problemas práticos, tais como vôo de papéis sobre a mesa e desarranjo de penteados, ao invés de exigências fisiológicas. No entanto, em climas quentes e úmidos, é provável que o poder refrescante provocado por uma maior velocidade do ar possa compensar essas desvantagens (TOFTUM, 2004). Dessa forma, ajustes se fazem necessários nos limites da *aceitabilidade* do movimento do ar para se considerar, mais adequadamente, os efeitos das variações da velocidade do ar no conforto térmico, principalmente para valores da velocidade do ar mais altos (TOFTUM, 2004; ZHANG *et al*, 2007).

Outro item que deve observado é que os valores obtidos como preferidos pelos usuários e utilizados como limites máximos aceitáveis, resultam, em muitos casos, de pesquisas realizadas em ambientes onde os pesquisadores têm controle das variáveis (tais como a abertura de janelas e a velocidade do ar). Pesquisas de campo vêm sendo indicadas como mais representativas para avaliar o impacto do uso da ventilação natural no conforto térmico dos usuários (ARENS *et al*, 1998). Neste caso, o pesquisador não deve interferir nas variáveis ambientais e comportamentais, visando caracterizar a condição de uso real do ambiente e as pessoas devem expressar suas sensações e preferências térmicas em escalas apropriadas, (TOFTUM *et al*, 2003; TOFTUM, LANGKILDE, FANGER, 2004). Estudos que associem o conforto térmico relatado pelos usuários e os valores de velocidade do ar preferidos pelos mesmos, especificamente em ambientes reais em climas quentes e úmidos, constitui-se em contribuição significativa para a área.

2 OBJETIVO

Este trabalho tem por objetivo investigar a relação entre a *aceitabilidade* do movimento do ar e o conforto térmico de usuários em edificações naturalmente ventiladas na cidade de Maceió/AL. Como objetivo complementar, o trabalho visa relacionar diferentes faixas de velocidade do ar com as preferências relatadas pelos usuários.

3 METODOLOGIA

A metodologia adotada consiste na análise dos valores da velocidade do ar medidas e as respostas dadas aos questionários pelos usuários de duas edificações naturalmente ventiladas em Maceió/AL. Para tal, foram realizadas medições das variáveis ambientais e, de forma concomitante, foram aplicados questionários de conforto e aceitabilidade térmica. Este trabalho apresenta os resultados obtidos na pesquisa de campo entre os meses de agosto e setembro de 2007.

3.1 Ambientes monitorados

Para a definição dos ambientes monitorados, foram escolhidos locais onde a ventilação natural fosse empregada como estratégia de resfriamento, podendo esta ainda ser complementada pelo uso de ventiladores. Em relação às aberturas, estas deveriam ser acessíveis e de fácil operação pelo usuário, que poderiam abrir, fechar e regular, bem como acionar ventiladores. No que concerne aos usuários,

estes deveriam apresentar perfil similar na idade, no tipo de vestimenta e na atividade desenvolvida. Nesse contexto, as edificações escolhidas para o desenvolvimento da pesquisa foram duas Faculdades de Arquitetura e Urbanismo, localizadas no Centro de Tecnologia de Universidade Federal de Alagoas - UFAL e no Centro de Estudos Superiores de Alagoas - CESMAC.

Na UFAL, as edificações estão dispostas espaçadamente no campus, com ambientes distribuídos em pavimentos térreo e superior, sendo estes interligados por corredores, integrados ao ambiente externo. As salas monitoradas são utilizadas para aula e ateliê de desenho (projeto), Figura 1a e b, e variam em tamanho, podendo medir entre 36m² e 50m², aproximadamente.

Em tais ambientes, o conjunto de aberturas favorece o insuflamento de fluxo de ar e pode ser dividido em duas partes. A primeira parte é voltada para o corredor da edificação, se constituindo na porta de acesso do ambiente, com elementos vazados (cobogós) na parte superior e inferior da parede. O segundo conjunto de aberturas é voltado para o exterior, dividindo-se em janelas do tipo de correr e elementos vazados (cobogós) na parte superior da parede, Figura 1c. O mobiliário existente varia de acordo com a atividade desenvolvida, sendo composto de carteiras escolares nas salas de aula e pranchetas inclinadas para desenho nas salas de projeto. No primeiro caso, os usuários desenvolvem as atividades em um plano de trabalho de 0,60m e, no segundo caso, esta altura eleva-se para 1,10m, Figura 1a e b. Em cada sala, a ocupação varia entre 20 e 40 usuários.

(a) (b)

(c)
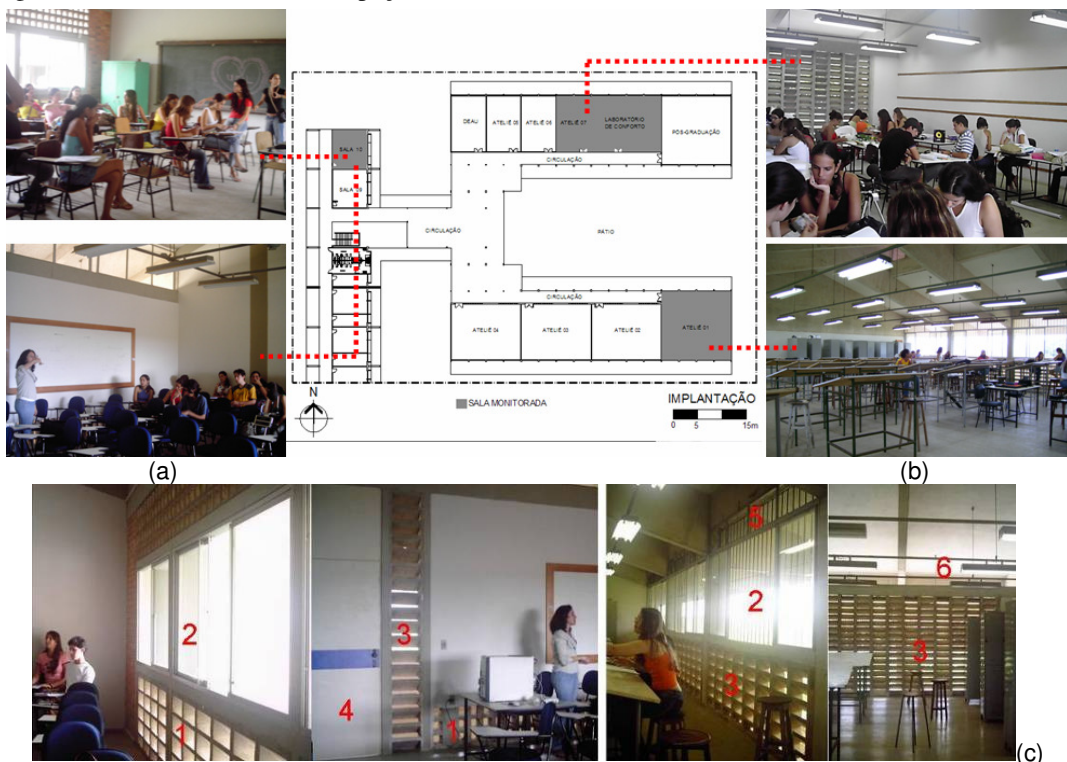
Legenda: 1 – Cobogó, 2 – Esquadria de correr, 3 – Elemento vazado, 4 – Porta, 5 – Bandeira ventilada, 6 – Vazio.

Figura 1 – Salas de aula (a), de urbanismo (b – acima) e de desenho (b – abaixo) e tipos de aberturas (e) encontradas na Faculdade de Arquitetura e Urbanismo - UFAL.

No CESMAC, as salas estão distribuídas em sete pavimentos, interligadas por circulação mais reclusa em relação à disposição adotada na UFAL. As salas são utilizadas para atividades de aula expositiva e desenho, Figura 2a e b. Nesta edificação, o conjunto de aberturas é formado por janelas do tipo maxilar, somadas a venezianas fixas e pela própria porta de acesso ao ambiente, Figura 2c. O mobiliário adotado é composto por carteiras escolares, com estofamento, nas salas de aula e pranchetas horizontais para desenho nas salas de projeto, Figura 2 a e b. Em relação à quantidade de usuários no ambiente, esta variou entre 20 e 30.
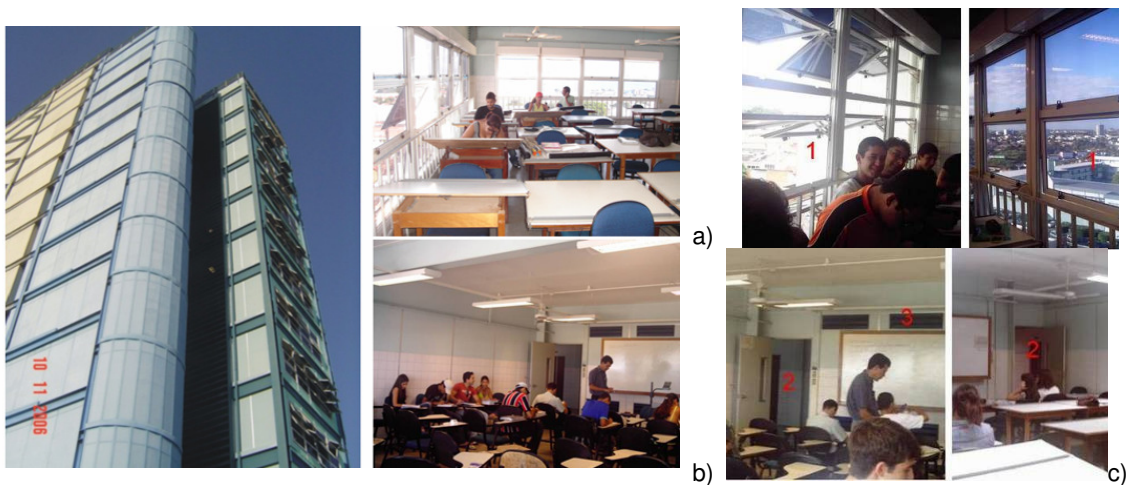
Figura 2 – Sala de desenho de aula (a)e de aula (b) e tipos de aberturas (c) encontradas na Faculdade de Arquitetura e Urbanismo - CTC/CESMAC.

3.2 Usuários

Os usuários dos ambientes são estudantes do curso de Arquitetura e Urbanismo das edificações estudadas. A idade varia entre 18 e 25 anos e a maioria é do sexo feminino (66%). As atividades desenvolvidas são sedentárias e variam entre 70 e 93W/m², visto que os usuários encontram-se sentados escrevendo ou desenhando ou em pé e desenhando. A vestimenta utilizada é leve, em média, com valores entre 0,30 *clo* para o verão e 0,70 *clo* para o inverno (Figura 3 a e b) e foram classificadas conforme a ASHRAE Standard 55 (2004).

Figura 3 – Vestimentas utilizadas pelos usuários dos ambientes em dias quentes (a) e em dias frios (b).

3.3 Variáveis ambientais

Para o monitoramento das variáveis ambientais foi utilizado o confortímetro Babuc A e termoanemômetro. O confortímetro Babuc A *(Laboratori di Strumentiazoni Industriali)* constitui-se em uma estação de medição que agrupa diversos instrumentos conectados a um *datalogger* utilizado para o registro e armazenamento dos dados obtidos, Figura 4 a. O equipamento foi utilizado para o monitoramento da temperatura de globo, da temperatura do ar, da velocidade do ar e da umidade. Para tal, foram empregados os seguintes instrumentos: termômetro de globo, o psicrômetro e o termoanemômetro, Figura 4 a.

Para o registro da velocidade do ar, na proximidade de cada usuário, foi utilizado um termoanemômetro de fio quente portátil. O equipamento *Airflow Developments*, modelo TA-35, possui resolução de 0,01m/s e faixa de medição de 0,05 a 20m/s, e é unidirecional, Figura 4 b. Tal equipamento foi adotado visando identificar o valor da velocidade de ar de maneira individualizada, sendo o procedimento de medição explicado no item a seguir (Metodologia de monitoramento). Visto que o termoanemômetro empregado é unidirecional, foram utilizados *sticks* de fumaça para visualizar a direção predominante do fluxo de ar durante as medições da velocidade do ar, Figura 4 c. Desta

forma, pode-se registrar o valor da velocidade do ar para a direção predominante do vento durante o período de preenchimento do questionário pelo usuário.

Figura 4 – Equipamentos de medição utilizados para o monitoramento: (a) Confortímetro Babuc A, (b) Termoanemômetro de fio quente portátil Airflow Developments, modelo TA-35 e (c) *Sticks* de fumaça utilizados para visualizar o fluxo de ar.

3.4   Metodologia de monitoramento

As medições foram realizadas durante duas semanas, no período da manhã, tarde e noite por, aproximadamente, duas horas em cada horário. As atividades dos alunos não foram interrompidas, visando caracterizar a utilização real dos ambientes, assim como foi permitido o uso de ventiladores de teto, acionamento de lâmpadas e controle das aberturas (fechar ou abrir portas), conforme descrito anteriormente.

3.4.1   Variáveis ambientais

O confortímetro Babuc A foi locado no centro do ambiente, sendo os seus instrumentos de aquisição (termômetro de globo, psicrômetro e termoanemômetro) adequados para duas alturas. A primeira foi de 0,60m, correspondendo ao plano de trabalho dos usuários sentados nas salas de aula. A segunda foi de 1,10m, para os usuários das pranchetas nas salas de projeto.

Para cada usuário, a velocidade do ar foi monitorada de forma individualizada visando caracterizar o comportamento do fluxo de ar e, posteriormente, cruzar esta informação com as respostas do questionário. Cada usuário respondeu ao questionário cinco vezes, durante o período de monitoramento do ambiente e, durante esse período, a velocidade do ar foi medida. Para cada preenchimento do questionário a velocidade do ar, em seu ponto, foi medida trinta vezes, o que totaliza cento e cinqüenta registros da velocidade do ar por cada usuário. Em cada medição, o termoanemômetro foi posicionado para a altura do plano de trabalho e direcionado para o fluxo de ar dominante mostrado pelo *stick* de fumaça. Tanto o termoanemômetro, quanto o *stick* de fumaça foram posicionados na altura do plano de trabalho dos usuários e expostos ao fluxo de ar sem que houvesse barreiras que modificassem a distribuição e a velocidade do escoamento do vento (tais como o corpo da pesquisadora, por exemplo).

3.4.2   Questionários

O questionário de aceitabilidade térmica tem como objetivo identificar a aceitabilidade dos valores da velocidade do ar com as respostas de conforto térmico dadas pelos usuários. O questionário baseia-se no modelo adotado por de Dear e Brager (2002)[1] e foi adaptado para o desenvolvimento deste

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[1] O questionário se baseia no modelo utilizado por deDear e Brager (1998) no desenvolvimento do projeto da

trabalho de acordo com as necessidades do mesmo, sendo dividido em três partes. A primeira corresponde aos dados pessoais dos usuários com idade, altura, peso e sexo. A segunda parte é dedicada às perguntas relacionadas ao conforto térmico, aceitabilidade do movimento do ar e utilização do ar-condicionado. A terceira, e última parte, compreende as atividades que os usuários desenvolveram no momento da medição e a vestimenta utilizada pelos mesmos.

Os usuários começaram a responder o questionário apenas meia hora após a sua chegada no ambiente para que condições prévias de atividade não influenciassem nos resultados posteriores, bem que as respostas dadas fossem representativas das condições reais que os mesmos estavam expostos. Os usuários que chegaram após o início do monitoramento ou que deixaram o ambiente durante o desenvolvimento do mesmo tiveram suas respostas excluídas da amostra final a fim de se evitar erros nas análises posteriores.

4   ANÁLISE DE RESULTADOS

Como item inicial do questionário, os usuários responderam a seguinte pergunta: *"Com relação a sua sensação térmica, como você está se sentindo neste momento?",* tendo como opções respostas baseadas na escala sétima variando entre -3 e 3 (com muito frio, com frio, levemente com frio, neutro, levemente com calor, com calor e com muito calor).

Observa-se a concentração da grande parte dos votos para neutro, em pelo menos 49% das respostas. Constata-se a incidência de respostas para *levemente com calor* e *levemente com frio,* variando entre 16 e 32% das respostas, Gráfico 1. Para as sensações de frio e calor, as respostas não ultrapassaram os valores de 3%. Não foram constatadas respostas para sensações de muito frio ou muito calor para nenhuma das temperaturas tabuladas. Outro item do questionário pretende identificar a preferência térmica do usuário (*Como você preferia estar se sentindo neste momento?*), sendo sugeridas como as respostas as opções de mais resfriado, assim mesmo ou mais aquecido. Como resultado, mais de 50% dos usuários respondeu preferir *assim mesmo*, em todas as temperaturas. Para pelo menos 20% dos usuários a preferência foi de mais resfriado e 10% para aqueles que relataram preferir estar *mais aquecido*, Gráfico 1.
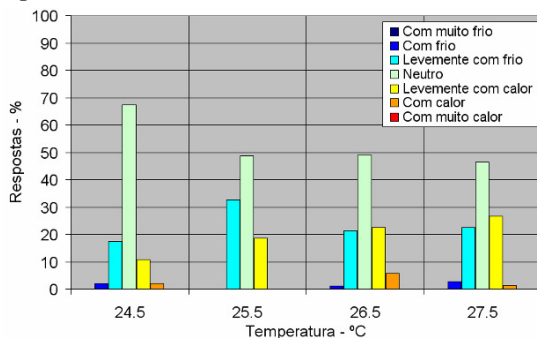

Gráfico 1 - Respostas das sensações térmicas dos usuários em relação às temperaturas.
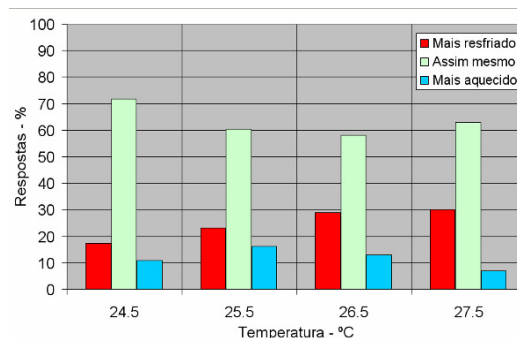
Gráfico 2 - Respostas das preferências térmicas dos usuários em relação às temperaturas.

Quando questionados sobre a classificação do ambiente *(Com relação ao ambiente, como você classifica neste momento?),* os usuários poderiam optar pelas respostas *aceitável* ou *inaceitável*. Nesse caso, mais de 75% dos usuários relataram considerar o mesmo *aceitável* para todas as temperaturas, Gráfico 3. Os usuários foram questionados também sobre o estado atual (*De que maneira você se encontra neste momento?),* podendo escolher como resposta as opções *confortável* ou *desconfortável*. Em relação a como o usuário se classifica no momento, observa-se comportamento similar em relação ao verificado na pergunta anterior, onde pelo menos 75% dos usuários indicaram estar confortáveis, Gráfico 4.
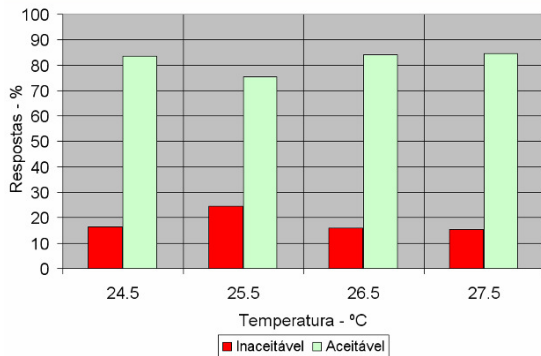

ASHRAE (Adaptive comfort project - model ASHRAE Project RP 884).

Gráfico 3 – Respostas do ambiente térmico dos usuários em relação às temperaturas.
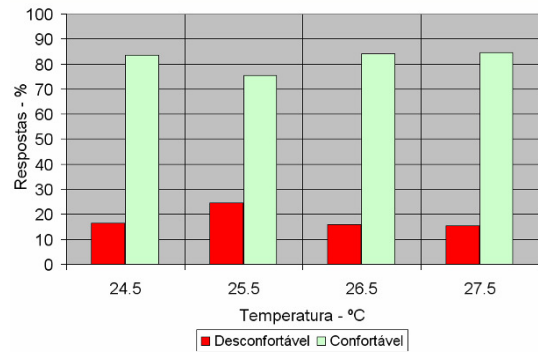
Gráfico 4 – Respostas da situação térmica dos usuários em relação às temperaturas.

Os usuários que se declaram em conforto foram classificados como *satisfeitos* e foram cruzados entre si para permitir a identificação de suas preferências térmicas e de movimento do ar segundo a metodologia proposta por Fountain *et al* (1994). Tal cruzamento serviu para identificar a ocorrência de respostas para *levemente com calor, levemente com frio, com frio* e *com calor*, mas que mesmo assim declararam *satisfeitos* com sua condição térmica. Após a análise dos dados referentes às perguntas de conforto térmico, foram analisadas as respostas para as perguntas relativas ao movimento do ar. Para tal foram utilizados os valores de faixas de velocidade do ar associados aos de temperatura do ar e as respostas dadas pelos usuários.

Como respostas possíveis para a preferência do movimento do ar, os usuários poderiam optar entre as respostas: *maior movimento do ar, assim mesmo* ou *menor movimento do ar.* Para análise deste item, as respostas dadas pelos usuários foram combinadas com os valores da temperatura e com as faixas do de velocidade do ar e podem ser observadas no Gráfico 5.

Para as velocidades do ar de até 0,25m/s, pelo menos 22% dos usuários indicaram preferência por *maior movimento do ar* enquanto que no mínimo 40% preferem permanecer sem mudanças ou *assim mesmo*. Observa-se a ocorrência de preferência por *maior movimento do ar* para a temperatura de 25,50 °C e menor incidência para temperatura de 27,50 °C. Apenas 4% das respostas dadas indicaram preferência por *menor movimento do ar*, ocorrendo somente para a temperatura de 25,50°C, Gráfico 5.
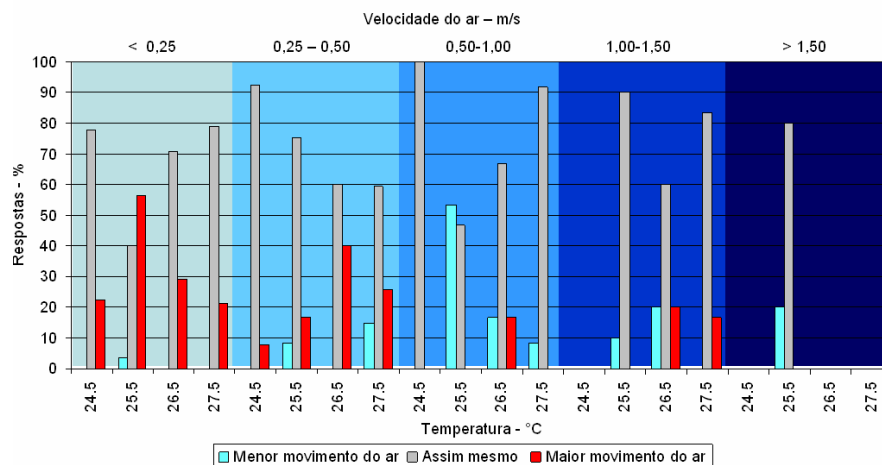

Gráfico 5 – Respostas da preferência do movimento do ar dos usuários em relação às temperaturas.

Para as velocidades do ar entre 0,25m/s e 0,50m/s, pelo menos 22% dos usuários indicaram preferência por *maior movimento do ar* enquanto que no mínimo 40% preferem permanecer *assim mesmo*. Observa-se a maior ocorrência de preferência por maiores valores da velocidade do ar para

temperaturas de 26,5 °C e 27,5 °C. A preferência por um *menor movimento do ar* foi identificada somente para a temperatura de 25,5 °C, Gráfico 5.

No que concerne às preferências dos usuários para a faixa de velocidade do ar entre 0,50 e 1,00m/s, identifica-se a necessidade de *maior movimento do ar* para apenas 18% dos usuários para temperatura de 26,5 °C. Em todos os valores de temperatura, os usuários indicaram preferir estar *assim mesmo* em, no mínimo, 48% das respostas, Gráfico 5.

Para velocidades do ar acima de 1,50m/s, registradas somente para a temperatura do ar média de 25,5 °C, 80% dos usuários indicaram não desejar modificação no movimento de ar. Não foi constatada nenhuma preferência por *maior movimento do ar*, sendo que os demais 20% dos usuários indicaram preferência por *menor movimento do ar*, Gráfico 5.

4.1   Conclusões

As respostas dadas para as questões relativas ao conforto e ambiente térmico, indicam que os usuários encontravam-se majoritariamente em condição de conforto. Por outro lado, este fato pode ter sido favorecido pelas características climáticas da região, onde os valores de temperatura e umidade para esta época do ano são amenas, com baixa amplitude diária. Desta forma, constata-se a importância da realização da pesquisa de campo para o período com temperaturas mais elevadas, buscando caracterizar o comportamento do usuário para condições diferenciadas.

Em relação ao movimento do ar, observa-se uma significativa tolerância a valores de velocidade do ar entre 0,50 e 1,00m/s. No que tange às preferências térmicas, observou-se a ocorrência maioria das respostas para a manutenção do estado (assim mesmo) e a necessidade de maior movimento ar. Observou-se uma significativa correlação entre as respostas dadas para preferência de menor movimento do ar e aquelas indicadas como frio ou levemente com frio.

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6   AGRADECIMENTOS