Title
Comfort is in the mind of the beholder: a review of progress in adaptive thermal comfort research over the past two decades

Authors
de Dear, Richard
Foldvary, Veronika
Zhang, Hui
et al.

Publication Date
2016-11-02

Peer reviewed

COMFORT IS IN THE MIND OF THE BEHOLDER: A REVIEW OF PROGRESS IN ADAPTIVE THERMAL COMFORT RESEARCH OVER THE PAST TWO DECADES

Richard de Dear[1)], Veronika Foldvary[2)], Hui Zhang[2)], Ed Arens[2)], Moahui Luo[2)]
Thomas Parkinson[1)], Xiuyuan Du[1)], Wei Zhang[1)], Chungyoon Chun[3)], Sijie Liu[1)]
1) IEQ Lab, The University of Sydney, Sydney NSW 2006, Australia
2) Center for the Built Environment, University of California at Berkeley, Berkeley CA, USA
3) Laboratory of Human & Building Environment, Yonsei University, Seoul, Korea

ABSTRACT

The classic or deterministic understanding of thermal comfort contends that it is driven exclusively by the physics of the body's heat exchange with its immediate thermal environment. But in recent decades there has been widespread recognition that a person's thermal history and adaptation level, including behavioral, physiological and psychological processes operating on various timescales, also influence whether indoor climatic conditions will be deemed comfortable and acceptable, or not, as the case may be. This contextual view of the comfort construct is referred to as the adaptive model, and its empirical basis is an extensive body of field studies conducted in diverse occupancy and building types located across a broad cross-section of the world's climate zones. The basic research design of the comfort field study consists of paired observations of objective indoor climatic parameters and their subjective evaluation by building occupants using comfort rating scales. The first global adaptive comfort standard, ratified by ASHRAE in 2004, was based on a statistical analysis of approximately 21,000 complete sets of objective indoor climatic observations and their "*right-here-right-now*" subjective evaluations by the building occupants who were exposed to them. Over a decade has elapsed since ASHRAE Standard 55-2004 was published and since then there has been an escalation in adaptive comfort field research activity around the world. Recently ASHRAE's thermal comfort technical committee (TC 2.1), in collaboration with the International Energy Agency (Annex 69), have taken on the challenge of systematically collating and harmonizing the raw data collected in recent comfort field studies from around the world into an expanded, quality-assured database. When the project is completed this public-domain resource will underpin myriad inquiries by the thermal comfort community, researchers and practitioners alike. The aim of this presentation is to describe the DB-II project, including the principles guiding the collation and quality assurance of its massive volume of raw input data, and also pointing to some of the new opportunities it will afford the research community over coming years.

Keywords: Thermal Comfort; Adaptive; Field study; IEQ Sensors; Database

1. INTRODUCTION

This paper describes the concept of a public domain database of thermal comfort field studies, and illustrates the range of potential applications with two specific case studies. The first deals with the use of elevated indoor air speeds to extend the adaptive comfort temperature range in ASHRAE Standard

55 (2013). The second case study describes the use of a statistical model of indoor clothing insulation to calculate in the PMV/PPD comfort index real-time for the purposes of comfort standard compliance. The paper concludes with an introduction to the ongoing ASHRAE Comfort Database Mk II project.

2. THE ASHRAE COMFORT DATABASE MK I

Underpinning each of the adaptive comfort standards, including the global standard of ASHRAE 55 (2013), the European EN15251 standard (CEN 2007), and the most recent Chinese standard GB/T 50785 (2012), is a statistical model built up from a large set of field data. Comfort field studies involve real buildings, in use by large numbers of occupants going about their normal daily routine. This research method retains the integrity of an holistic person-environment relationship (Auliciems 1981). The ASHRAE-sponsored research project (RP-884) in the 1990s on adaptive comfort (de Dear and Brager, 1998), required a large database of thermal comfort field data to be assembled from diverse climate zones across the world (de Dear, 1998). In order to identify and disentangle various processes of climatic adaptation, the RP-884 project required field data of a high quality where the standards of measurement, both physical and subjective, were as close as possible to laboratory-grade, and comprehensive enough to enable the classic or deterministic heat-balance comfort indices such as PMV/PPD to be calculated. Furthermore, the database was built up from raw data files generated by the original researchers instead of their processed or published findings. This approach allowed a variety of quality controls to be applied and enhanced the consistency and integrity of the entire database. At the time of its publication in 1998 the ASHRAE comfort database Mk I comprised over 21,000 rows of paired *subjective* comfort votes and *objective* instrumental measurements of concurrent indoor climatic parameters.

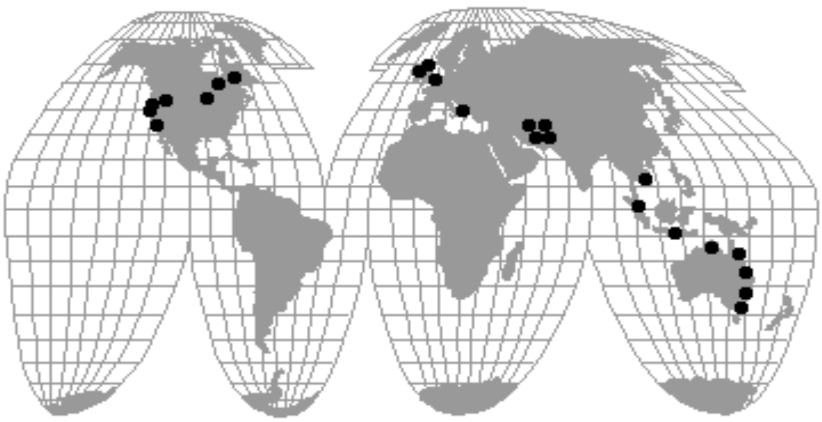

Figure 1. The geographic scope of the ASHRAE comfort database Mk I (de Dear, 1998).

The 21st Century era of massive data is turning the scientific method on its head (Anderson, 2008). At its simplest, the hypothetico-deductive scientific method begins with the proposal of a hypothetical explanation of observed phenomenon. Once the hypothesis is in place, researchers then design experiments specifically to generate exactly the type of data that allows their hypothesis to be critically tested. In this way well designed and scaled experiments either support or falsify theoretical models about how the world works. For hundreds of years that's how science has advanced our knowledge, but the availability of massive amounts of data on the internet in the 21st century is prompting a shift away from a deductive model towards an inductive alternative; one where the research data already exists and the researcher's task is to work backwards from that resource to pose useful research questions to which those data can be addressed (Anderson, 2008).

It's probably premature to be talking about "big data" in the relatively small world of thermal comfort research, but in recent years we've witnessed a methodological inversion comparable to the one described above. The ASHRAE Thermal Comfort Database Mk I (de Dear, 1998) was compiled in the late 1990s with the singular purpose of critically testing a hypothesis – the adaptive model (de Dear and Brager 1998). Upon completion of that project for the funding agency (ASHRAE) the database was made freely available on the internet without any clear expectation of how it would end up being used by others. Research search engines indicate over 50 papers have been published in the peer reviewed literature based upon the data contained in database Mk I. The two examples given below have been selected because of their relevance to practical applications of the ASHRAE thermal comfort standard (2013).

2.1 Extension of the adaptive comfort zone with elevated airspeed

Practitioners using the adaptive thermal comfort standard as a design tool have long been asking whether the upper threshold of acceptable indoor temperatures could be extended by the introduction of elevated airspeeds into the occupied zones of buildings. An answer to this practical question was sought by ASHRAE's TC 2.1 by referring back to the original research data underpinning the ASHRAE 55 adaptive comfort model. The first step was to establish what the baseline airspeed was in ASHRAE's adaptive comfort model. By focusing on just those naturally ventilated buildings in ASHRAE comfort database Mk I in which indoor operative temperatures exceeded 25°C it was discovered that 0.3 m/s was the average airspeed within the occupied zones of those buildings, so this defined where "elevated" airspeed actually started from. The SET* comfort index was then used to calculate how much the upper threshold of acceptable adaptive comfort temperatures could be lifted by incrementing airspeed above the baseline of 0.3 m/s. The results of that analysis are presented in Table 1 below. If indoor operative temperature t_0 > 25°C, then it is permitted to increase the upper acceptability temperature limits in the adaptive comfort standard by the corresponding Δt_0 in the table (ASHRAE 2013).

Table 1. ASHRAE Standard 55-2013 method for calculating increases in acceptable operative temperature limits (Δt0) in occupant-controlled, naturally conditioned spaces resulting from increasing air speed above 0.3 m/s

Average Air Speed *(V_a)* 0.6 m/s	Average Air Speed *(V_a)* 0.9 m/	Average Air Speed *(V_a)* 1.2 m/s
1.2°C	1.8°C	2.2°C

2.2 Real-time assessment of a building's thermal comfort performance (standard compliance)

The internet of things is making low-cost sensors available to monitor in real-time IEQ within the occupied zone of a building. The IEQ Lab at the University of Sydney has developed a compact, desk-based monitor (SAMBA) with sensors covering all the key IEQ parameters, including: thermal comfort (air and radiant temperatures, air speed and humidity), acoustics (SPL), lighting (lux) and air quality (CO2, CO, TVOC, Formaldehyde and PM10). Low unit costs make it feasible to place SAMBAs in each HVAC zone of complex commercial buildings. The SAMBA's communication approach is based on a self-forming mesh network within a building and does not require access to the host organisation's internal computing infrastructure. Measurements across the mesh network are relayed wirelessly to a central SAMBA gateway that, in turn, transmits them through the cellular data network back to the University of Sydney IEQ Lab's file server every five minutes. Various IEQ indices and compliance metrics are then calculated in real-time en route to being presented in a web-based IEQ dashboard to which the building operator has access. This simple system effectively provides the building manager with "eyes, ears, nose and skin" throughout the occupied zone of the building they are managing, enabling them to more effectively optimise the building's comfort and IEQ performance. SAMBA represents a vastly more sophisticated approach to the current practice of facilities managers, which relies on the vagaries of their building tenants' employee complaints, which are haphazard at best and potentially misleading.

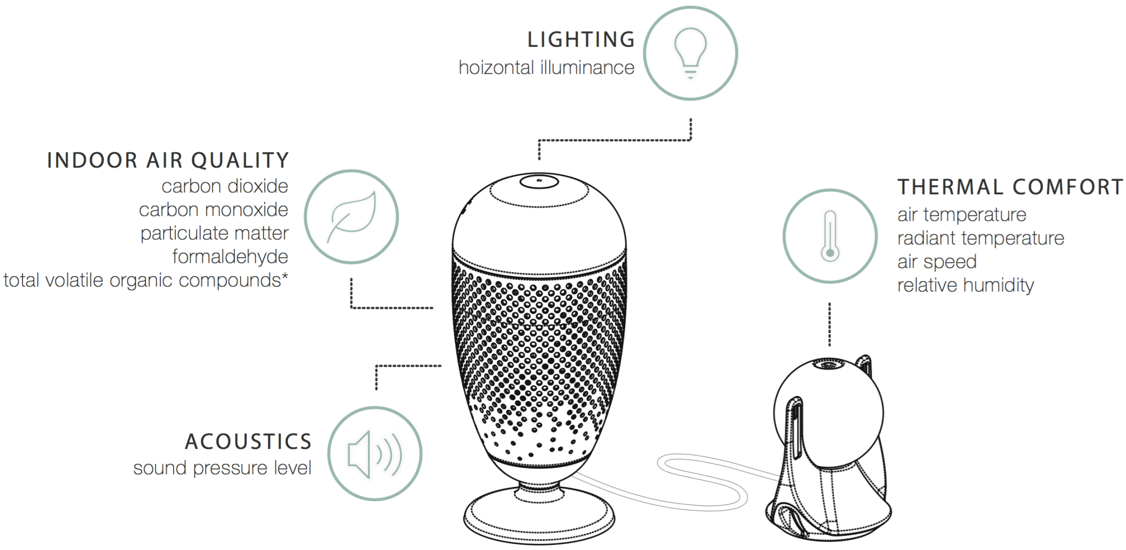

Figure 2. The University of Sydney's desktop IEQ comfort monitoring device - SAMBA.

SAMBA's assessment and trend-logging of thermal comfort performance against the HVAC industry standard, ASHRAE 55-2013, requires calculation in real-time of an integrated comfort index known as PMV/PPD (Fanger, 1970). While SAMBA measures the four environmental input parameters, it is unable to assess the two personal parameters from the occupants – metabolic rate and clothing insulation. The first problem is readily solved by assuming typical office occupant behavior, equating to 1.2 met units. The second one, clothing insulation worn by building occupants, is complicated by the fact that indoor clothing behavior varies in an adaptive response to climatic, seasonal and meteorological conditions prevailing outside the building.

Schiavon and Lee (2013) addressed this issue with a statistical model of the dependence of building occupant clothing insulation on 6am outdoor air temperatures (see Figure 3 for a graphical representation on the clothing prediction model). The large volume of diverse empirical data necessary to fit the statistical model was drawn from a selection of thermal comfort field studies conducted across various climate zones within the online ASHRAE comfort database Mk I.

Because the SAMBA comfort monitoring system is connected to the internet it is able to scrape daily

6am meteorological data from the online meteorological observatory nearest the building in question. These geo-located weather data are then applied to Schiavon and Lees' (2013) clothing model (Figure 3) to derive an estimate of daily mean clothing insulation worn by building occupants. The clo estimate, in combination with an assumed metabolic rate for the building occupants are then merged with SAMBA's instrumental observations of indoor climatic conditions every five minutes to enable real-time PMV/PPD calculations to be performed and ASHRAE Standard 55 comfort compliance assessed.

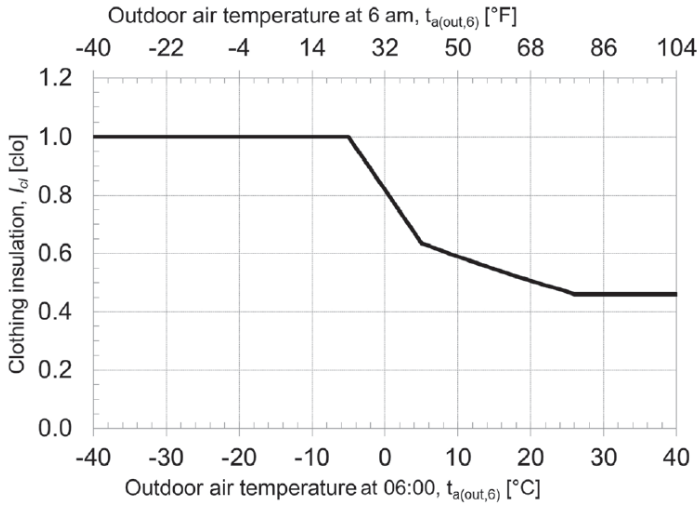

Figure 3. The ASHRAE Standard 55-2013 method of predicting indoor clothing insulation values from outdoor 6am air temperature (source: ASHRAE, 2013).

3. THE ASHRAE COMFORT DATABASE MK II

It's nearly two decades since the ASHRAE Comfort Database Mk I was placed on the internet, and in that time the domain of thermal comfort has experienced an explosion of research activity around the world (de Dear et al., 2013). This is largely because of the nexus between indoor comfort technology (HVAC) and building energy consumption, which in turn, is a major culprit behind the global climate crisis unfolding in the 21st century.

Literally hundreds of new thermal comfort field studies have been published in the last 20 years, and each one has used the same fundamental research design – pairing objective indoor climatic observations with their "*right-here-right-now*" subjective evaluations by the building occupants who were exposed to them. Recognising the value of open-source research databases in advancing the advancing the arts and science of HVAC, ASHRAE's thermal comfort technical committee (TC 2.1), in collaboration with the International Energy Agency (Annex 69), have recently taken on the challenge of systematically collating and harmonizing the raw data collected in recent comfort field studies from around the world into an expanded, quality-assured database. In 2014 the ASHRAE Comfort Database Mk II project was launched under the leadership of University of California at Berkeley's Center for the Built Environment and the University of Sydney's IEQ Lab. Dozens of thermal comfort research groups from around the world have generously made their raw data freely available to the project, and the volume of data continues to grow. When it is completed, this public-domain resource will underpin myriad inquiries by the thermal comfort community, researchers and practitioners alike.

Table 2. New data contributions to the ASHRAE Comfort Database Mk II project

Experiment location	Climate zone	Typology	System type	Sample Size	Number of buildings
Toyko, Japan(summer)	Humid subtropical	School	AC	31	1
Gumyoji, Japan(summer)	Humid subtropical	School	NV	43	1
Tsxas, USA(winter)	Tropical desert and steppe	Office	AC	85	1
Midland,England(summer)	Marine west coast	office	MM	9523	8
Midland,England(winter)	Marine west coast	office	MM	11474	8
Chennai, India(winter)	Tropical savana	office	AC(446),NV(38),ACoff(81)	6048	14
Chennai, India(summer)	Tropical savana	office	AC(605),NV(30),ACoff(137)		14
Chennai, India(southwest monsson)	Tropical savana	office	AC(617), NV(7), ACoff(33)		14
Chennai, India(northeast monsson)	Tropical savana	office	AC(854), NV(57), ACoff(2)		14
Hyderabad, India(winter)	Tropical savana	office	AC(779), NV(834), ACoff(66)		14
	Tropical savana	office	AC(563),NV(112),ACoff(40)		14
	Tropical savana	office	AC(268), NV(177), ACoff(23)		14
	Tropical savana	office	AC(178), NV(97), ACoff(4)		14
Ilam,Iran (Cool)	Mediterranean	office	NV	377	1
Ilam,Iran (hot)	Mediterranean	office	NV	512	1
Tokyo, Japan	humid subtropical		AC	120	
San Francisco	Mediterranean	office	MM	2482	
Alameda, USA	Mediterranean	office	NV	1408	3
Philadelphia US	Humid subtropical	office	AC	2497	1
Guangzhou	Humid subtropical	dormitory	NV	5045	
Makati, Phillipines	Trade-wind littoral	office	AC	277	1
Singapore	Wet equatorial			408	
Sydney, Australia	Humid subtropical	office	AC(431)，NV(50)	481	2
Sydney, Australia	Humid subtropical	office	AC(634)，NV(244)	878	2
Jaipur,India	Tropical desert and steppe	multifamily housing	NV	1418	17
			AC	642	6
			MM	809	13
Kota Kinabalu, Malaysia	Wet equatorial	university	AC	100	
Malaysia	Wet equatorial	Residential		890	
Samorin, Slovakia	Humid continental	multifamily housing	NV	94	6
Samorin, Slovakia	Humid continental	multifamily housing	NV	74	
Samorin, Slovakia	Humid continental	multifamily housing	heating	244	6
Bratislava, Slovakia	Humid continental	multifamily housing	heating	236	6
Copenhagen, Denmark	Humid continental	School	AC with constant air volume	170	1
Gabes, Tunisia	Mediterranean	multifamily housing	NV	831	1<n< 19?
		Office	NV	820	1<n< 19?
Nigel, South Africa	Mediterranean	office	NV	11474	8
			AC	9523	8
London, UK	Marine west coast	office	NV/AC	4659	
Brazil				279	
Florianópolis, Brazil	Humid subtropical	university classroom	MM	3762	1
			AC	1274	
Maceio, Brazi	Humid subtropical	university classroom	NV	703	2
Seoul,Korea	Humid subtropical	office	AC	191	
Tsukuba, Japan	Humid subtropical	multifamily housing	MM	715	
Lodi, Italy	Humid subtropical	office	NV	81	2
Shanghai, China	Humid subtropical	classroom	NV	1810	
Liege, Belgium	Marine west coast	multifamily housing	heating	85	85
Ahmedabad, India	Tropical desert and steppe	office	NV	1507	
Mexicali, Mexico	west-coast desert	multifamily housing	NV	1424	21
Cherrapunje, India	Tropical savanna	multifamily housing	NV	109	

The sources of data at this point in the evolution of the ASHRAE comfort database Mk II have been geo-located in Figure 3. In many ways this maps shows the expanding geography of thermal comfort research activity. When compared the Figure 1 it is clear that Asia, particularly China and India, have become emerged as major participants in thermal comfort research in the 21st century (de Dear et al., 2013).

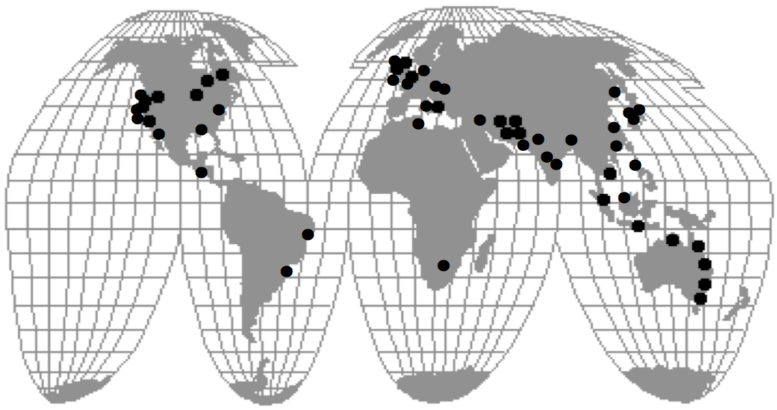

Figure 3. The geographic scope of the ASHRAE comfort database Mk II.

4. CONCLUSIONS

The era of 'big data' is unfolding in these early decades of the 21st century. Every field of human endeavor is affected, including thermal comfort research. This paper described public domain databases of thermal comfort field studies, and illustrated their applications with two examples. The first dealt with the use of elevated indoor air speeds to extend the adaptive comfort temperature range. The second illustration described the use of a statistical model of indoor clothing insulation to calculate in the PMV/PPD comfort index real-time for the purposes of comfort standard compliance.

5. ACKNOWLEDGMENTS

The ASHRAE Comfort Database Project Mk II referred to in this paper is partially funded by an American Society of Heating, Refrigerating and Air Conditioning Engineers grant in aid.

6. REFERENCES

Anderson, C. 2008. The end of theory. Wired magazine, 16(7), pp.16-17.

ASHRAE. 2013. Standard 55 - Thermal Environmental Conditions for Human Occupancy. Altanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Auliciems, A. 1981. Towards a psychophysiological model of thermal perception. International Journal of Biometeorology, V.25, pp.109-122.

CEN 2007. Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings: Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, EN15251, Brussels, Comite Europe en de Normalisation.

de Dear, R.J. 1998. A global database of thermal comfort field experiments, ASHRAE Transactions., V.104(1b), pp.1141-1152.

de Dear, R.J. and Brager, G. 1998. Developing an adaptive model of thermal com- fort and preference, ASHRAE Trans., 104, 145–167.

de Dear R.J., T. Akimoto, E. Arens, G. Brager, C. Candido, K.W.D. Cheong, B. Li, N. Nishihara, S.C. Sekhar, S. Tanabe, J. Toftum, H. Zhang and Y. Zhu Y. 2013. Progress in thermal comfort research over the last twenty years. Indoor Air 23, (6), pp.442-461.

Fanger, P.O. 1970. Thermal Comfort, Copenhagen: Danish Technical Press.

GB 2012. Evaluation standard for indoor thermal environment in civil buildings GB/T 5-785. Chinese Ministry of Housing and Urban Development; Beijing.

Schiavon, S. and Lee, K.H. 2013. Dynamic predictive clothing insulation models based on outdoor air and indoor operative temperatures, Building and Environment, V.59, pp.250-260,