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Review Article

Progress in thermal comfort research over the last twenty years

Abstract Climate change and the urgency of decarbonizing the built environment are driving technological innovation in the way we deliver thermal comfort to occupants. These changes, in turn, seem to be setting the directions for contemporary thermal comfort research. This article presents a literature review of major changes, developments, and trends in the field of thermal comfort research over the last 20 years. One of the main paradigm shift was the fundamental conceptual reorientation that has taken place in thermal comfort thinking over the last 20 years; a shift away from the physically based determinism of Fanger's comfort model toward the mainstream and acceptance of the adaptive comfort model. Another noticeable shift has been from the undesirable toward the desirable qualities of air movement. Additionally, sophisticated models covering the physics and physiology of the human body were developed, driven by the continuous challenge to model thermal comfort at the same anatomical resolution and to combine these localized signals into a coherent, global thermal perception. Finally, the demand for ever increasing building energy efficiency is pushing technological innovation in the way we deliver comfortable indoor environments. These trends, in turn, continue setting the directions for contemporary thermal comfort research for the next decades.

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Practical Implications

Thermal comfort is one of the most immediate and direct impacts exerted by the built environment on its occupants, and it is one of the strongest determinants of the overall postoccupancy evaluation of a building. In the past, most thermal comfort questions about buildings and building designs were addressed by applying instrumental observations or simulations of indoor climate parameters to predictive models of human thermal comfort. But in the last few decades, field studies involving large samples of actual occupants in real buildings have highlighted the shortcomings of such models. The reinstatement of building occupants and experimental subjects as the final arbiters of thermal comfort leads to a clearer understanding of thermal interactions between occupants and buildings, and a more complete understanding of how thermal comfort interacts with other elements of indoor environmental quality to influence overall occupant satisfaction. This, in turn, should lead to better design and operation of buildings and building services.

Introduction

This article aims to review major trends and developments in the indoor thermal comfort research domain over the last 20 years and to summarize areas of major progress in our knowledge. Two decades ago, the peer-reviewed indoor air literature was dominated by Indoor Air Quality (IAQ) papers, but there has been a resurgence of interest and intensification of activity in thermal comfort, particularly in the last 7 years. There has been an order of magnitude increase in the annual frequency of peer-reviewed papers with the words 'thermal comfort' in their title, abstract, or keywords between 1991 and 2011. Obviously, the incremental electronic transformation of the research publication industry in that 20-year period may bias the time series toward more recent publication events, but the more senior members of the comfort research community who have been active throughout the period are unanimous that the general trend is reasonably representative of what has *actually* happened.

The likely explanation for this dramatic growth in research activity is the strong connection of this topic to the issue of climate change (e.g., Nazaroff, 2008). 'Climate skeptics' notwithstanding, there remains little doubt that the buildings sector is one of the largest emitters of CO_2 to the global atmosphere (Kwok and Rajkovich, 2010; Levine et al., 2007; Urge-Vorsatz et al., 2007). For example, buildings account for 38.9% of the total primary energy used in the United States, and of this, 34.8% is used by buildings for space heating, ventilation, and air-conditioning – of which thermal comfort is the primary 'product'. In response to early climate change warnings in the 1980s and 1990s, research funding agencies world over began prioritizing the basic climate sciences with the aim of reducing uncertainties in the climate system's operation and improving resolution of climate forecasts. As consensus that anthropogenic climate change was actually happening began permeating political and public spheres in the late 1990s, funding priorities started shifting toward the basic question of '*so what are we going to do about it*?' Therefore, it comes as little surprise that there's been an intensification of research effort, particularly in the last decade, directed at improving our understanding of indoor thermal comfort, and the active building services and passive bioclimatic design approaches to its delivery.

There were dozens of database and search engines to choose from when preparing this article and using them all would have ensured a truly exhaustive coverage of the thermal comfort literature in the last 20 years. We have opted for *Scopus* because of its claim to be the largest abstract and citation database of peer-reviewed literature. Another useful feature of *Scopus* is its citation-tracking capability which has been used to identify which papers are having the greatest impact on the peer-reviewed indoor thermal comfort literature. We have relied upon frequency of citation as an index of research activity in the various thermal comfort themes and also the impact of individual researchers and ideas within this domain. To render tractable, the task of reviewing that body of research, we have classified the material into a set of themes that evolved inductively out of the literature search. These themes form the basic structure of this article. Within each of these themes, we have conducted a more focused literature search and then manually culled those yields down to just those papers presenting original contributions on the topic at hand. This focused subset or articles for each research theme were then ranked in terms of article citations, and the more heavily cited items provide most of the content of each research theme's commentary and summary.

Adaptive thermal comfort

One of the most sweeping changes across the field of thermal comfort research in the last 20 years is the acceptance of a fundamentally different, but not new, model of comfort. At the beginning of the two-decade period, there was little doubt in the literature about what was *the* model of thermal comfort – Fanger's seminal (1970) Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD). PMV/PPD reduces thermal comfort to a steady-state heat balance equation that, according to its author, could be used without modification, *anywhere* in the world. This global scope was further reinforced by the inclusion of PMV/PPD in various comfort standards, most notably ISO 7730 (1984) and ASHRAE 55-1992, lending the model an authority that HVAC engineers and others responsible for delivering thermal comfort inside buildings strongly need in this litigious age.

The history of thermal comfort models, both past and present, has been frequently reviewed in recent years (e.g., Ferrari and Zanotto, 2012; van Hoof et al., 2010; Nicol and Humphreys, 2010; Roaf et al., 2010); so, it need not be repeated here suffice to say that the main contender to PMV/PPD comfort paradigm is known as the 'adaptive model'. The name derives from a view of building occupants as integral component of the comfort 'system'. The adaptive processes were classified by de Dear and Brager (1998) as physiological (acclimatization), behavioral (using operable windows, fans, doors, awnings, etc.), and psychological (adjusting comfort expectations toward climatic conditions prevailing indoors and outdoors). The original papers on the adaptive model were published by Humphreys and Nicol in the 1970s. They described a strong relationship of the comfortable temperatures (a.k.a. *neutrality*) inside a building, to the mean temperatures prevailing inside the building, and for naturally ventilated buildings (or those in 'free-running mode'), the mean monthly temperature *outdoors* at the time of the survey also correlated with neutrality.

The adaptive approach was brought into mainstream thinking in comfort research and practice by ASHRAE when it commissioned de Dear and Brager in the mid-1990s to develop a rigorous adaptive comfort model from quality-assured field data–collected across the major climate zones of the world. A secondary goal of the ASHRAE adaptive model was to shed some light on the 'black box' of the adaptive comfort theory by *explaining* the adaptive regression model (i.e., including not just air temperature measurements but *all* the other heat balance input parameters to the PMV/PPD model as well). The *ASHRAE Transactions* paper that resulted from that project now ranks as the most frequently cited paper on the topic of thermal comfort (de Dear and Brager, 1998).

The intense scrutiny of that paper by other comfort researchers is due in no small measure to the fact that it evolved into the first adaptive comfort standard, ANSI/ASHRAE 55-2004R *Thermal Environmental Conditions for Human Occupancy*. After countless iterations and simplifications of de Dear and Brager' (1998) adaptive model, ASHRAE's committee in charge of Standard 55 (SSPC 55) agreed to include it in the 2004 edition of the standard as an option for premises without any installed mechanical cooling capacity. This precluded its application in mixed-mode buildings. Another modification of the proposal saw new effective temperature (ET*) replaced with dry bulb temperature on the x-axis to make the calculations more accessible to practitioners. This simplification meant that the effects of humidity on comfort were not captured by ASHRAE's adaptive comfort standard.

A couple of years after the ASHRAE adaptive project was published, an European project named SCATS (McCartney and Nicol, 2002) replicated the exercise with a longitudinal survey of 26 offices located in Europe (France, Greece Portugal, Sweden, and the UK), stretching over approximately 1 year. The exclusive focus on Europe reflected the intention for SCATS to provide the empirical basis of an exclusively European adaptive comfort standard, EN15251, published in 2007 (CEN, 2007).

Both EN15251 and ASHRAE standard 55-2004 contain simple linear equations relating acceptable temperatures inside naturally ventilated buildings to the temperature prevailing outdoors and apart from a 1 K difference between the y-intercepts of the two standards' equations, they look remarkably similar. But there are also differences, some of which have already been noted by Nicol and Humphreys (2010). The geographical scope of input data to ASHRAE 55-2004 standard was global, whereas EN15251 relied exclusively upon European field study data. Secondly, the analytic method used to determine thermal neutrality (indoor temperature corresponding with a neutral thermal sensation) in each of the database's constituent buildings. Large sample sizes within ASHRAE's database (naturally ventilated subsample was ~9000 of a total 21 000 questionnaires) enabled de Dear and Brager (1998) to fit statistically significant regression models that could be solved backwards to identify each building's optimum comfort temperature (neutrality). In effect, the individual building represented the unit of analysis in ASHRAE's database. Smaller sample sizes in the SCATS project (free-running sample n = 1449 out 4655 in total) led Nicol and Humphreys to rely on the Griffiths method to derive neutrality, with inherent uncertainties. The Griffiths constant is a presumed rate of change in building occupants' thermal sensation with respect to indoor operative temperature, and it is used to extrapolate beyond the range of temperatures observed in the building to the point where neutrality *might* be expected to occur in the absence of any adaptation by the occupants, *ceteris paribus*. The validity of this extrapolation hinges on the Griffith's Constant which Nicol and Humphreys' (2010) presumed to be 0.5 /K. Fanger's PMV/PPD model presents a plausible alternative way to estimate the Griffiths Constant. Taking typical summertime office attire of 0.6 clo, metabolic rate = 70 W/m^2, air speed = 0.13 m/s, rh = 50%, PMV/PPD suggests a value of 1/3.5 = 0.29/ K which is only about two-thirds of the 0.5/K presumed in EN15251 (Nicol and Humphreys, 2010), so the 'true' value of Griffith Constant remains moot.

Implicit in all adaptive models is the hypothesis that occupants of naturally ventilated buildings achieve thermal comfort across a wider range of indoor temperatures than occupants of buildings with centrally controlled HVAC systems *because of the increased levels of personal control* afforded by operable windows. Brager et al. (2004) conducted a field study in a naturally ventilated office building located in Berkeley USA where occupants had varying degrees of control over windows. Combining continuous measurement of each subject's workstation microclimate with a web-based comfort survey, they found that occupants with different degrees of personal control had significantly diverse thermal responses, even though they experienced the same thermal environments while wearing the same clothing insulation (clo) and performed the same activities (met). These findings offer further empirical support for the role of window control in shifting comfort expectations.

Since publication in 1998, ASHRAE's adaptive comfort model has been criticized for its crude bifurcation of buildings into centrally air-conditioned and naturally ventilated (free running). De Dear and Brager regarded these two classes as polar opposites on a continuum of adaptive opportunity, so centrally controlled HVAC buildings, *ipso facto*, fall beyond the scope of ASHRAE adaptive comfort standard. Nevertheless over the last 20 years, there have been several studies into the relevance of adaptive comfort concepts in air-conditioned buildings. Langevin et al. (2012) re-analyzed three centrally HVAC building field studies from the original ASHRAE RP-884 adaptive database (de Dear, 1998) and found statistically significant correlations between building occupants' level of *perceived* control over their thermal environment and their thermal comfort responses in those centrally controlled HVAC buildings. Another confirmation of this hypothesis came in an original adaptive comfort field study in office buildings in Japan (Goto et al., 2007). That longitudinal study in six buildings found that a regression gradient of indoor comfort temperature in relation to outdoor temperature fell half-way between ASHRAE RP-884's adaptive models for centralized HVAC and naturally ventilated buildings (de Dear and Brager, 1998). This was suggested by Goto et al. (2007) to result from the fact that the occupants in the Japanese study had more opportunity to control their thermal conditions than normally expected in centralized HVAC buildings (i.e., operable windows, controllable HVAC, or personal fans). The thermal comfort literature published as ASHRAE's adaptive comfort standard in 2004 is suggesting that adaptive comfort theory may well extend to air-conditioned environments, providing the occupants of those spaces have access to adequate adaptive opportunities.

Well, over two hundred peer-reviewed research articles have been published between 1991 and 2011 with the words 'adaptive thermal comfort' in their titles, abstracts, or keywords. The early years in this review's 20-year census period had fewer than ten articles per year, but then a very sudden and sustained increase around the time that the adaptive models made their appearance in AHSRAE 55 and EN15251 comfort standards (2004–2007). In the closing years of this review's census period, there were three to four times as many adaptive thermal comfort articles being published each year. It would appear as if the phenomenal worldwide growth in sustainable buildings in the last decade continues driving keen interest in the concept of adaptive thermal comfort, and the publication of ASHRAE 55 and EN15251 standards on this subject has further intensified research effort in this topic.

Thermal comfort and air movement inside buildings

This topic exemplifies the paradigm shift that has swept through the research field of thermal comfort in the last 20 years. At the beginning of the 1990s when the *Indoor Air* journal was launched, the focus of thermal comfort air movement research was *draft*, defined as unwanted local cooling. Underlying the air movement criteria included in several standards and guidelines of the time was a model of draft risk (DR), which initially estimated the percent of occupants exposed to a given combination of air velocity and temperature (Fanger and Christensen, 1986). With the understanding that airflow characteristics differed between spaces with different types of heating and ventilation systems, turbulence intensity was subsequently added to a more comprehensive version of the DR model to account for the effect of air velocity fluctuations on perceived discomfort (Fanger et al., 1988; Hanzawa et al., 1987; Melikov et al., 1988, 1990). Although the intention was that the model should be applicable to thermally neutral occupants, Fanger et al.'s experiments used progressively increasing air velocities that resulted in a steadily decreasing overall thermal sensation. In a later study, an overall thermal sensation on the cool side was found to have an aggravating effect on draft discomfort and a decrease in thermal sensation of 1 scale unit on the 7-point scale from neutral resulted in 2–3 times higher percent draft dissatisfied (Toftum and Nielsen, 1996).

In 1998, ASHRAE initiated research to evaluate the then current draft criteria in indoor environment standards and guidelines. One objective of the study was to evaluate subjects' air movement preferences under varying overall thermal sensation and temperature, and whether stated preferences for more air movement could be verified when more air movement was actually provided under controlled conditions (Toftum et al., 2002). Subjects' stated preference for more air movement was actually verified, but in general, air movement preference depended on both overall thermal sensation and temperature, and large interindividual differences existed between subjects.

In the two decades that have elapsed since the development of the DR model, emphasis has shifted away from negative ***dis***comfort of draft to the positive benefits of moving air inside buildings to enhance occupant comfort, particularly under warmer temperatures. Large field studies in office buildings in a range of climates found actual levels of dissatisfaction expressed by building occupants bearing little resemblance to the DR predictions and that occupants were more forgiving than predicted by the model. In conditions they judged as 'slightly cool' to 'warm', occupants expressed preference for more air movement, even when measured air speed was above the 0.2 m/s limit imposed by the DR model (Hoyt et al., 2009; Toftum, 2004; Zhang et al., 2007a,b). Although most of the field studies have been in office buildings with mechanical cooling and generally low air speeds within the occupied zone (de Dear, 1998), a number of researchers have examined offices, schools, and residences with window or fan ventilation, in which the air movement is higher (Brager et al., 2004; Busch, 1992; Cândido et al., 2011; Kwok, 1998; Zhang et al., 2007a,b). Especially in tropical examples, combinations of higher air speeds and temperatures were commonly evaluated as 'comfortable'.

In laboratory studies addressing warmer climates, a pioneering study by Rohles et al. (1974) examined the effects of airflow provided by fans. The study results indicated that for an air velocity of 1 m/s, the effective temperature could be extended to 29°C. In a similar investigation, Scheatzle et al. (1989) found that at least 80% of the occupants could be comfortable at a temperature limit of 28°C and air velocities up to approximately 1 m/s. Arens et al. (1998) extended this line of inquiry and found that over 80% of the subjects at 1.2 met were able to achieve comfort at air speeds up to 1.4 m/s when the temperature was 29°C, lifting to 31°C at 1 met. The study defined a *Zone of Likely Use* (ZLU) within which personally controlled air movement provided a likely alternative to mechanical cooling. Also with a focus on air movement preference, Fountain et al. (1994) defined a model for prediction of the *Percent Satisfied* (PS) people when locally controlled air movement was available. The model predicts PS as a function of air velocity and temperature in the transition zone from neutral to warm environments (25.5–28.5°C). In contrast to the DR model, the PS model recognized that people actively participate in shaping their environment. Other studies found that in the warm side of the comfort zone, the *preferred* air velocity values varied from 1 to 1.5 m/s (Cândido et al., 2010; Gong et al., 2006; Khedari et al., 2000; Kwok, 1998; Zhou et al., 2006). Even higher values, up to 1.6 m/s, were suggested for a temperature of 31°C (Tanabe, 1988; Tanabe and Kimura, 1994). Collectively, these studies emphasize that elevated air speeds not only impact indoor environmental quality in a negative way through draft in cool environments, but can also positively enhance thermal acceptability and comfort in warm environments.

Indoor airflow is nearly always dynamically changing, and human perception of it is a complex process involving not only cutaneous thermoreceptor detection of the net heat loss from skin tissue resulting from convective and latent heat transfers into the passing air, but also the occupant's nonthermal sensory perception of air motion through mechanoreceptors in the skin, particularly near hair follicles. These cutaneous thermal and nonthermal sensory mechanisms both have heightened sensitivity to the dynamic, transient nature of airflow across the skin surface. Therefore to obtain a detailed understanding of air movement comfort, it is necessary to investigate the effects of turbulence, frequency spectrum, and waveform on comfort. A series of human subject studies have been addressing this issue (e.g., Arens et al., 1998; Li et al., 2007; Ouyang et al., 2006; Tanabe, 1988; Zhao, 2007; Zhou et al., 2006). Because much of this research has been conducted in China, it is reviewed more thoroughly in the 'Emergence of China' section of this article. In general, there is much more to be carried out, aiming at including such measures in indoor environmental standards and in design specifications for fans and other occupant-controlled equipment.

With so much empirical evidence accumulating in the last 20 years supporting the comfort potential of increased air movement (Aynsley, 1999, 2008; Chow and Fung, 1994; Chow et al., 2010; Gong et al., 2006; Ho et al., 2009; Scheatzle et al., 1989; Schiavon and Melikov, 2008; Toftum et al., 2003; Zhang et al., 2007b, 2009, 2010e; Zhou et al., 2006), recognition is finally being made in the standards. In Brazil, there is currently a proposal to include minimum air speeds in design guidelines for natural ventilation (Cândido et al., 2011), and the most recent revisions in ASHRAE Standard 55-2010 (ASHRAE, 2010) indicate how much warmer the comfort zone can be stretched by increasing air speeds up to 0.8 m/s, without requiring individual occupant control and then beyond 0.8 up to 1.2 m/s when the occupants are granted control (Arens et al., 2009). These new provisions represent a significant step forward in enhancing indoor environmental quality with elevated air speeds, as well acknowledging the important role played by occupant environmental control (and perceived control).

For the building designer or the HVAC equipment manufacturer, it has been a challenge to meet the rather conservative air movement limits in indoor climate standards and guidelines (ASHRAE, 2004; ISO, 2005). Also, it may be that the air movement preferences seen in field studies are driven by the common belief that links air movement to perceived air quality and freshness improvements (Arens et al., 2008, 2011; Melikov and Kaczmarczyk, 2012). Indeed, the tight air movement criteria may have impeded the use of air movement in higher indoor temperatures and prevented decreased energy use and greenhouse gas emission (Hoyt et al., 2009; Zhang et al., 2011). On the other hand, discomfort caused by air movement has for many years been one of the most prevalent complaints of the indoor environment in buildings located in cold or temperate climate regions, which is the reason a larger part of the earlier research was focused on draft. It seems there is a need in the future to formulate more flexible and diverse criteria for air movement in buildings with differing demands acknowledging that occupant air movement sensitivity and preferences differ and that the broader external climatic context of a building affects how its occupants relate to indoor air movement.

Thermal acceptability under personal comfort systems

Building energy simulation and thermal performance software seems to be one of the key drivers for research into the topic of personal comfort systems. Popular simulation tools in design and energy efficiency certification such as *EnergyPlus*, *Design Builder*, *ESP-r*, *TRNSYS*, etc. require users to specify building occupancy and behavior schedules. This reflects the growing recognition that occupant interaction with the building, fenestration, and comfort controls is as significant as building envelope and HVAC system efficiency in determining the overall thermal performance and energy demand of a building. Typical thermal comfort papers in this theme are those by Rijal et al. (2009) and Haldi and Robinson (2011). Haldi and Robinson (2011) administered a daily web-based comfort questionnaire to a sample of office workers in Lausanne in conjunction with continuous monitoring of indoor and outdoor environmental conditions. Variations in clothing insulation worn *in*doors were best predicted by the daily mean *out*door temperature. These observations add further support to the adaptive comfort approach of permitting indoor temperatures to drift with outdoor weather and seasonal conditions instead of being tightly regulated around a static indoor design temperature. Rijal et al. (2007) used both longitudinal and transverse research designs in a study of comfort control behavior of office workers in 15 office buildings in the UK. By presuming that windows were opened for thermal rather than IAQ control, the researchers were able to develop a behavioral control algorithm for windows that could be implemented within the *ESP-r* building thermal simulation tool.

Why building energy simulation and thermal performance softwares are driving research interest in the issue of Personal Environmental Control (PEC) and thermal comfort can probably be accounted for by the inclusion of credits for occupant control in the IEQ sections of various building sustainability rating tools. For example, the US Green Building Council's rating tool, LEED, offers one credit point for projects that provide a high level of thermal comfort system control by individual occupants or groups in multi-occupant spaces (USGBC, 2009). To qualify for this point, the project must provide at least 50% of the building's occupants some form of thermal adjustment such as operable windows or controls that impact the primary environmental comfort parameters of air temperature, mean radiant temperature, air movement, and humidity. The Green Building Council of Australia's *Green Star* also encourages designs that facilitate individual control of thermal comfort by offering two points when the base building provides occupants control over airflow rates, air temperature, mean radiant temperature within each workspace, through any combination of natural or mechanically assisted natural ventilation, mechanical air-conditioning, and mixed-mode ventilation systems (GBCA, 2010). Japan's CASBEE rating tools recognize five levels of individual control – from manual control of air volume delivered to the space (level 1), up to occupant-adjustable local temperature and airflow volumes (level 5) (JSBC, 2011). The UK's BREEAM also offers two credits for thermal comfort for design-stage projects, and although it mentions occupant control, the precise nature and amount of personal control required are less prescriptive than the other rating tools mentioned above (BRE, 2001).

In the most highly cited article in this research theme of occupant control, Leaman and Bordass (1999) analyzed the Post Occupancy Evaluation (POE) data of the *PROBE* study in UK office buildings. They found that comfort, perceived health, and self-assessed productivity of occupants were all related to occupants' perceived control. For the occupant, '*satisficing*' may be a better description of occupant behavioral control than comfort optimizing. It was noted that the biggest threat to occupant satisfaction occurs when a building and its systems are too complicated, unintelligible, or unresponsive to occupant control behaviors.

PEC also refers to systems that provide thermal comfort or ventilation to the occupant under their control. Such systems include fans or local duct outlets, radiant or convective heaters, and warmed or cooled surfaces on chairs, desks, and floor. In the last 20 years, a number of such systems have been developed and tested, driven by the twin goals of improving comfort and ventilation effectiveness while at the same time expending less energy to accomplish it. By providing the individual occupant with the capacity to fine-tune their thermal environment to meet their unique comfort requirements at each point throughout the working day, such systems hold the promise of meeting 100% satisfaction, which is virtually impossible in a uniformly conditioned space because of interpersonal differences in clothing, gender, age, body mass, metabolic rate, localized appliance heat loads, etc. The systems have had a variety of names in the literature such as 'task-ambient conditioning', 'local thermal distribution', 'PEC', and 'personal ventilation', in addition to some trade names such as 'personal environmental module'. The seminal research work in this area was a large field experiment by Kroner et al. (1992) on personal environmental modules in a US insurance office where the work rate was automatically monitored. The study highlighted productivity gains but the methods used (providing the personal control options but intermittently disabling them) provoked controversy about the validity of the research design. Lost in the debate was the undisputable finding that the systems were very popular with the occupants simply because they improved comfort. Field studies by Bauman et al. (1998) manipulated the interior conditions of several corporate offices while measuring the responses of two groups of occupants with and without personal environmental modules. The control group's highest level of thermal acceptability was 80%, while the occupants with personal systems achieved 100% thermal acceptability across a range of ambient temperatures and energy expenditures. To date, this appears to be the only field study based on thermal comfort observations from building occupants with personalized environmental control systems.

There have been many laboratory studies of such personal comfort systems worldwide. Comfort and perceived air quality are both key outcome variables in the research designs. Although the systems vary, they all have the ability to correct for excursions beyond the adaptive model's neutral comfort zone in either the warming or cooling direction, or sometimes both. Zhang et al. (2010d) are typical of several studies that tested a set of PEC devices focusing air and radiation on the exposed face and extremities to determine optimally energy-efficient configurations. Comfort was obtained at very low wattages for both cooling and heating across a wide range of ambient temperatures. Perceived air quality was also improved for a range of ambient temperatures by providing air movement near the face, although the underlying causal mechanisms are not fully understood. Both the perceived air quality and productivity benefits accruing from PEC systems appear to be more a function of enhanced comfort than of air temperature *per se*, contradicting previous studies that made those links.

With personal environmental control systems, the allowable indoor ambient (room) temperature ranges can exceed the adaptive comfort zones by up to 4.5 K on either boundary (Zhang et al., 2011). What proportion of this is due to the perception of personal control and what is due to actual heat transfer provided to individual occupants by the PEC system is currently unresolved in the research literature.

Thermal comfort in nonuniform and nonsteady-state environments

The conventional models of thermal comfort such as Fanger's PMV/PPD and the Pierce Lab's 2-node model are premised on steady-state conditions, but the energy balance between building occupant and their immediate indoor thermal environment is seldom steady due to the complex interactions between building envelope, outdoor weather, fenestration, occupancy, HVAC systems, and of course, building occupants whose metabolic rate is constantly changing as they go about their daily lives. Changes in air temperature, radiant temperature, and air movement are most often the reasons for transient and nonuniform indoor environment. Occupants' activities, such as change in metabolic rate, opening of windows, etc., often generate transients in the thermal state of the body. Building design and systems may also generate transient environment. For example, temperature drifts are generated by active slab heating and cooling systems or cycles caused by demand response strategies in air-conditioning. Comfort dynamics have multiple signals operating on diverse time scales, all superimposed on each other.

Hensen published the most thorough literature review to date of work on thermal comfort under variations in the key comfort parameters to examine acceptable range of temporal variability (Hensen, 1990). But since that paper was published 22 years ago, there have been significant further developments on the topic of comfort dynamics. The major development in this since 1990 has been in the area of multinode models of human thermal physiology and comfort (Fiala et al., 1999, 2001; Huizenga et al., 2001; Tanabe et al., 2002), reviewed elsewhere in this article ('Multinode models of human thermophysiology and comfort'). The most highly cited article on this topic was the classic paper by Gagge et al. (1967). That high impact is, in part, due to its contribution of empirical data to multinode modelers. But it has also provided the analytical basis for specifications of acceptable temperature drifts, ramps, and cycles in several versions of ASHRAE's Standard 55. Recommendations for indoor temperature drifts and ramps are defined in the present thermal comfort standards (ASHRAE, 2004; ISO, 2005). Recent laboratory studies with human subjects verified the recommendations on drifting temperatures as stated in the standards (Kolarik et al., 2009; Toftum, 2010). Thermal sensation of the subjects who were free to adjust clothing insulation did not differ significantly from that of subjects with fixed clothing insulation levels. However, it was found that longer exposure to temperature drifts may increase reports of Sick Building Syndrome symptoms and negatively affect self-estimated task performance. Even moderate ramps (±0.6 K/h) were sensed by sedentary subjects after 3–4 h delay (depending on the clothing thermal insulation). The relationship between mean thermal sensation and the percentage of thermally dissatisfied subjects was in fairly good agreement with predictions by the PMV/PPD model developed under steady-state exposures and included in current thermal comfort standards.

Typically, room temperature fluctuations occur at relatively slow frequencies. But relatively fast and large temperature fluctuations, up to 3 K, have been measured in rooms with exhaust mechanical ventilation and window slits, while in spaces with mixing and displacement air distribution, the standard deviation of the temperature fluctuations was generally <0.5 K (Melikov et al., 1998). The frequency of the temperature fluctuations observed to contribute up to 90% of the measured standard deviation of the air temperature was in the range 0.2–1.2 Hz.

Human response to transient thermal environments due to changes in air velocity has been studied but peer-reviewed journal publications are relatively few. Climate chamber experiments reveal mean velocity, turbulence intensity, and frequency of velocity fluctuations all affect heat and mass transfer from the human body. The effect of mean velocity and turbulence intensity is considered in the standards when predicting local discomfort due to draft (ISO, 2005). Research indicates that, within the comfortable range of temperatures defined in the standards, airflow with velocity fluctuations between 0.5 and 0.7 Hz is perceived as more uncomfortable than airflow with lower or higher frequency fluctuations. An explanation for this observation was provided by numerically modeling heat transfer through skin tissue in which warm and cold cutaneous thermoreceptors had been embedded (de Dear et al., 1993; Ring et al., 1993). Anatomical and functional data required to describe thermoreceptors numerically were obtained from the definitive work by Hensel (1981). The numerical skin model demonstrated that the discharge rate of cold cutaneous thermoreceptors peaked when the skin surface was exposed to an airflow with frequencies in the range noted above (circa 0.5 Hz).

Although the overwhelming majority of comfort research to date has focused on homogenous thermal environments (isothermal), in practice, most built environments present more complex thermal settings to the occupants. Occupants may be immersed in asymmetric radiant fields (e.g., due to solar radiation through the windows), vertical temperature gradient (e.g., due to ceiling radiant heating), localized air movement at elevated velocity, and/or low temperature [e.g., in rooms with displacement ventilation (DV)] and high floor temperature (e.g., in the case of floor heating). Plenty of research in this domain of 'local thermal discomfort' was performed and published prior to the period under review in this article, but it mainly dealt with the comfort effect of singular nonuniformities or asymmetries. The collective knowledge and practical implications of these studies are encapsulated in the various comfort standards' sections on local thermal discomfort (e.g., ASHRAE, 2010; ISO, 2005).

The combined effect of two or more thermal nonuniformities has received relatively little research attention to date. Conceptually, the current generation of thermal comfort standards begin with the notion of 95% comfort (or acceptability) and then progressively decrement that number by applying a suite of predictive dissatisfaction models such as PPD and DR to the circumstances under analysis. However, recent thinking in the literature suggest that nonuniform environments may in fact provide occupants with *better* thermal comfort, perhaps even thermal pleasure, compared with homogenous, isothermal, and steady environments (de Dear, 2011). In a climate chamber study, Melikov and Knudsen (2007) exposed subjects to nonuniform individually controlled environment generated at workstations and comprising several heating/cooling methods, including personalized ventilation with cooling air focused at the face and the chest, an under-desk air terminal device supplying cool air to the lower chest, a chair with convectively heated backrest to provide local heating to the back, an under-desk radiant heating panel to heat the legs, and a floor-heating panel for providing thermal comfort at the feet. At room air temperatures of 20, 22, and 26°C, subjects reported higher thermal acceptability of the nonuniform environments than at the reference exposures under uniform thermal environments.

Multinode models of human thermal physiology and comfort

Three leading multinode models for thermal comfort in circulation at present were developed independently in the UK, USA, and Japan (Fiala et al., 1999, 2001; Huizenga et al., 2001; Tanabe et al., 2002). The underlying algorithms of these models are based on the pioneering work by Wissler (1964) and Yale's J.B. Pierce Laboratory in the 1970s (Stolwijk, 1980) that evolved into the two-node model that underpins the widely used thermal environmental indices *ET** and *SET**. Stolwijk's multinode model is a product of the development of computer programs capable of predicting the thermal response of astronauts from the Apollo program in the 1960s. Its six segments included head, trunk, upper extremities, lower extremities, hands, and feet. Each segment is further divided into nodes representing the core, muscle, fat, and skin layers. Heat exchanges between the segments are conducted through the central blood (as another node). Along with the multinode human physiology modeling, there have been other finite difference (Wissler, 1964) and finite element schemes (Smith, 1991) or 3D models (Werner, 1989), which are not discussed in this review.

The evolution from two nodes to the current generation of models with hundreds of nodes has been made possible by the exponential growth in computational power in recent decades. The modern multinode models are all based on a numerical solution of the heat balance of individual nodes (skin tissue, muscle tissue, fat tissue, bone), each of which has its own distinct physical properties (heat capacitance, conductivity, etc.). Nodes are grouped together to form anatomical segments (finger, hand, fore arm, upper arm, head, etc.), all of which are thermally connected by a common node which exchanges heat with each node by Pennes' blood perfusion model. Each anatomical segment exchanges heat to the environment by its own radiative, convective, latent, and conductive heat transfer coefficients (e.g., de Dear et al., 1997). Typically, the heat balance of each node is solved in discrete time steps of duration that is scaled according to the rate of thermal transient affecting the segment. These models have evolved in complexity to the point that they can now resemble numerical thermal manikins, with the advantage over their analog counterparts being that outputs include not just thermal status of the segments and nodes, but also physiological responses to those thermal states (see Table 1 in detail).

Table 1 History of numerical models of human thermoregulation and thermal comfort

Wissler (1964)	The body was divided into 15 cylinders whose temperature distribution calculated with a simple finite differencing solution of the heat conduction equation.
Stolwijk and Hardy (1966)	The body is idealized as 3 cylinders. Head and Limbs are divided 2 nodes: core and skin. Body is divides 3 nodes: core, muscle, and skin. Every nodes are connected each other with central blood pool.
Gagge et al. (1967, 1986)	A sphere represents the human body, divided into two nodes: core and shell.
Stolwijk (1971)	This model is divided 6 body parts. Head is idealized as sphere, and the others are idealized as 5 cylinders. Every body parts are divided 4 nodes: core, muscle, fat, and skin. This model uses the central blood pool.
Smith (1991)	The model consists of 15 cylindrical body elements. The blood system is modeled to calculate heat exchange with blood flow. Blood flow regulation is considered by changing the caliber ratio of blood vessel near skin surface according to temperature.
Fiala et al. (1999)	The body is idealized as 15 spherical or cylindrical body elements. This model provides the analysis underlying UTCI (Universal Thermal Climate Index) developed by the World Meteorological Organization and International Society of Biometeorology for application in all outdoor meteorological settings and climate zones, from hot to cold.
Tanabe et al. (2000)	This model consists of 16 body segments. Head is idealized as a sphere, and the other body parts are represented as cylindrical elements. Every segment is divided into 4 nodes: core, muscle, fat, and skin. The nodes are connected with vascular system and central blood pool.
Huizenga et al. (2001)	The Berkeley model can work under any number of segments, depending on the complexity of the application. Each segment consists of core, muscle, fat, and skin nodes. The model includes a clothing node that includes heat and moisture transfer qualities of clothes.
Zhang et al. (2010a,b,c)	These models can predict the local thermal sensation and local comfort of 19 individual body parts and the whole-body sensation and comfort responses based on thermo physiological inputs (skin and core temperatures). The model can be applied to a range of environments: uniform and nonuniform, transient, and stable.

Having successfully solved the physics and physiology of the human body, now the challenge is to model thermal comfort at the same anatomical resolution and to combine these localized signals into a coherent, global thermal perception. For example, a subject's whole-body heat loss may not be far from zero, but if their hand is cold, they will probably describe the overall environment as uncomfortably cold. In complex, thermal environments (with radiant floor and ceilings, stratified environments, solar radiation, or warm/cold windows) localized sensation and discomfort determine whole-body thermal sensation, acceptability, and preference. For example, the same degree of face cooling by convection (and having the same cool sensation) may feel pleasant or unpleasant, depending on the whole-body thermal state: Pleasant when whole-body thermal state is warmer than neutral; unpleasant when whole-body state is cool. To evaluate comfort in nonuniform and transient environments, a model that predicts both sensation and comfort at the local body parts level, as well as the whole-body level, are required. To date, the most comprehensive attempt to collect subjective local comfort and sensation responses to steady-state, nonuniform, and transient thermal stimuli was performed at UC Berkeley (Zhang et al., 2010a,b,c). Their approach consisted of a series of climate chamber experiments with human subjects (Arens et al., 2006a,b; Huizenga et al., 2004) who had localized thermal stimuli applied to individual body segments in isolation from the rest of the body. This was achieved by a system of customized cuffs fitting the body segment in question. These cuffs were connected to independently controlled air-handling units. Their thermal sensation model derived from this complex set of subjective comfort and sensation data was derived by regression of skin and core temperatures against thermal sensation votes obtained in the chamber experiments. The sensation for each local body part is predicted by a logistic function with four inputs: local skin temperature, mean-skin temperature to represent the whole-body thermal state, and the time derivatives of skin and core temperatures representing the response to transients. Each of the four predictors can be mapped to a specific output of the Berkeley multinode physiological model.

In trying to make sense of this complex set of human sensation and comfort experiments, the Berkeley researchers made use of the concept of thermal alliesthesia. Cabanac (1971) proposed a general physiological theory of pleasure in relation to the body's homeostatic systems, including thermoregulation. According to the theory of alliesthesia, the hedonic tone of peripheral thermal stimuli is determined by cross-reference to displacement and/or trend of core temperature. For example, when core temperature is trending downward any peripheral thermal stimulus that has the prospect of restoring it to set point will be perceived as pleasant. Conversely, if the peripheral thermal stimulus has the prospect of enlarging core temperature's displacement from its set point, the subject experiences that stimulus as unpleasant. Cabanac's evidence was cool and warm stimuli applied to subjects' hands. Mower (1976) and Attia expanded Cabanac's study by applying stimuli to other body segments and including the neutral whole-body thermal state (Attia, 1984; Attia and Engel, 1981). An important observation was that, under neutral conditions (30°C room air, 0.05 clo in Attia's study), the most comfortable vote recorded on a thermal comfort scale was close to a vote of 'indifferent'. Positive thermal comfort could only be induced in hyper- and hypothermic conditions, when localized cooling and heating were applied. In neutral thermal conditions, subjects appeared oblivious of the thermal environment and did not feel strong comfort/pleasure responses. Maximum pleasure was felt primarily, while discomfort was being relieved or partially relieved. de Dear (2011) recently proposed alliesthesia as a logical framework to differentiate thermal pleasure from thermal neutrality, but a comprehensive model of alliesthesia for application in transient and asymmetrical human thermal environments remains elusive at this point in time.

Uniformity within the indoor environment has been the conventional design target in the past, but increasingly we recognize that our bodies are not exposed uniformly in complex, real thermal conditions. Therefore, we can expect multinode models to play more important roles in the future, especially when coupled with high-resolution computational fluid dynamics (CFD) simulations of complex indoor environments. Coupled CFD and multinode physiological models offer an ideal platform for assessment of indoor thermal conditions under personal environment control, and several exploratory studies on this research frontier have been published recently (Gao et al., 2006, 2007).

Thermal comfort in alternative HVAC designs

HVAC has been directly implicated in both major anthropogenic crises in the global atmospheric environment over the last 20 years. First came the Montreal Protocol on substances that deplete the stratospheric ozone layer at the end of the 1980s, compelling the HVAC sector to develop alternative refrigerants. But it was the emergent climate change issue of the late 1980s and 1990s and the ensuing green building movement that forced a fundamental rethink of HVAC systems. The Kyoto Protocol to the United Nations Framework Convention on Climate Change came into force in 1997, and the research literature suggests that technological evolution in HVAC systems, such as chilled beams, radiant ceiling panels, and DV, arose in response to the energy efficiency imperative and then research into their thermal comfort implications has come after the event. *In the last 20 years*, 93 articles were published in the broad area of thermal comfort under alternative HVAC designs that collectively received a grand total of 445 citations between 1996 and 2011.

Chilled beams are classified into active and passive systems. Passive chilled beams are increasing in popularity due to the obvious efficiency of not having to transport large volumes of conditioned air around the building. Space efficiency, combined with their energy efficiency and quiet operation, is making them a regular feature of many so-called ‘green buildings’. A passive chilled beam is a source of natural convection, causing a negatively buoyant plume of cold air to drain from above into the occupied zone. Relying on natural convection the plume is susceptible to disturbances in the near vicinity. The performance characteristics of a passive beam convective regime within the occupied zone were investigated by Fredriksson et al. (2001) using a full-scale simulated office, complete with fluorescent tube lighting, a personal computer, and thermal manikin providing ‘typical’ heat loads. The occupied zone airflow regime was monitored at 2 Hz by an array of 26 thermo-anemometers, while the air temperature field underneath the chilled beam was measured with infrared thermography. Two low-frequency disturbances in the downward density flows were observed; one relating to discrete eddies (swirls) of cold air detaching from the 15°C chilled beam and the other resulting from interaction of the density flow with background room air circulations that set-up a lateral oscillation in the convective plume beneath the chilled beam. The experiment did not include any subjective evaluations from human subjects, so Fredriksson et al.’s (2001) conclusions about the impact of passive chilled beams’ intermittent flow characteristics on comfort were based purely on the theoretical DR model reviewed elsewhere in this article. Indeed, inferring DR purely from a low-frequency intermittence, without reference to the ambient air temperature, seems to be an oversimplification of human perception of airflow and misses potentially *positive* alliesthesial effects of intermittent flow in warmer-than-neutral ambient temperatures.

Active beam systems have the chilled air being entrained by a jet of conditioned air and then the mixture being delivered into the occupied zone from above. Like their passive beam relatives, active beams are becoming increasingly popular in green buildings due to their energy efficiency that results from substantially reduced primary airflow requirements compared with all-air systems. From the point of view of occupant’s comfort, active chilled beams are often regarded as indistinguishable from conventional all-air systems like VAV with overhead slot diffusers, but this overlooks a fundamental difference – the temperature of the beam’s discharge mixture is typically 2–3 K warmer than that of all-air systems, necessitating higher airflow discharge rates into the space. These higher airflow rates potentially increase the risk of draft according to the DR model (discussed in the air movement section of this article). Loudermilk (2009) identified the biggest risk to comfort from active chilled beams as the region directly under the point where two adjacent beams’ discharge streams converge, ‘dumping’ cold air down into the occupied zone, and in particular, onto the draft-sensitive region at the back of the occupant’s neck. Based on the DR model, Loudermilk developed a set of simple installation guidelines using inputs such as the confluence velocity, the difference between the supply airstream and room temperatures, and the vertical distance between the point of collision and the top of the occupied zone. But as with Fredriksson et al.’s (2001) analysis above, there was no empirical comfort basis underpinning Loudermilk's (2009) design guidelines. Indeed, despite the growing popularity of chilled beams, to date, there is very little research into their comfort performance characteristics, either field or laboratory based, involving human subjects.

DV systems are premised on the delivery of conditioned air near floor level, at temperatures slightly below the mean air temperature within the occupied zone and then relying on natural convective processes to transport that air from floor to ceiling where it is returned to the HVAC plant. Delivery of conditioned ventilation air directly into the occupied zone ensures good ventilation effectiveness of DV systems. The size of cooling load that can be handled by DV systems depends upon the magnitude of the thermal gradient established from floor to ceiling; the higher the cooling load, the larger the gradient, and so the limiting factor on DV systems really comes down to the local thermal discomfort and acceptability limits on vertical temperature gradients. The recommended vertical temperature limit, typically measured between ankle (0.1 m) and neck (1.1 m) heights, of 3 K/m was stipulated in a variety of conference papers summarized and reviewed by Novoselac and Srebric (2002). Wyon and Sandberg (1996) performed laboratory experiments with 207 human subjects who were exposed to 4 K/m and found that it is still acceptable, providing that air quality was satisfactory, and individual control of whole-body heat loss was provided for sensitive individuals. In another laboratory study, Cheong et al. (2006) found that a vertical temperature gradient up to 5 K/m was acceptable to their tropically acclimatized human subjects. The sensitivity of these vertical gradient temperature limits to mean temperature within the occupied zone has yet to be experimentally evaluated with human subjects.

Draft is an issue that must not be neglected in DV systems (Melikov et al., 2005). Wyon and Sandberg (1990) performed a series of full-scale experiments on the thermal comfort provided by a DV system, but used a thermal manikin rather than actual human subjects for their inferences about thermal acceptability. They found that the 'thermal comfort' was better above table height, and thermal discomfort conditions were mostly observed between leg and ankle heights. Lian and Wang (2002) used actual human subjects ($n = 18$) to obtain subjective ratings and also physiological observations (skin temperature gradients between chest and foot, $\mathrm{D}t_{sk}$) of thermal comfort states during 1-h exposures in a climate chamber in which various DV configurations were operating. Their data showed that the four factors that affect thermal comfort in DV systems, in order of importance, were distance between occupant and outlet, temperature of supply air, velocity of supply air, and type of outlet (Lian and Wang, 2002). They concluded that skin temperature difference $\mathrm{D}t_{sk}$ was the best index to evaluate the thermal comfort of DV environments, and based on their regression equation, the DV environments will be comfortable if $\mathrm{D}t_{sk}$ is maintained at or <3 K.

The combination of chilled ceilings and DV systems has been popular in Europe since the 1990s due to the promise of high energy efficiency (low greenhouse emission) and high ventilation effectiveness. Again thermal comfort has been relegated to a secondary performance criterion, but there are some research papers. Alamdari et al. (1998) reported results from CFD simulation of room with such a combined system. Predicted velocity vectors within the occupied zone were then used as inputs to ISO-7730 (2005) comfort standard's PPD and DR models. These indices use air temperature, air speed, and turbulence intensity as inputs to predict the percentage of occupants who will be dissatisfied with the thermal environment specified.

A pattern has emerged from this short review of thermal comfort of alternative HVAC designs – and that is the paucity of real human subjects in the evaluations, probably reflecting the very large costs of paying subjects for their time, plus the additional complexities of negotiating with human research ethics committees. Instead, most researchers on thermal comfort performance of alternative HVAC systems seem content to trust the comfort predictions of the PPD and PD models, despite the vast body of empirical evidence casting doubt on the relevance of these models to warm environments, which happens to be precisely the context where one would expect to apply 'green' alternative HVAC designs.

Thermal comfort in mixed-mode buildings

Mixed mode refers to a hybrid approach to space conditioning that uses natural ventilation through windows or vents, either automatically or manually controlled, and then switches over into air-conditioned mode whenever natural ventilation is insufficient to provide occupant comfort (Brager, 2006). The practice is as old as air-conditioning itself, but the actual terms 'mixed-mode' and 'hybrid ventilation' only appeared in the literature over the last couple of decades, and systematic research on these topics is even more recent. This growing interest in operable windows has been driven, in part, by the mainstream acceptance of the adaptive thermal comfort concept (reviewed elsewhere in this paper), reduced energy consumption, and greenhouse gas emissions compared with conventional air-conditioned buildings (e.g., Emmerich, 2006) and fewer Sick Building Syndrome symptoms (e.g., Seppanen and Fisk, 2001). But this rehabilitation of the operable window comes with some reservations on the part of engineers and architects. The lack of predictability and control over indoor thermal conditions in purely naturally ventilated buildings potentially exposes them to dissatisfied, or even worse, litigious clients.

Mixed-mode buildings therefore represent a pragmatic compromise – the best of both worlds – naturally ventilated during benign weather conditions and air-conditioned at other times.

Although based on a relatively small body of empirical evidence from mixed-mode buildings, it appears as if the cooling systems in buildings located in diverse climatic contexts start to be switched on by their occupants (or their building management system algorithms) at approximately the same outdoor temperature, about 25°C, and there was a 50% probability of mechanical cooling being switched on at the higher temperature of 30°C in both European and Pakistani commercial buildings (Nicol and Humphreys, 2004). Classical thermal comfort field studies in mixed-mode buildings, based on simultaneous instrumental and subjective comfort observations, are few and far between. An extensive longitudinal study by Rowe (2004) in subtropical Sydney showed that adaptive comfort behavior in an academic office building was clearly taking place even in the presence of supplemental cooling equipment. A more recent 'right-here-right-now' comfort survey by Deuble and de Dear (2012), also in a Sydney academic office building but different to the one studied by Rowe, found that occupants' acceptance of the same combination of thermal conditions was dependent on the building's mode of operation – identical thermal environmental conditions deemed acceptable while the building was operating in natural ventilation mode were found to be unacceptable by the same occupants in the same building during its air-conditioned mode of operation.

More POE surveys have been carried out in mixed-mode buildings using only occupant surveys, but without accompanying physical measurements. Holmes and Hacker (2007) reported POE results from a UK mixed-mode building of the 'changeover' type, switching from natural ventilation to air-conditioning whenever internal temperatures were sensed above 25°C. The mixed-mode building's very favorable POE results were benchmarked against the BUS database and found to be in the top 2–5% of the entire UK building database. Brager and Baker (2009) benchmarked occupant satisfaction ratings in twelve mixed-mode buildings in the US against the remaining 370 commercial buildings that were in the CBE database at that time. The mixed-mode buildings performed exceptionally well compared with the overall building stock in the CBE database, especially with regard to thermal comfort and air quality. The best performing mixed-mode buildings were newer than the benchmark average, were located in moderate climate zones, had radiant cooling or mechanical ventilation only, and allowed high degrees of direct user control. Summertime complaints did not cite draft from open windows, but did refer to draft when the buildings were operating in air-conditioned mode, suggesting problems with overcooling during air-conditioned mode.

From a thermal comfort point of view, mixed-mode buildings raise interesting theoretical and regulatory questions because of the 'duality of comfort expectations' they induce in their occupants. The adaptive comfort literature reviewed elsewhere in this article has established that identical indoor climatic conditions can receive disparate evaluations by their occupants, depending on whether the building is air-conditioned or naturally ventilated, and the comfort standards for both types of building reflect this thermal perceptual ambivalence. But in a mixed-mode building, there still remains some uncertainty about whether occupant expectations can shift modes as quickly as the building can, and further research is clearly needed on how to optimize setpoint control algorithms for the different operating modes.

Thermal comfort and productivity

Productivity is defined as the extent to which activities have provided performance in terms of system goals (Parsons, 1993). In the context of this review article, the implicit chain of causation is that indoor thermal environments affect physiological thermoregulation and psychological process involved in thermal comfort, which may in turn affect performance at certain tasks that may interact with other factors to affect overall productivity of the building occupant.

It is accepted wisdom that salary costs of workers inside a typical commercial building are about two orders of magnitude more expensive than the operational energy and maintenance costs of the building's fabric and plant (Table 2). While there may be some minor disagreement between researchers about the exact numbers in Table 2, they all provide a compelling explanation for the numerous research attempts to quantify thermal effects on performance and productivity and to answer the basic question of whether or not optimal thermal comfort conditions coincide with those associated with maximum productivity?

Despite the large volume of research effort directed at it over the last couple of decades, our understanding of the thermal comfort effects on productivity is far from clear. This is largely due to diverse definitions of the productivity metric and their varying degrees of validity. Performance has variously been quantified by educational achievement tests, psychological tests, neurobehavioral tests, simulated office tests, commercially accepted work-place task performance indices, and subjective self-assessments of productivity, to mention just a few. There is also a plethora of approaches to the quantification of thermal comfort in this productivity literature, ranging from simple air temperature, through operative temperature, up to rational comfort indices (*ET**, *SET**, *PMV*), and finally self-rated

Table 2 Comparison of energy and staff costs for offices

Costs	North American Offices (CIBSE, 1999)					Japanese Offices (Nishihara and Tanabe, 2010)
	Rosenfeld	Abdou and Lorsch	EPA	Woods	BOMA	
Staff costs [$/m^2/year]	3000	2180	2000	2370	1300	3700
HVAC running costs [$/m^2/year]	–	20–100	60	120	29	–
Energy costs [$/m^2/year]	15	10–20	20	20	15	36
Ratio of staff to energy costs	200	114–218	100	118	87	103
Equivalent increased productivity ratio of annual energy cost [%]	0.5	0.5–0.9	1.0	0.9	1.2	1.0
Equivalent working time of daily energy cost [min/day per person]	$2^1/_4$	$2 - 3^3/_4$	$4^1/_3$	–	5	$4^3/_5$

subjective thermal assessments on the familiar 7-point scales. In view of this inconsistency in definitions of independent and dependent variables, it is not surprising the results are confusing (CIBSE, 1999; Fisk and Rosenfeld, 1997). For example, even within one paper (Pepler and Warner, 1968) contradictory associations were found with classroom temperature; school children performed mental tasks faster at 20°C, but made fewer mistakes at 27°C. Some researchers claim to have shown that thermal conditions providing thermal comfort do not correspond with maximum *efficiency* (e.g., Wyon and Wargocki, 2006) but these are in a minority. Different task types, exposure times, or workers' psychological factors such as motivation or arousal level are all potential confounders to the relationship between thermal comfort and productivity.

Seppänen and Fisk (2006) conducted literature review of the subject, collating the data from 26 separate studies into a meta-analysis of task performance data (dependent variable) and concurrent room temperature (independent variable). A parabolic curve was forced through the very scattered cloud of 26 datapoints, its vertex coinciding with 21.6°C which Seppanen and Fisk interpreted as the optimum temperature for productivity. Their interpretation has become highly contentious due to its suggestion of diminished productivity toward the warmer side of the comfort zone commonly found in green buildings. One of the most common criticisms leveled at the meta-analysis is its disconnection with contemporary thermal comfort thinking in their choice of independent variable: simple room temperature instead of a more logical comfort metric. Adaptive comfort theory has firmly established that neutrality can be attained in indoor temperatures ranging almost 10 K above Seppanen and Fisks' 21.6°C productivity optimum, depending on the subject's prior thermal history, and calibration of the independent variable in relation to group neutrality may have improved the very small amount of variance in the 26 datapoints explained by Seppanen and Fisks' parabolic model. Another meta-analysis of thermal effects on task performance was performed by Pilcher et al. (2002) whose literature search catch was culled to just 22 papers containing original, quality-assured data. Performance measures were normalized as *d*-scores for 515 different task/exposure experiments. Contradicting Seppänen and Fisk (2006), Pilcher et al.'s analysis indicated that performance peaked across a 6 K range, from 21 to 27°C, which coincides with the normal comfort zone for sedentary occupancy.

Tanabe and Nishihara (2004) took a different approach to the problem by introducing some new evaluation methods for factors affecting productivity, not only task performance but also the symptoms of fatigue. This included subjective self-assessments of fatigue and also objective measures including voice analysis and cerebral blood oxygenation changes. Forty subjects performed various cognitive processing tasks under three different temperature conditions (25.5, 28, and 33°C). Consistent with the majority of peer-reviewed research findings on this topic, Tanabe and Nishihara found thermal environmental effects on task performance were contradictory among the various task types. However, their subjects complained of the feeling of mental fatigue whenever more cerebral blood flow was required to maintain the same level of task performance during the 33°C exposure compared with the thermally neutral condition.

The industry standard building use studies (BUS) methodology for POE (Leaman and Bordass, 1999, 2001) contains a scale of *perceived* productivity. The question does not relate specifically to temperature within the building, and nor are there concurrent physical measurements of temperature accompanying the POE questionnaire, so Leaman and Bordass (1999) have relied on statistical correlations with other items on their POE questionnaire to make inferences about the impact of thermal comfort (or rather, discomfort) on productivity. Their Probe studies (2001) showed a pronounced difference in perceived productivity between occupants who reported that their building was *comfortable* and those describing their building as *uncomfortable*. Uncomfortable staff reported productivity impacts attributable to their indoor environment of 8.8% below 'normal', whereas comfortable staff reported productivity gains of 4.0% above their normal expectation. Of the 39 articles on thermal comfort and productivity retrieved in our literature search, the Leaman and Bordass productivity publications ranked very highly: third and fifth in terms of citations in the 1996–2010 census period, suggesting that their pragmatic solution to the difficulties of productivity metrics resonated with researcher and end-user communities alike.

Emergence of China as a contributor to thermal comfort research

The earliest studies on thermal comfort using experimental research methods in China started from the end of 1980s under the leadership of Rongyi Zhao at Tsinghua University mainly focused on dynamic (nonsteady state) thermal environments. His research program emerged at that time in response to increasing demand for space cooling in China, so he focused on energy-efficient strategies for improving thermal comfort in warm-to-hot environments. Within the last 20 years though, the earliest comfort research was on variable thermal environments, but reported in Chinese only – mainly dissertations or Chinese language peer-reviewed journals. Xia's laboratory studies into the perception of fluctuating airflow (Xia et al., 2000) found that in warmer environments (to = 26–30.5°C), the oscillation frequencies in the range of 0.3–0.5 Hz received the highest acceptability scores and that increased turbulence intensity (ratio of mean and standard deviation airspeeds) improved non-neutral thermal sensations in warm environments.

Working from the premise that natural wind is perceived differently to mechanically generated wind, a variety of analytic tools such as stochastic analysis, turbulence statistics, spectral power analysis, fractals, and wavelet transformations have been used by Chinese thermal comfort researchers to characterize air velocity fluctuation. Several indexes such as power spectrum exponent, turbulent intensity, turbulence integral length scale, and phase space reconstruction map (Li et al., 2007; Ouyang et al., 2006; Zhu and Ouyang, 2003) have been proposed to differentiate natural and mechanical wind on the basis of their thermal perceptual characteristics, and air supply terminal devices have been specifically developed to mimic natural wind characteristics in indoor air (Li et al., 2010). Climate chamber experiments with human subjects indicated thermal neutrality could be elevated up to 30°C if the airflow was delivered with a mean speed of 0.8 m/s and flow characteristics resembling those of natural wind. Furthermore, complaints of draft resulting from imitation of natural wind were significantly reduced compared with the other types of airflows at the same mean speeds (Hu et al., 2009).

The 1990s saw the topic of adaptive thermal comfort being taken up by several research groups around China. Field studies in Chinese free-running buildings have confirmed the adaptive model's predictions that occupants' thermal sensations depart from the heat balance model's calculations and that indoor thermal neutrality is 'calibrated' by the local climatic context of the building, in both warm and cool settings (Cao et al., 2011a; Ji et al., 2004; Jiang et al., 2006; Wang et al., 2011; Zhang et al., 2007a,b). Based on the field survey results from 13 Chinese cities, separate adaptive thermal comfort models have been established for five distinct Chinese climate zones (Yang et al., 2007). All these models describe the comfortable indoor temperature as a linear function of outdoor temperature, confirming the general form of the ASHRAE 55 adaptive comfort standard (de Dear and Brager, 1998; Nicol and Humphreys, 2010). Through large field surveys on natives of different Chinese climate zones, Cao et al. (2011b) found that long-term indoor thermal history strongly influenced thermal neutrality, as predicted by the adaptive comfort hypothesis, and that this adaptation persisted for up to 1 year when subjects transferred to different climate zones. This hypothesis that indoor exposure can drive thermal adaptation was independently reinforced in the Yu et al. (2011) climate chamber experiment with subjects from Shanghai and Beijing. The Shanghai sample's wintertime neutrality was 2.5°C lower than that for the Beijing sample. It was speculated that the former had acclimated to significantly colder indoor environment without space heating compared with their Beijing counterparts, despite the fact that outdoor temperature in winter is consistently warmer in Beijing, because of national Chinese policies on space heat are based on somewhat arbitrary geographical criteria.

Several Chinese researchers have attempted to clarify the specific processes underpinning occupants' thermal adaptation in free-running buildings. An 'adaptive' version of Fanger's predicted mean vote (aPMV) heat balance model of thermal comfort was proposed and included technological, personal, and psychological reactions to variations of indoor thermal environment (Liu et al., 2012; Yao et al., 2009a, 2010). Zhang et al. (2010e) combined over two thousand sets of raw data from a Chinese comfort field survey and observations from subjects in climate chamber experiments, to identify specific thermal adaptations under different seasons, climate zones, thermal histories, and levels of perceived control. The results reiterated the finding mentioned above that a warmer thermal history, indoors or out, was associated with elevated thermal neutrality and reduced thermal sensitivity.

A climate chamber experiment (Yu et al., 2012) with a group of Chinese subjects acclimated to air-conditioned environments (AC) and a control group acclimated to naturally ventilated environments (NV) found that during high temperature exposures (36°C), the NV group had a significantly stronger capacity for physiological thermoregulation than the AC group. The NV group also registered thermal sensations significantly closer to neutral in a 36°C environment than the AC acclimated group, registered higher thermal comfort ratings, higher sweat rate. The NV group's blood samples registered higher levels of heat stress proteins (HSP70) than their AC counterparts, both before and after the experiment.

To find relationships between health, productivity, and thermal comfort, physiological parameters underpinning thermal perception have been studied by Chinese researchers. Besides, skin temperature, heart rate variability, and electroencephalograph (EEG) were suggested as markers of thermal comfort that are accessible instrumentally and potentially helpful in understanding the mechanisms involved (Liu et al., 2008; Yao et al., 2007, 2008, 2009b).

As to the effects of thermal comfort on human performance in office settings, the neurobehavioral research approach has been applied in Chinese comfort research. This method focuses on the identification and measurement of behavioral changes for the influence of environment on brain functions. The key neurobehavioral functions of perception, learning and memory, thinking, and executive functions were quantified with a battery of nine different psychometric tests, but focused mainly on the cognitive components as these are most prominent in office work. Generalization from these simplistic psychometric tests to real office work and productivity, in all its complexity, remains moot as the external validity was not established, but the experimental measurements indicate that optimum performance coincided with thermal sensations slightly below neutral. The generally accepted principle that thermal discomfort was associated with reduced performance was supported by these neurobehavioral research findings (Lan and Lian, 2009; Lan et al., 2009), directly contradicting the minority claim by Wyon and Wargocki (2006) that thermal conditions providing thermal comfort do not correspond with maximum efficiency.

Thermal comfort in some special environments was studied by Chinese research groups. One such study looked at the effect of local cooling on thermal sensation and perceptions in neutral-warm environment (Zhang and Zhao, 2007, 2008). Localized facial cooling was seen to influence overall thermal sensation most significantly, mainly due to its great impact on local thermal sensations of the other body parts, resulting in an obvious shift of the upper limit of the acceptable temperature range from 26 to 30.5°C (Zhang and Zhao, 2007). Under nonuniform thermal conditions, not only overall thermal sensation, but also nonuniformity of thermal sensation among body regions was found to have significant impacts on comfort and acceptability (Zhang and Zhao, 2008).

Human thermal sensation under hypobaric environment was studied as well in recent Chinese studies. Hypobaric chamber experiments indicate that thermal sensation drops as the atmospheric pressure decreases. Hypobaric environmental exposure tended to make subjects feel cooler and more sensitive to draft and hence preferring lower air velocity than subjects under normal atmospheric pressures (Wang et al., 2010). The neutral temperature under 0.85 atm is around 1.4°C higher than that under 1 atm, so comfort indices like PMV cannot be used directly for the hypobaric environments (Hu et al., 2009).

Conclusions

The research topic of thermal comfort has undergone a dramatic intensification of activity over the last two decades, but especially since 2006, as evidenced by the rapid increase in articles being published each year in the peer-reviewed literature and also the number of citations being registered by bibliometric indexing services. This probably reflects the intense focus on built environments resulting from the plethora of voluntary and mandatory greenhouse mitigation strategies being rolled out in various jurisdictions around the world. With increased policy attention has become increased research and development investment, the results from which are starting to appear in the literature.

There seems to be a very close connection between the impact that research has on the literature and its inclusion in the comfort standards. Many if not most of the most highly cited thermal comfort researchers have had their research findings incorporated into international or national standards relating to indoor environment. Even papers and literature reviews that contribute no new findings, but just discuss thermal comfort standards, all achieve very high impact factors.

All literature cited in this article contributed significantly to the considerable progress in thermal comfort knowledge over the past 20 years, but it is not meaningful to list all conclusions from each and every study included. Instead, general conclusions within the themes dealt with in the article are summarized in the following.

A paradigm shift away from heat balance–based thermal comfort models toward adaptive comfort modeling has taken place over the last 20 years. All adaptive models implicitly build on the hypothesis that occupants of naturally ventilated buildings achieve thermal comfort across a wider range of indoor temperatures than occupants of buildings with centrally controlled HVAC systems and that comfort ranges for indoor temperatures shift up down in concert with outdoor seasonal and climatic settings.

Another major conceptual shift is that perceptible air movement inside buildings has been rehabilitated in thermal comfort research over the last 20 years. At the start of that period, the research language of air movement was overwhelmingly negative (draft, nuisance), but now the focus is on the positive hedonic aspects of air movement; aerodynamic pleasure, breeze, esthetics of air, thermal delight are all examples of the new language being applied to moving air. The most recent revisions of thermal comfort standards even include estimates of how much warmer the comfort zone can be stretched by increasing air speeds up to levels that in earlier versions would never be permitted without a requirement of individual occupant control of the air movement.

In general, there has been growing recognition that occupant interaction with the building and its systems is a significant determinant for occupant satisfaction and thermal responses and that the biggest threat to occupant satisfaction occurs when a building and its systems are too complicated, unintelligible, or unresponsive to occupant control behaviors. Consequently, credits for occupant control are now included in the IEQ sections of various building sustainability rating tools. Addressing this issue of occupant control, a number of systems for personal comfort control that permits the individual occupant to meet their own unique comfort requirements have been developed, tested, and demonstrated to improve comfort and ventilation effectiveness, while at the same time expending less energy than conventional, centrally controlled systems.

Technological evolution in HVAC systems such as chilled beams, radiant ceiling panels, and DV arose, in part, in response to the energy efficiency imperative. The thermal settings presented by these systems and the resulting complex, nonuniform thermal exposures shifted research toward nonuniform environments and also provided the impetus for development of multinode models of human thermal physiology. The modern multinode models are all based on a numerical solution of the heat balance of individual nodes (skin tissue, muscle tissue, fat tissue, bone), each of which has its own distinct physical properties (heat capacitance, conductivity, etc.). This enhanced anatomical resolution of multinode models enables the subtle nuances of heterogenous indoor thermal environments and nonsteady-state exposures to be more realistically captured at the physiological level.

There is reason to believe that the progress in thermal comfort research over the next 20 years will be driven by climate change and the urgency of decarbonising the built environment. Demand for ever increasing building energy efficiency is pushing technological innovation in the way we deliver comfortable indoor environments. These trends, in turn, continue setting the directions for contemporary thermal comfort research.

Continued evolution and penetration into the market of new and energy-efficient HVAC technology, including personal comfort systems, call for research on the combined effects of several thermal nonuniformities, nonsteady-state exposures, and the interaction between occupant and control opportunities. Mixed-mode buildings raise interesting theoretical and regulatory questions because of the 'duality of comfort expectations' of their occupants. Exposures and other factors influencing occupant perceptions in mixed-mode buildings may receive additional attention from the research community as such buildings become more prevalent. Despite this surge in research funding and activity, our understanding of thermal comfort effects on task performance and productivity remains ambiguous. Notwithstanding the disappointing returns from that intense research activity thus far, there is almost certainly going to be sustained investment of research resources in this topic due to its obvious economic implications.

The methods used in contemporary thermal comfort fall into two broad classes; (i) climate chamber studies and (ii) field studies in real buildings. Both approaches attempt to fit statistical models to the relationship between instrumental measurements of indoor climates and how those environments are perceived by human subjects (building occupants). Climate chamber studies have the benefit of experimental control and superior internal validity of their research designs, while field studies have the benefit of larger samples and enhanced external validity. This literature review detected a growing number of comfort researchers using neither chamber nor field methods. The method of *comfort simulation* is becoming increasingly popular in the research literature – based on readily accessible numerical simulation tools of the built environment to produce indoor climatic data that is then applied to a thermal comfort model or local discomfort index. At no point in the research process is a human subject used to provide an evaluation of an actual thermal environment. As with all fields of applied research, it is important that the outputs of simulations are regularly 'ground-truthed' with real comfort assessments from human subjects in either chamber studies or 'real' building occupants in field studies. Practitioners' reliance on comfort models in design stage and engineering calculations, as well as compliance assessments for existing buildings, is widespread and perfectly reasonable. But in a research context, thermal comfort evaluations by human subjects are a superior contribution to knowledge, having longer-lasting value to the research community than simulated comfort evaluations coming out of a comfort model.

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