BRI Building Research & Information 2015
http://dx.doi.org/10.1080/09613218.2015.993536

INFORMATION PAPER

Evolving opportunities for providing thermal comfort

Gail Brager, Hui Zhang and Edward Arens

Center for the Built Environment, University of California, 390 Wurster Hall, Berkeley, CA 94720-1839, US.
E-mails: gbrager@berkeley.edu, zhanghui@berkeley.edu and earens@berkeley.edu

The building industry needs a fundamental paradigm shift in its notion of comfort, to find low-energy ways of creating more thermally dynamic and non-uniform environments that bring inhabitants pleasure. Strategies for providing enriched thermal environments must be conjoined with reducing energy; these are inseparable for any building striving for high performance. The objective of current comfort standards is to have no more than 20% of occupants dissatisfied, yet buildings are not reaching even that scant goal. A significant energy cost is incurred by the current practice of controlling buildings within a narrow range of temperatures (often over-cooling in the summer). If building designers and operators can find efficient ways to allow building temperatures to float over a wider range, while affording occupants individual control of comfort, the potential for energy savings is enormous. Five new ways of thinking, or paradigm shifts, are presented for designing or operating buildings to provide enhanced thermal experiences. They are supported by examples of research conducted by the Center for the Built Environment, and include shifts from centralized to personal control, from still to breezy air movement, from thermal neutrality to delight, from active to passive design, and from system disengagement to improved feedback loops.

Keywords: adaptation, adaptive behaviour, air movement, buildings, energy use, personal control, solutions, thermal comfort

Introduction

What would life be like if we ate the same foods at every meal, never experienced weather or changing light levels, listened to a constant monotone sound and had no music or the sounds of birds, and had no art in our lives to delight our visual senses? There is probably unanimity on this point – it would be dreadful. But that is analogous to what is experienced in thermal environments designed for static, uniform, neutral conditions. This has been called thermal monotony, or thermal boredom. The irony is that achieving thermal monotony is highly energy-intensive. There is need for a paradigm shift in the notion of comfort, moving toward more thermally dynamic and non-uniform environments that brings pleasure and energizes building inhabitants, while requiring less energy to do so.

The objective of this paper is to encourage new ways of thinking about designing or operating buildings to optimize both comfort and energy performance, while hopefully creating more rich and variable environments. The ideas are primarily illustrated with examples of research done by the Center for the Built Environment (CBE) at the University of California, Berkeley. CBE is an industry/university research centre whose mission is to improve the environmental quality and energy efficiency of buildings. CBE's research not only contributes to academic literature, but also seeks to have an impact on the building industry by removing barriers to effective building technologies, and speeding their implementation. Such barriers exist in current standards, rules of thumb and design practices, all of which can be examined and revised. CBE does this by active collaboration with its industry partners, who are wrestling with the same issues in practice. The industry consortium helps CBE researchers develop a keen sense of what needs to be addressed to make real improvements in the built environment.

Providing enriched thermal environments must go conjointly with the critically important goal of reducing the energy use in buildings. It is estimated that buildings contribute 39% of the total US greenhouse gas (GHG) emissions (US Energy Information Administration) primarily due to their operational energy use, and 80% of that energy use is for heating, cooling, ventilating and lighting.

Comfort and energy efficiency may impose similar priorities on building design and operation. The first *design priority* for both might be the envelope of the building: reducing solar heat gains through orientation and shading of glazing, using appropriate levels of insulation and high-performance windows, and considering the role of thermal mass. For comfort performance, it makes sense to start with the occupants and their relationship with the interiors systems and the architecture, before one thinks about the building's mechanical system. For energy reduction, it makes little sense to examine renewable energy sources until one has first addressed the higher-priority and more cost-effective strategies at the top of the triangle described in Figure 1 (McGregor, Roberts, & Cousins, 2013). For *operational priorities*, the most important step is to ensure that today's target indoor conditions are actually necessary, or even desirable.

For a building to be considered 'high performance', energy and comfort performance are inseparable. One cannot call a thermally comfortable building successful if it consumes vast amounts of energy to achieve comfort, and conversely even a zero-net energy building is a failure if it provides a less-than-satisfactory environment for the occupants.

Cost of comfort

The theme of this special issue is the 'cost of comfort', and there is no doubt that comfort of building occupants has strong economic implications beyond the cost of the energy used to condition the space. As

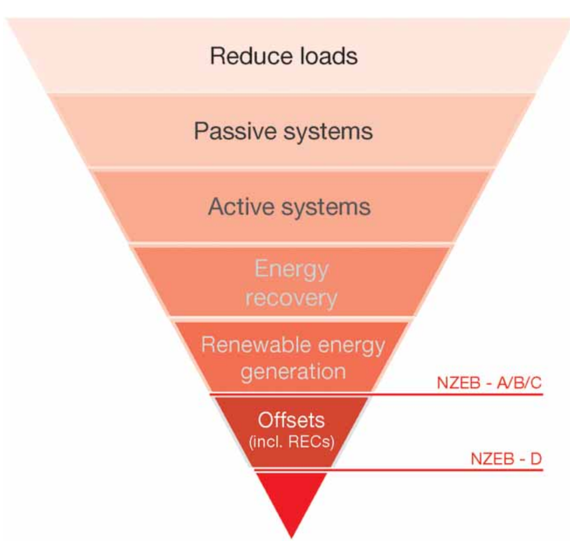

Figure 1 Setting priorities for net-zero energy buildings
Source: McGregor et al. (2013)

people in many countries typically spend over 90% of their time indoors, the quality of the indoor environment must influence their comfort, performance, health and well-being. These translate into economic terms. Broadly, the people-related costs of poor indoor environmental quality (IEQ) can be thought of as either direct medical costs arising from health problems caused by the building, or indirect costs of reduced individual work performance either in the building (presenteeism) or away from it (absenteeism). The health impacts of IEQ have been easier to assess than the effects on individual performance, which vary from job to job. Conceptually, the benefits of good IEQ are the opposite of the detriments described above (*i.e.* reduced medical costs, reduced absenteeism, better work performance), plus other factors such as improved recruitment and retention of employees, and lower building maintenance costs due to fewer complaints. For each of these, the costs of worker performance and healthcare are very large compared with capital costs or energy operating costs. Various sources estimate that 80–90% of the costs of a building are associated with worker salaries, compared with only 3% being associated with owning and maintaining the property (Clements-Croome, 2006; Kats, 2003; Wilson, 2005). If one is able to make even small improvements in productivity through better IEQ, then the value to the company's bottom line will be significantly higher than the financial costs or benefits of reduced energy use. Building owners know this, and may use it to justify maintaining indoor environmental conditions that are energy intensive.

A paradigm shift requires the critical examination of certain perceptions of high IEQ quality that are inherently energy-intensive, and which may be causing huge waste if not warranted.

As an example of health-related issues, the California Healthy Buildings study found 50% fewer sick building symptoms occur in naturally ventilated buildings than in air-conditioned buildings (Mendell et al., 2002). In a comparison of 12 field studies from the United States and six countries in Europe, covering 467 buildings with approximately 24 000 total occupants, the air-conditioned buildings (with or without humidification) showed between 30% and 200% more cases of sick building syndrome (SBS) symptoms than in the naturally ventilated buildings' occupants (Seppänen & Fisk, 2002). In these studies, the causal links were not established, nor the extent of actual illness, but there is a high likelihood that there would be productivity costs associated with such a large difference in symptoms.

For the work productivity issues mentioned above, there is a prevailing view that optimum productivity occurs in a narrow range of temperatures, coming from fitting a curve to the results of different studies

(Seppänen & Fisk, 2006; Wargocki & Seppänen, 2006) Economically, such a curve might economically justify holding interior temperatures within a range of 1–2°C. However, 11 of these studies showed no obvious best temperature for productivity, with optima occurring within a much wider range of air temperatures between 21 and 27°C (Seppänen, Fisk, & Faulkner, 2004; Zhang, Arens, & Pasut, 2011).

The environments were controlled for air temperature and humidity only, and the conclusions of researchers have been expressed in the same narrow terms. This is where critical examination is needed. There is now evidence that performance is more strongly related to thermal comfort, rather than temperature *per se* (Uchida et al., 2009). This means that in buildings where air movement and natural ventilation are creating comfortable conditions in temperatures warmer than today's typical indoor range, then it is likely that occupant performance would also be maintained beyond this range. It should be noted, however, that there have been limited productivity studies involving occupant access to elevated air movement under warm conditions, or occurring in free-running or naturally ventilated buildings. One recent study investigated the effects of a personalized ventilation system on people's health, comfort, and performance in warm and humid environments (26 and 28°C at 70% relative humidity). The system provided increased local air movement and improved perceived air quality (PAQ) and thermal sensation, decreased the intensity of SBS, and improved self-estimated and objectively measured performance (Melikov, Skwarczynski, Kaczmarczyk, & Zabecky, 2013). The authors of another overview of various studies of productivity concluded that robust measures such as occupant control of temperature, operable windows and providing for adaptive thermal comfort could be more effective than increased ventilation or mechanical temperature control (Leyten, Laue, & Kurvers, 2014).

There is substantial reluctance in the building and property (real estate) industries to try such non-mainstream measures for indoor comfort control. It is widely felt that a tightly controlled uniform space temperature is the goal and that one needs full control of temperature and humidity through the heating, ventilation and air-conditioning (HVAC) system. Since their inception, comfort zones have been visualized in terms of temperature and humidity; surface temperatures were factored in within limits, and air movement (for a long time) was actively discouraged. Other options are considered risky and ultimately burdensome on occupants, and that they will ultimately backfire on the building owner and operator.

In order to overcome this reluctance, the productivity effects need to be documented more comprehensively in terms of the environmental factors involved. Naturally ventilated and mixed mode (i.e., combining mechanical cooling and natural ventilation) designs, and non-temperature strategies such as indoor air motion or personal comfort systems (PCS) rely on non-temperature factors, and also on the variability in those factors, both more complex situations than those involved in past productivity studies. Beyond this, the links between measured comfort and productivity needs further evidence, since comfort measurement is occurring on a must greater scale than productivity measurement.

Comfort in existing buildings – how good is it?

Standards define thermally comfortable environments in 'comfort zones' within which 80% of the occupants are to be thermally satisfied. This is certainly a low bar compared with other types of services and products, but it appears to be an inherent maximum for a uniformly conditioned environment housing a naturally variable group of occupants. Do existing buildings even meet this 80% level?

Figure 2 shows the acceptability/satisfaction responses of occupants for an occupant IEQ satisfaction survey widely administered by CBE in office buildings. Of all the questions in the CBE survey, including the various IEQ factors along with other questions about the workplace, temperature consistently receives the second lowest rank (Frontczak et al., 2011). When the data are analysed in other ways, overall 41% of workers are dissatisfied with the thermal environment (Huizenga et al., 2006).

In practice, indoor temperatures are usually controlled within zones narrower than the standards allow. A study of 100 US office buildings found that in summer temperatures were below the comfort zone and on average were even cooler than in winter (Mendell & Mirer, 2009). These conditions also coincide with the temperature ranges for which there were increased symptoms of SBS. Overcooling appears to be a problem that is growing worldwide. In as-yet unpublished analysis of the ASHRAE-884 Database (de Dear, 1998), summer data from occupant surveys from over 160 buildings worldwide showed that across a range of indoor temperatures (70–75°F, 21–24°C), more people were feeling too cool rather than too warm. The same study found that in winter the buildings were perceived to be overheated, and that there were SBS symptoms associated with this.

The industry is not doing a very good job of creating thermally comfortable environments in buildings. They should welcome a thorough look at new opportunities to improve this record.

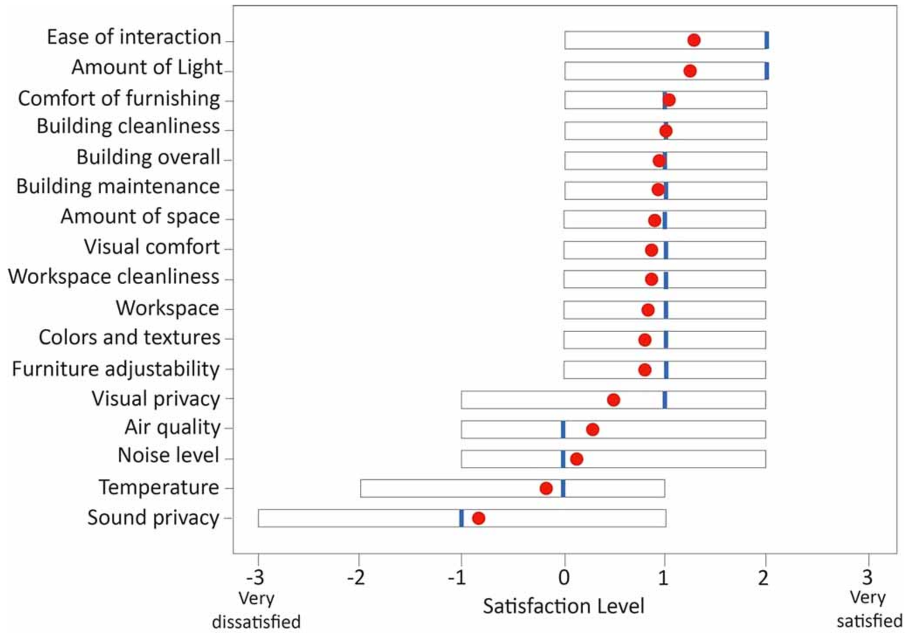

Figure 2 Center for the Built Environment (CBE) occupant satisfaction survey results (351 buildings, 53 000 occupants)
Source: Frontczak et al. (2011)

Evolving opportunities

The foregoing illustrates clear opportunities for operation and design. If building operators could raise summer set-points and reduce overcooling, energy would be saved and the comfort and health of occupants improved, all with minimal financial investment. Beyond this operational change, there are old and new design strategies that might be used to provide thermal comfort in both new and retrofitted buildings. They address the significant energy cost in operating buildings across narrow temperature set-point ranges. If one can find efficient and successful ways to allow building temperatures to float over a wider range, the potential for energy savings is enormous.

Figure 3 shows the results of simulations done in three climates – temperate, warm, cold –showing the annual energy savings achieved with a range of possible interior set-points (Hoyt, Lee, Zhang, Arens, & Webster, 2009, Hoyt, Arens, & Zhang, 2014). Conventional buildings in the United States typically operate between 22 and 24°C; the resulting 'deadband' is 2°C. The simulation results show that if new strategies and systems were to allow the building operator to expand the range of temperatures at which occupants are comfortable, one can reduce annual central HVAC energy consumption by roughly 10% per 1°C of expansion in either direction. The savings from increasing the deadband come both from reducing the intensity of heating/cooling when the HVAC is running and reducing the amount of time during which the HVAC system needs to operate. This is an enormous savings opportunity that should be exploited to the extent possible.

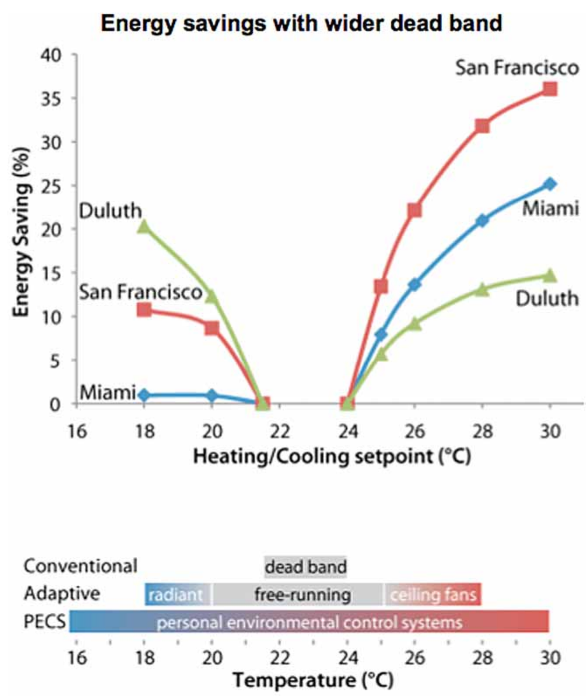

Figure 3 Per cent energy savings for widened air temperature set-points relative to conventional ranges
Source: Hoyt et al. (2009)

Strategies shown in Figure 3 for widening the temperature deadband include: (1) passive or naturally ventilated (free-running) buildings with access to air movement and radiation; (2) providing increased air

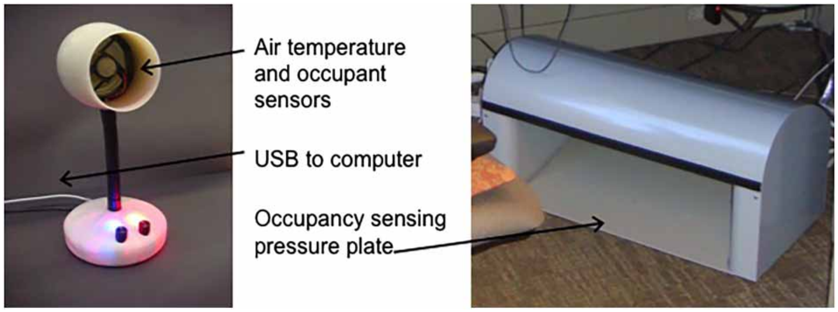

Figure 4 Components of the Personal Comfort System (PCS) devices developed by the Center for the Built Environment (CBE)
Source: Zhang et al. (2010a)

movement on the warm side by utilizing interior fans; or (3) utilizing energy-efficient radiant systems that allow the building air temperatures to operate across a wider range while the hydronic system provides person-based conditioning through radiant exchange with warm or cool panels. Expanding on this, the Performance Measurement Protocol Best Practice Guide (ASHRAE, 2012) describes five strategies for expanding the set-point range, which include: adjusting thermostat and supply air temperature set-points for climate adaptive seasonal comfort, including air movement cooling and radiant heating; providing local thermal comfort control options; reducing excessive minimum supply air volumes; controlling direct sunlight in work areas; and controlling humidity independently of supply air temperature. In particular, the presence of individual control over one's thermal conditions may be even more important than the type of ventilation system (Toftum, 2010).

This paper provides five new ways of thinking, or paradigm shifts, about the ways one might design or operate buildings to provide enhanced thermal experiences in energy-efficient ways. While the ideas in this paper might be familiar to researchers in the field of thermal comfort, the current state of building design and operation suggests that practitioners have a long way to go in familiarizing themselves with, and implementing, these concepts.

From centralized to personal control

Researchers at the CBE have been active in developing PCS that allow occupants personally to control their local thermal environment. These have the potential to enhance comfort and simultaneously save energy. A familiar analogy for these systems is task-ambient lighting, a widely accepted method with two primary features: (1) dimming the ambient light levels, since one does not need the same amount of light everywhere; and (2) putting task lighting on the desk, so that people have the brighter light just when and where they need it, and under their control.

On the 'task' side, PCS provides occupants with the opportunity to meet their own personal preferences. On the 'ambient' side, the 'corrective power' of localized conditioning provides comfort over a wider range of coincident ambient temperatures, which leads to the large energy savings (Hoyt et al., 2009, 2014). CBE's first-generation PCS units, shown in Figure 4, include a desktop fan and under-desk radiant foot warmer. They are low cost, have personal controls, consume little energy (the fan and controls use 1–4 W and the foot warmer approximately 30 W), and can easily be used in retrofit applications (Zhang et al., 2010). Both units have integrated occupancy sensors – turning themselves off when not in use. Both incorporate sensors to measure temperature and use patterns that are transmitted to the central system (or in this case to researchers) via the internet.

CBE's laboratory testing confirmed that comfort was well maintained over a wide range of room temperatures and that PAQ was significantly improved (Zhang et al., 2010). The experiments also addressed the impact on task performance by giving the test subjects three tasks (Sudoku, maths and typing) that were pre-scheduled into the computers on which the subjects worked. The non-uniform test environments did not lower occupants' task performance, and some performance indicators improved.

A subsequent field study of the footwarmers in an 18-person office wing also showed strong comfort performance over the course of a winter. Figure 5 shows people's votes on a seven-point acceptability scale changed as the set-point was experimentally reduced from 21°C (70°F) to 19°C (66°F) and back again. In the cooler temperatures, acceptability was unchanged, indicating that the footwarmers had provided 2°C of comfort correction (Taub, 2013; Taub et al., 2014).

The 20 W/occupant consumed by the footwarmers is negligible compared with the 500 W/occupant reduction in HVAC consumption caused by the set-

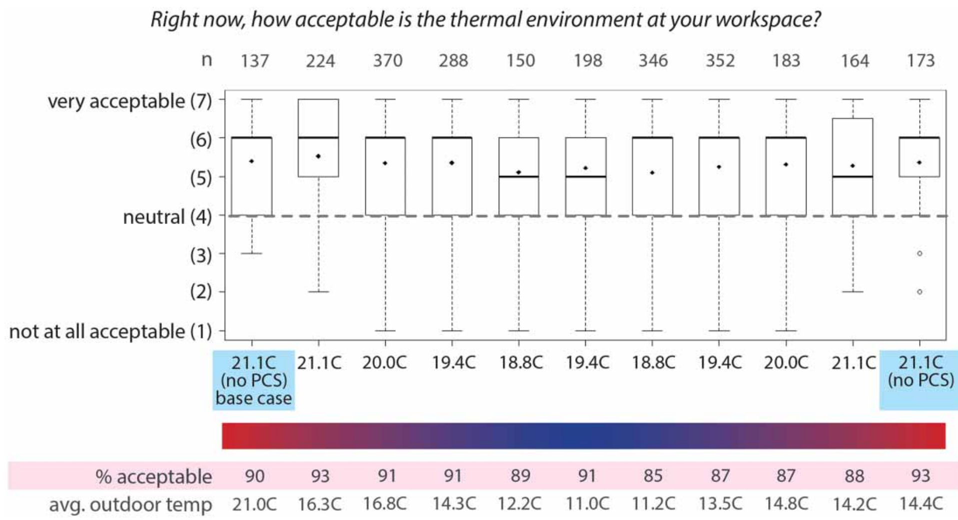

Figure 5 Thermal acceptability in a field study of footwarmers
Sources: Taub (2013); Taub et al. (2014)

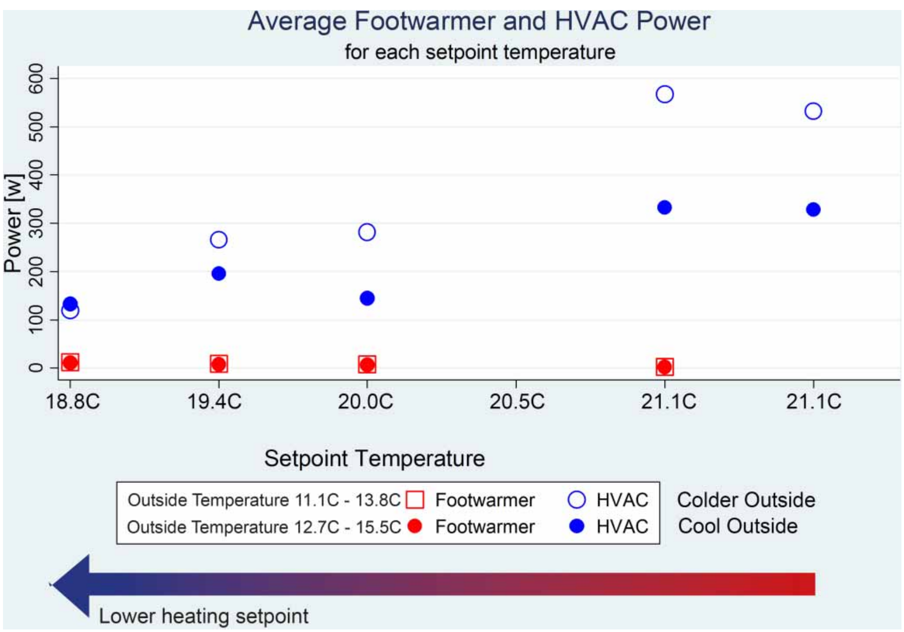

Figure 6 Energy use in a field study of footwarmers
Sources: Taub (2013); Taub et al. (2014)

point change. Figure 6 shows energy usage during the same time period as the comfort tests described above (Taub, 2013). While Figure 5 shows the progression of tests over time, Figure 6 shows the base case of 21°C on the far right, and the reduced heating set-points to the left. Since multiple tests were done at each set-point, the tests are divided into two groups representing the relatively cool versus colder outdoor conditions that were naturally occurring during the test dates. As expected, as one reduced the heating set-point, energy use went down. And this was significant, showing approximately 50% savings. At the same time, the additional energy from the footwarmers was almost negligible.

CBE's second-generation PCS is a heated and cooled office chair (Figure 7), described in Pasut, Zhang, Arens, and Zhair (2014). The chair operates with rechargeable batteries so that it can be untethered in use and be charged overnight. It uses very low energy – a maximum of 3.6 W in cooling mode and 14 W in heating mode – and has a very fast reaction time. The chairs were tested in the CBE controlled environment chamber with temperatures set at 16, 18 and 29°C, and with subjects having full control of the chair power through a knob located on the side of the chair. Subjective response about thermal sensation and comfort were obtained at 15-min intervals. The laboratory studies demonstrated a 90% thermal acceptability rate over a wide range of 18–29°C ambient temperature (Pasut et al., 2014). These results have important implications not only for comfort but also for energy use, as shown in Figure 3. Various field tests of the chairs' comfort, indoor temperature and energy use are now underway.

By letting ambient temperatures float over a wider range and providing localized, person-focused conditioning that is under the control of the occupant, PCS offers enormous potential for simultaneously improving both the energy and comfort performance of buildings.

From still to breezy air movement

The traditional comfort zones in standards are based on the idea that 'still air' conditions are ideal. They were backed up with draft risk provisions that prevented air motion within a wide range of interior temperatures. The draft risk came based on laboratory studies in which air movement was directed at the back of the neck, the limiting direction on one of the most sensitive parts of the body. The question was whether this risk was actually occurring in buildings. An examination of detailed field studies provided evidence that significantly more people prefer having *more* air movement compared with *less*, in both seasons, and in all conditions between 'slightly cool' and 'warm' as shown in Figure 8 (Zhang et al., 2007) Additional analysis began with a worldwide database of thermal comfort field studies (de Dear, 1998), and this evidence was used to implement a change in ASHRAE Standard 55, reducing the temperatures under which draft risk obtains, and providing for the encouragement of increasing air movement in neutral to warm conditions (Arens, Turner, Zhang, & Paliaga, 2009).

Figure 7 Personal Comfort System (PCS) heated and cooled chair.
Source: Pasut et al. (2014)

Both laboratory and field studies are showing that air movement compensates for warmer temperatures in making people comfortable, but also that people prefer a perceptible level of air movement even when their sensations are slightly cool (Toftum, 2004; Zhang et al., 2007). In other words, they may want the air movement just for its refreshing effect – not merely for thermal compensation. An example of this analysis from field study data is shown in Figure 9, where people's responses to a question about preference for air movement (do you want more, less or no change?) are shown in comparison with thermal sensation (a seven-point scale ranging from cold to neutral to hot). At sensations of slightly cool, about an equal number want more versus less air movement, but 80% want no change. This means that the only way to accommodate the group who want more air movement in cooler conditions is with localized fans and personal control, otherwise you affect the larger group.

Studies have also shown that air movement can have a positive effect on PAQ, particularly when people are able to control the air movement. Figure 10 shows results from in which PAQ was found to be closely correlated to thermal comfort rather than temperature, as long as thermal comfort was maintained by air movement (Zhang et al., 2011). The graph shows that under still air PAQ did not vary much from 18 to 25°C, but then dropped to between 25 and 28°C even though the physical characteristics of the air quality were exactly the same. With the addition of air movement in the facial area, PAQ returned to the level found under neutral conditions, allowing the PAQ threshold to go beyond 30°C (Zhang et al., 2011). This is a particularly important finding that provides evidence that elevated air motion – through ceiling fans, PCS fans or operable windows – not only can provide comfort in warmer conditions, but also can improve PAQ and provide the potential for energy savings through reduced air-conditioning loads.

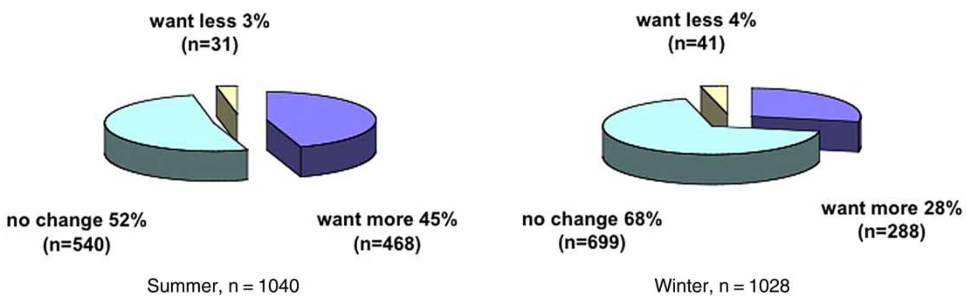

Figure 8 Air movement preferences, two seasons
Source: Zhang et al. (2007)

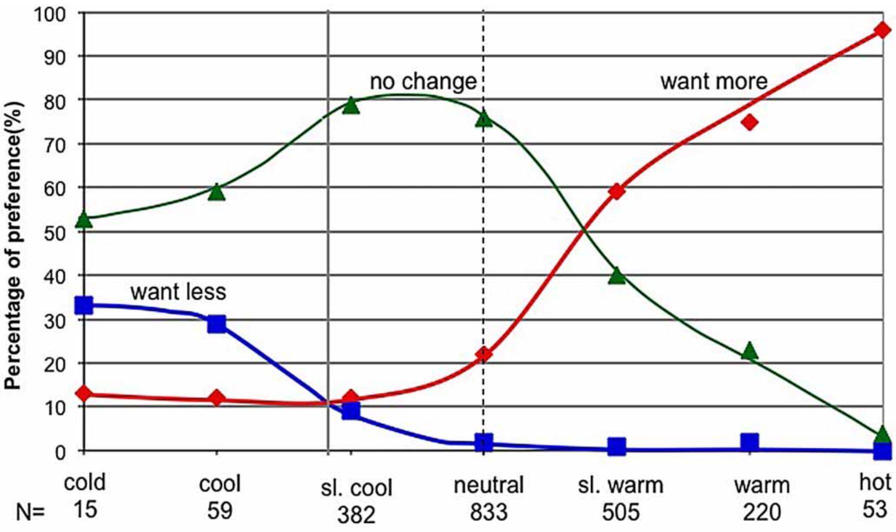

Figure 9 Air movement preference versus thermal sensation
Source: Zhang et al. (2007)

From thermal neutrality to delight

Many of these ideas are not just about improving the 20% dissatisfaction threshold in ASHRAE Standard 55, but moving beyond the goal of simple neutrality for thermal experience. Alliesthesia is a concept that describes the physiological basis for thermal pleasure or delight (de Dear, 2011; Parkinson & de Dear, 2015; Parkinson, de Dear, & Cândido, 2012; Zhang, Arens, Huizenga, & Han, 2010a, 2010b). The earliest studies (Cabanac, 1971) began with the premise that these hedonic, or pleasurable, sensations are generated by the dynamic response of thermoreceptors, and focused exclusively on transient effects. These can be described as ‘temporal alliesthesia’, which occurs when the body is in a slightly less comfortable state to begin with, and then perceives pleasure from thermal stimuli that move the body toward comfort. An example might be feeling slightly overheated on a hot day, and then walking into a cool movie theatre or supermarket. A short-term ‘very pleasant’ sensation is found (temporal alliesthesia). When the body starts in a neutral condition, the higher pleasant sensations are not achieved. Figure 11 shows an early study showing this effect: for temporal alliesthesia to occur, two things have to happen: (1) your initial body needs to be in a slightly warm or cool state, not neutral; and (2) the dynamic stimulus needs to bring back towards the direction of neutrality.

‘Spatial alliesthesia’ is a relatively new concept being proposed and investigated by researchers at CBE, based on the literature of human physiology and comfort, and ongoing investigations of the human responses in the PCS tests (Zhang, 2003; Zhang et al., 2010b). This new phrase refers to the pleasure one gets from differences in temperature across the

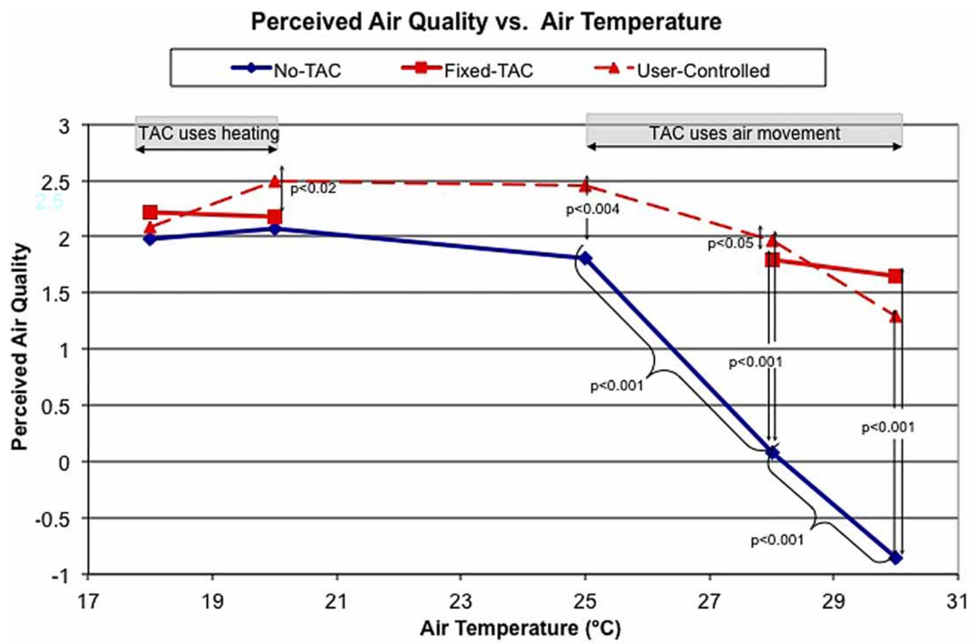

Figure 10 Air movement and perceived air quality.
Source: Zhang et al. (2011)

skin's surface, and tends to occur when these differences are localized on the body. An example of this might be the pleasure one gets from feeling a breeze on one's face on a warm day, or the personalized comfort systems described above. One example of laboratory studies of spatial alliesthesia at CBE focused on heating and cooling of the feet, but for longer periods of time than the early hand studies so that it was not simply a transient effect (Figure 12). Similar to temporal alliesthesia, the stronger positive sensations occur when the localized heating or cooling is in the opposite direction of the initial body state. It is also interesting to note that the responses are asymmetric – since people are more sensitive to cold than warmth, they were more uncomfortable when the feet were too cool, even when the body was warm.

While there are many examples of alliesthesia in the natural environment, the challenge is how to design for it in the built environment. Temporal alliesthesia requires an excursion outside the physiological neutral zone. One opportunity might be transition spaces, such as over-cooled lobby spaces, where the occupants are moving through such spaces temporarily. There might therefore be fewer design opportunities in, say, offices spaces because it would be difficult to create intentionally a situation that is less than comfortable. In comparison spatial alliesthesia is appealing because it is less dependent on the corrective nature of the stimulation and may be better suited for creating more sustained pleasurable sensations rather than temporary ones. This is where the personalized comfort systems may offer their greatest potential.

From active to passive design

Figure 1 had passive strategies as a top priority for designing low-energy buildings, and there are also comfort-related benefits to be had from using climate-responsive designs rather than sealed mechanically conditioned ones. It has become accepted, for example, that people in naturally ventilated buildings are comfortable over a broader range of temperatures than those in air-conditioned buildings. Figure 13 shows the basis for the adaptive comfort zone in ASHRAE Standard 55 (ANSI/ASHRAE, 2013), an optional alternative to the conventional comfort zone that can be applied to naturally ventilated buildings. The findings are based on a global database of 22 000 sets of physical and survey data collected in approximately 160 buildings, both air-conditioned and naturally ventilated, on four continents (de Dear & Brager, 1998, 2001).

Looking first at the results in the centrally controlled buildings, there is just a slight upward slope of the lines, showing that people are comfortable in slightly warmer indoor temperatures as the outdoor temperature gets warmer, which could be explained almost entirely by lighter clothing levels. More importantly, the findings show a clear difference between the preferred indoor temperatures predicted by laboratory experiments and those observed in the field. The match between observed and predicted lines in the different building types is dramatically different, which means that people are adapting to conditions in naturally ventilated buildings in ways that the laboratory-based predictive models do not account for.

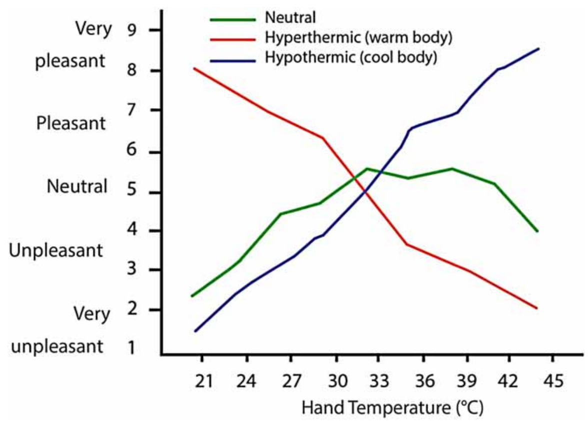

Figure 11 Early studies of alliesthesia by warming/cooling the hand
Source: Mower (1976)

Furthermore, people in naturally ventilated buildings are comfortable over a wider range of indoor conditions. We believe that these differences are due to shifting expectations and preferences as a result of occupants having a greater degree of personal control over their thermal environment; they have also become more accustomed to variable conditions that closely reflect the natural rhythms of outdoor climate patterns. As mentioned above, naturally ventilated buildings also have fewer problems associated with indoor air quality (Mendell et al., 2002; Seppänen & Fisk, 2002).

Turning to the broader characteristics of IEQ in mixed-mode buildings, Figure 14 shows the results of a CBE web-based survey administered in 12 mixed-mode buildings, compared with the performance of 370 conventional buildings that existed in the database at the time (Brager & Baker, 2009). The mixed-mode buildings performed exceptionally well compared with the overall building stock, especially in thermal comfort and air quality. The best performers were newer, in more moderate climates, had radiant cooling or mechanical ventilation only (*i.e.* not centralized air-based systems), and allowed high degrees of direct user control without window interlock systems, which might either lock the window when the HVAC is on or turn off the HVAC when the window is open. This suggests that such complicated interlock systems, while adding expense to the building, might interfere with a user's sense of personal control and therefore their satisfaction. There have not been any systematic studies to date about the effect of these systems on energy use.

From disengagement to improved feedback

Sometimes the barriers to achieving better energy performance in buildings are technological, but often they are about the flow of information. Buildings are sensor- and data-starved, and building control systems do not provide the types of interpreted information needed by buildings' diverse stakeholders to operate the building efficiently. As shown in Figure 15, there should be complete feedback loops in place across a wide range of time scales, from seconds for building controls, to minutes for operators and occupant engagement, to days to years for owner/occupant insight, to the decades-long time frame of university education of future building professionals (Arens & Brown, 2012).

In present-day practice, each of these feedback loops is either broken or needs significant change and improvements. From automated building controls responding to faulty sensors, through the designers, owners or

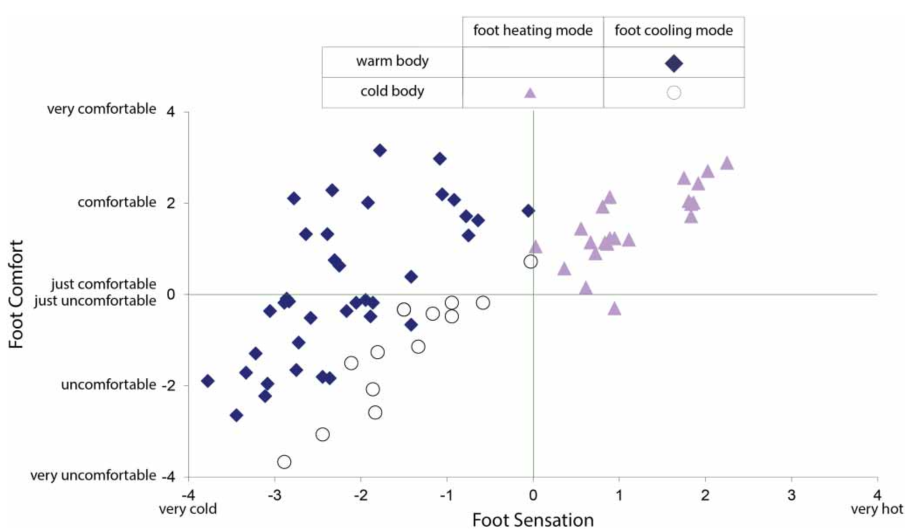

Figure 12 Center for the Built Environment (CBE) laboratory studies of spatial alliesthesia (non-uniform conditioning)
Sources: Zhang (2003); Zhang et al. (2010b)

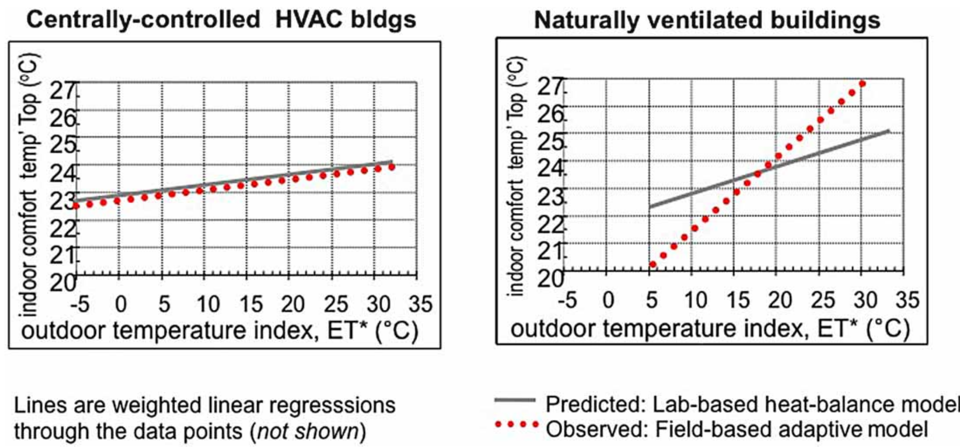

Figure 13 Observed and predicted indoor comfort temperatures in centrally controlled and naturally ventilated buildings
Source: de Dear and Brager (1998)

operators who need to understand better their building's predicted or measured performance, there are far too many situations where fundamental and vital information is not available. The necessary changes might be either technological or organizational in nature, but most often a combination is needed. For example, occupant education is very limited in commercial buildings. Operators in turn are often only responding to complaints from individuals and lack accurate information about the physical and operational causes of the particular complaints, and in relation to other worker's experiences nearby or in other zones in the building. Owners would benefit from post-occupancy evaluations, but these are done far too rarely.

Another way of framing this need for information exchange, especially from the viewpoint of the building occupants, is David Wyon's 3-I principle of user empowerment (Wyon, 2000):

- *Insight*: an understanding of how the building systems work, especially with regard to energy performance
- *Information*: continuous feedback on system status indoor and outdoor conditions, energy use, etc.
- *Influence*: mechanisms through which occupants might interact with the building, such as opening windows, having thermostats or personal heating or cooling systems, or even understanding whom to call if something is not working

Although the 3-I principle was framed in terms of feedback exchange with the occupant, it can be applied to many of the other feedback loops shown in Figure 15, involving building operators, owners, and even regulators and financers. All these loops benefit from the newly available internet and wireless sensor networks. The technical and intellectual challenge is to integrate a new mode of distributed data acquisition and storage with new tools for visualizing and interpreting data, and for independently actuating building systems in new occupant- and climate-responsive ways (Arens, Federspiel, Wang, & Huizenga, 2005). This is an important area for CBE and the Electrical Engineering/Computer Science Department's Software Defined Buildings Group; its products have included sMAP (Dawson-Haggerty, Jiang, Tolle, Ortiz, & Culler, 2010) and several start-up companies developing occupant-responsive building control systems.

Finally CBE contributed to the Performance Measurement Protocols (PMP), an effort by ASHRAE, the US Green Building Council (USGBC), and the Chartered Institution of Building Services Engineers (CIBSE) to standardize and formalize continuous commissioning and post-occupancy evaluation; combining physical measurements and occupant surveys for the four IEQ elements (thermal, air quality, lighting and acoustics) together with physical measurements of energy and water use (ASHRAE, 2013).

Summary

Today, too many buildings are damaging the planet without properly serving their occupants. Energy efficiency and IEQ must both be goals of a high-performance building, and solutions must be linked. This paper reviews research conducted by the CBE to encourage more effective building design and operation.

Extensive field research is key; this has proven the extent of occupants' dissatisfaction with today's

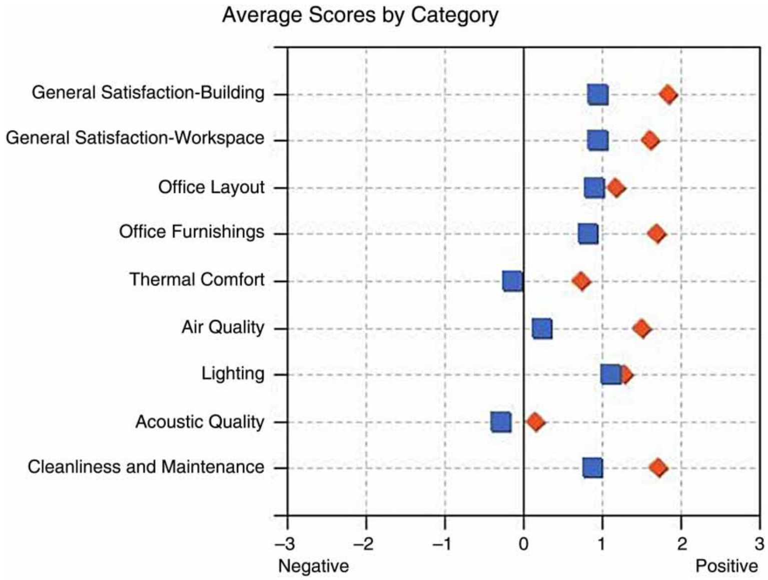

Figure 14 Average satisfaction scores for occupants in mixed-mode buildings compared with larger database
Source: Brager and Baker (2009)

Figure 15 Information feedback loops for building energy performance
Source: Arens and Brown (2012)

thermal environments. The causes include the ubiquitous over-conditioning of buildings and the inability of occupants to adjust the environment individually to meet their personal needs. Recognizing there is a tremendous energy opportunity in operating buildings with a broader range of indoor temperatures, can this be done together with equal or better comfort? CBE has focused on broad themes and also moved specific solutions into practice.

A major theme has been indoor air movement, a long-neglected resource for cooling and air quality, requiring new understanding, products and control approaches. Solutions include PCS with distributed intelligence and the power to compensate for both floating interior temperatures and interpersonal differences at the same time. Both of these will benefit from the emerging understanding of alliesthesia in surpassing the traditional ideal of 'neutral' thermal experience through static, uniform environments, to richer, variable indoor environments that enhance satisfaction and well-being. The new knowledge and systems should encourage more climate-responsive architectural design, using mechanical systems judiciously when and where needed.

Building researchers and practitioners must associate closely to create transformational change in the industry. Researchers are equipped to investigate promising strategies for optimizing both energy use and occupant well-being; practitioners to identify the critical barriers to adopting the most innovative knowledge and technologies into their buildings. Together, they must collaborate to influence building standards, design guidelines and green building rating systems to help remove those barriers, and to promote the improved performance of our built environment.

References

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2012). *Performance measurement protocols for commercial buildings: Best practices guide* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

ANSI/ASHRAE 55-2013: Thermal environmental conditions for human occupancy, (2013).

Arens, E., & Brown, K. (2012). Broken information feedback loops prevent good building energy Performance – Integrated technological and sociological fixes are needed. *ACEEE Summer Study on Energy Efficiency in Buildings*, 2012, 59–70.

Arens, E., Federspiel, C. C., Wang, D., & Huizenga, C. (2005). How ambient intelligence will improve habitability and energy efficiency in buildings. In W. Weber, J. M. Rabay & E. Aarts (Eds.), *Ambient intelligence* (pp. 63–80). Springer.

Arens, E. A., Turner, S., Zhang, H., & Paliaga, G. (2009). Moving air for comfort. *ASHRAE Journal*, *51*(5), 18–29.

Brager, G. S., & Baker, L. (2009). Occupant satisfaction in mixed-mode buildings. *Building Research & Information*, *37*(4), 369–380. doi:10.1080/09613210902899785

Cabanac, M. (1971). Physiological role of pleasure. *Science*, *173*(4002), 1103–1107.

Clements-Croome, D. (Ed.). (2006). *Creating the productive workplace* (2nd ed.). New York, NY: Taylor & Francis.

Dawson-Haggerty, S., Jiang, X., Tolle, G., Ortiz, J., & Culler, D. (2010). sMAP: A simple measurement and actuation profile for physical information. *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems*, 197–210.

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

de Dear, R. J. (2011). Revisiting an old hypothesis of human thermal perception: Alliesthesia. *Building Research & Information*, *39*(2), 108–117. doi:10.1080/09613218.2011.552269

de Dear, R. J., & Brager, G. S. (1998). Developing an adaptive model of thermal comfort and preference. *ASHRAE Transaction*, *104*(1a), 145–167.

de Dear, R. J., & Brager, G. S. (2001). The adaptive model of thermal comfort and energy conservation in the built environment. *International Journal of Biometeorology*, *45*(2), 100–108.

Frontczak, M., Schiavon, S., Goins, J., Arens, E. A., Zhang, H., & Wargocki, P. (2011). Quantitative relationships between occupant satisfaction and aspects of indoor environmental quality and building design. *Proceedings of International Conference Indoor Air Quality and Climate 2011*, Austin, US.

Hoyt, T., Arens, E., & Zhang, H. (2014). Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. *Building and Environment*, (0) doi:http://dx.doi.org/10.1016/j.buildenv.2014.09.010

Hoyt, T., Lee, K. H., Zhang, H., Arens, E. A., & Webster, T. (2009). Energy savings from extended air temperature setpoints and reductions in room air mixing. Paper presented at the *Proceedings of International Conference on Environmental Ergonomics*, Boston. Retrieved from http://escholarship.org/uc/item/28 × 9d7xj

Huizenga, C., Abbaszadeh, S., Zagreus, L., & Arens, E. A. (2006). *Air quality and thermal comfort in office buildings: Results of a large indoor environmental quality survey*. Proceedings of Healthy Buildings, Lisbon, Portugal, *III*, 393–397.

Kats, G. H. (2003). *Green building costs and financial benefits*. Massachusetts Technology Collaborative.

Leyten, J. L., Laue, A. K., & Kurvers, S. R. (2014). *Robust design for high workers' performance and low absenteeism – an alternative approach*. Proceedings of 8th Windsor Conference: Counting the Cost of Comfort in a Changing World. Windsor, UK.

McGregor, A., Roberts, C., & Cousins, F. (2013). *Two degrees: The built environment and our changing climate*. New York: Routledge.

Melikov, A. K., Skwarczynski, M., Kaczmarczyk, J., & Zabecky, J. (2013). Use of personalized ventilation for improving health, comfort, and performance at high room temperature and humidity. *Indoor Air*, *23*(3), 250–263.

Mendell, M. J., Fisk, W. J., Kreiss, K., Levin, H., Alexander, D., Cain, W. S., . . . Wallingford, K. M. (2002). Improving the health of workers in indoor environments: Priority research needs for a national occupational research agenda. *American Journal of Public Health*, *92*(9), 1430–1440. doi:10.2105/AJPH.92.9.1430

Mendell, M. J., & Mirer, A. G. (2009). Indoor thermal factors and symptoms in office workers: Findings from the US EPA BASE study. *Indoor Air*, *19*(4), 291–302. doi:10.1111/j.1600-0668.2009.00592.x

Mower, G. D. (1976). Perceived intensity of peripheral thermal stimuli is independent of internal body temperature. *Journal of Comparative and Physiological Psychology*, *90*(12), 1152–1155.

Parkinson, T., & de Dear, R. (2015). Thermal pleasure in built environments: physiology of alliesthesia. *Building Research & Information*, *43*(3). doi:10.1080/09613218.2015.989662

Parkinson, T., de Dear, R. J., & Cândido, C. (2012). *Perception of transient thermal environments: Pleasure and alliesthesia*. Proceedings of 7th Windsor Conference: The Changing Context of Comfort in an Unpredictable World, Windsor, UK.

Pasut, W., Zhang, H., Arens, E., & Zhair, Y. (2014). Energy efficient comfort with a heated/cooled chair. *Building and Environment*. [Earlier version presented in Proceedings of the 13th International Conference Indoor Air, 2014, HK].

Seppänen, O. A., & Fisk, W. J. (2002). Association of ventilation system type with SBS symptoms in office workers. *Indoor Air*, *12*(2), 98–112. doi:10.1034/j.1600-0668.2002.01111.x

Seppänen, O. A., & Fisk, W. J. (2006). Some quantitative relations between indoor environmental quality and work performance or health. *HVAC&R Research*, *12*(4), 957–973. doi:10.1080/10789669.2006.10391446

Seppänen, O. A., Fisk, W. J., & Faulkner, D. (2004). Control of temperature for health and productivity in offices. Report LBNL - 55448. Lawrence Berkeley National Laboratory.

Taub, M. (2013). Power to the people: Personal control in offices for thermal comfort and energy savings. *Master of Science Thesis, Dept. of Architecture, University of California, Berkeley*.

Taub, M., Zhang, H., Arens, E., Bauman, F., Dickerhoff, D., Fountain, M., . . . , Pigman, M. (2014). The use of footwarmers in offices for thermal comfort and energy savings in winter. Submitted to *Building and Environments*.

Toftum, J. (2004). Air movement–good or bad? *Indoor Air*, *14*, 40–45.

Toftum, J. (2010). Central automatic control or distributed occupant control for better indoor environment quality in the future. *Building and Environment*, *45*(1), 23–28. doi:10.1016/j.buildenv.2009.03.011

US Energy Information Administration. Annual energy review 2010. Retrieved from http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf

Uchida, S., Tanabe, S., Nishihara, N., Haneda, M., Nakamura, S., & Kawaguchi, G. (2009). The evaluation of productivity in COOL BIZ office by field measurement of thermal environment and questionnaire survey. *Proceedings of Healthy Buildings*.

Wargocki, P., & Seppänen, O. A. (Eds.). (2006). *Indoor climate and productivity in offices*. Brussels, Belgium: REHVA, Federation of European Heating and Air-conditioning Associations.

Wilson, A. (2005). Making the case for green building. *Environmental Building News*, *14*(4), 1–15.

Wyon, D. P. (2000). *Enhancing productivity while reducing energy use in buildings*. Proceedings of the E-Vision 2000 Conference, 11–13.

Zhang, H. (2003). Human thermal sensation and comfort in transient and non-uniform thermal environments, PhD Thesis, Center for Environmental Design Research (CEDR), University of California at Berkeley, December. Retrieved from http://www.escholarship.org/uc/item/11m0n1wt

Zhang, H., Arens, E., & Pasut, W. (2011). Air temperature thresholds for indoor comfort and perceived air quality. *Building Research & Information*, *39*, 134–144.

Zhang, H., Arens, E. A., Fard, S. A., Huizenga, C., Paliaga, G., Brager, G. S., & Zagreus, L. (2007). Air movement preferences observed in office buildings. *International Journal of Biometeorology*, *51*(5), 349–360.

Zhang, H., Arens, E., Huizenga, C., & Han, T. (2010a). Thermal sensation and comfort models for non-uniform and transient environments, part II: Local comfort of individual body parts. *Building and Environment*, *45*(2), 389–398.

Zhang, H., Arens, E., Huizenga, C., & Han, T. (2010b). Thermal sensation and comfort models for non-uniform and transient environments: Part I: Local sensation of individual body parts. *Building and Environment*, *45*(2), 380–388. doi:http://dx.doi.org/10.1016/j.buildenv.2009.06.018

Zhang, H., Arens, E. A., Kim, D., Buchberger, E., Bauman, F. S., & Huizenga, C. (2010). Comfort, perceived air quality, and work performance in a low-power task-ambient conditioning system. *Building and Environment*, *45*(1), 29–39. doi:10.1016/j.buildenv.2009.02.016