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A review of the corrective power of personal comfort systems in non-neutral ambient environments

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Abstract

This paper discusses a spectrum of systems that cool or heat occupants personally, termed 'personal comfort systems' (PCS), in order to quantify their ability to produce comfort in ambient temperatures that are above or below the subjects' neutral temperatures.

The comfort-producing effectiveness may be quantified in terms of a temperature difference, coining the index 'corrective power' (CP). CP is defined as difference between two ambient temperatures at which equal thermal sensation is achieved - one with no PCS (the reference condition), and one with PCS in use. CP represents the degree to which a PCS system may "correct" the ambient temperature toward neutrality. CP can alternatively be expressed in terms of thermal sensation and comfort survey scale units.

Published studies of PCS are reviewed to extract their CP values. Cooling CP ranges from -1 to -6K, and heating CP from 2K to 10K. The physical characteristics of the particular PCS systems are not reported in detail here, but are presented as prototypes of what is possible.

Deeper understanding of PCS will require new physiological and psychological information about comfort in local body segments and subsegments, and about spatial and temporal alliesthesia. These topics present many opportunities for productive future research.

Introduction

'PEC' refers to the 'personal environmental control' of the thermal and air quality conditions directly surrounding the occupant. A limited number of devices and systems have existed for that purpose over many years. Systems providing personal control were formerly called 'task-ambient conditioning' (TAC), drawing on the analogy with task-ambient lighting, which has been generally understood for a long time. A working committee of researchers and manufacturers in the indoor environment field decided in 2008 to favor the term 'PEC' over 'TAC'.

PEC includes a subcategory, 'personal ventilation' (PV), that explicitly entails delivering outside air to a person. PEC itself does not necessarily involve outside air ventilation, because it may instead use room air to control or improve the person's local thermal conditions and local air quality.

We introduce the term 'personal comfort system' (PCS) at this point, to refer only to the thermal aspects of a PEC system. We suggest that within the general concept PEC (or TAC), there are two subcategories: PCS that operates without supplying outside air, and PV, that does. A desk fan or radiant heater would be a PCS, but not PV. PV systems must have a conduit to an outside air source.

This paper focuses on the thermal rather than the air-quality performance of PEC. We examine mostly PCS systems, but where comfort data have been published for PV systems, we include it in the review.

PCS offers both *comfort* and *energy* benefits:

1) PCS has the potential to satisfy individual comfort requirements. Individuals differ due to variation in gender, age, body mass, clothing habits, and metabolic rate, and thermal adaptation [1, 2, 3]. Interpersonal differences among subjects in a typical laboratory study cause a standard deviation of 1 - 2 scale units on the standard ASHRAE seven-point thermal sensation scale [4], even when all are experiencing the same well-controlled conditions. This variation can be larger in field studies due to the non-uniform space conditions found in typical buildings. The 1 - 2 sensation scale units are equivalent to 2 - 5K difference in ambient temperature. In jointly occupied spaces, it is therefore impossible for everyone's individual requirements to be met by *any* uniformly distributed temperature. ASHRAE Standard 55's target satisfaction rate among occupants is 80%, but in practice buildings often rate much lower than that. The large dataset of CBE occupant satisfaction surveys shows that 42% of occupants express dissatisfaction with their thermal environment [5]. There is ample room for improvement over the way existing buildings are conditioned. The only published case of a field study of office workers reporting 100% satisfaction involved PCS installed in each workstation [6, 7].

2) PCS offers an opportunity to save HVAC energy in buildings. HVAC consumes a large portion of the world's energy demand (approaching 20% of total energy use in developed countries, and growing everywhere). Much of this energy goes into maintaining narrow indoor temperature ranges that building operators consider necessary for comfort. If it were possible to relax the temperature range in either the hot or cold direction, total HVAC energy is reduced at a rate of 10% per degree C [8]. Savings of this magnitude exceed those of virtually any energy-conserving technology available in the industry, and they can be obtained through reprogramming controls sequences--without changing the building's HVAC hardware. Saving in real buildings can be even higher due to the prevalence of faulty building HVAC operation, such as simultaneous heating/cooling within zones, whose energy waste is intensified by narrow temperature setpoints.

Widening the temperature range for energy must continue to ensure occupants' comfort, or at least provide the same level of comfort as in current buildings, which as we have seen is not perfect. Occupants themselves require far less energy to heat and cool than does the entire indoor space that houses them. PCS offers the opportunity to accomplish this. With small amounts of energy, it can provide individual comfort within a broader range of indoor ambient temperatures (varying over both time and space). It would be good to know the ability of different types of PCS and PV systems to correct for ambient conditions that might otherwise be outside the comfort range of individual occupants.

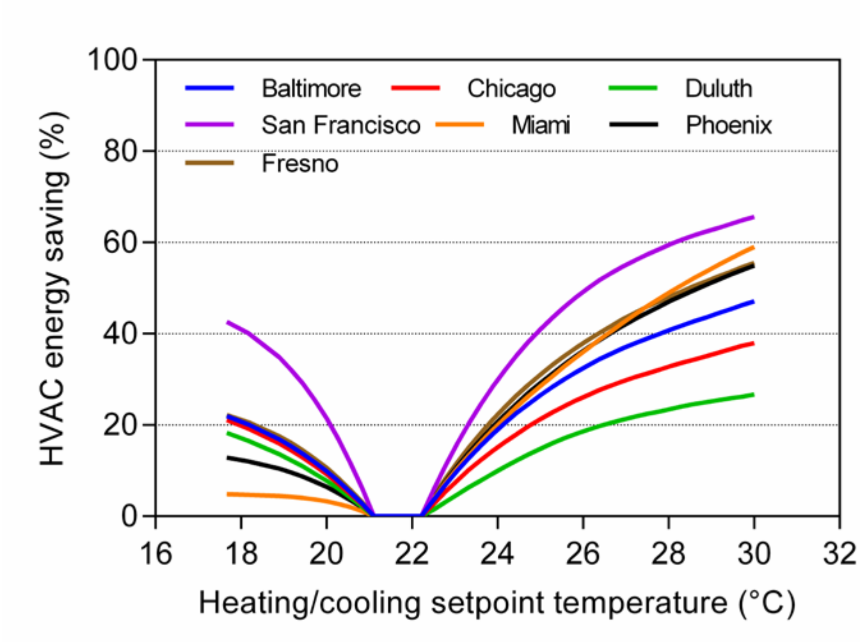

Figure 1 Percent of total HVAC energy saved in different climates by widened air temperature setpoints, relative to conventional setpoint range. (‘cup diagram’, [8])

This paper reviews PCS research studies that have reported comfort results by human subject tests or by manikin tests in the literature. It extracts common performance indices from the test results. These can be used to compare PCS effectiveness, and to allow engineers to design HVAC temperature control sequences appropriate for operation together with PCS. The paper also evaluates whether PCS is superior to conventional uniform systems in providing thermal satisfaction and encouraging adaptive behavior.

It should be noted that, beyond a large variety of desk and ceiling fans, there are not many formal PCS commercially available in the marketplace. A substantial part of the available literature is comprised of generic studies of air movement where the specific sources or their layout within the workspace are not important. In the studies where the PCS does involve integration with furniture, it is often a prototype system designed and fabricated by the researchers. Nonetheless, a review of such studies would be helpful in encouraging the future design and manufacture of effective and energy-efficient forms of PCS.

Finally, it should be noted that PCS is not a new phenomenon except in the context of air-conditioned or centrally heated buildings where the assumption is made that all spaces should have a more or less uniform temperature. Most of the heating/cooling systems that preceded HVAC were in effect PCS. An open fire works on the basis of providing a source of radiant heat that the room occupants could move towards or away from according to their needs, and the background temperature will generally have been relatively low and is likely to have varied from room to room. As a cooling/heating element a window has some of the same function, though in a wider sensory context. These relatively complex traditional systems were difficult to analyze with the tools and methods of today’s engineering practice, and have perhaps for this reason been ignored. The authors hope this review of mechanical PCS may also help form a basis for the engineering analysis of a wide range of heating and cooling systems within NV or free-running buildings.

Background

Ambient indoor temperature and air movement

Air and surface temperature: It makes sense to first review the ambient thermal environment surrounding both occupants and their PCS. This environment is conditioned by the building's HVAC system, with resolution down to the zone level within which temperature is controlled by a thermostat. The zone is usually intended to be uniformly mixed, and standards limit the extent of nonuniformity permitted (usually this non-uniformity is in the vertical temperature gradient, which cannot exceed 3K in the seated occupied zone). There may also be radiant asymmetries within the zone associated with heated or cooled floors or ceilings, but such room surface temperatures are intentional and controlled by the building's HVAC system. Their comfort effects have long been accounted for in comfort standards by the use of 'operative temperature' to appropriately average air and surface temperatures. Most HVAC systems are designed to produce minimal air movement in the occupied part of the zone, so the still-air operative temperature is the primary metric of occupant comfort.

The ASHRAE [4] and ISO Standards [9] specify fairly wide ranges of operative temperatures as being comfortable, depending on humidity and occupants' clothing and activity levels. Figure 2 (ASHRAE 55 Figure 5.3.2) shows the comfort zone boundaries for ASHRAE Std 55, for two clothing levels, resting activity level, and 0.1 m/s air movement, which is well within the standard's definition of still air (now 0.2 m/s).

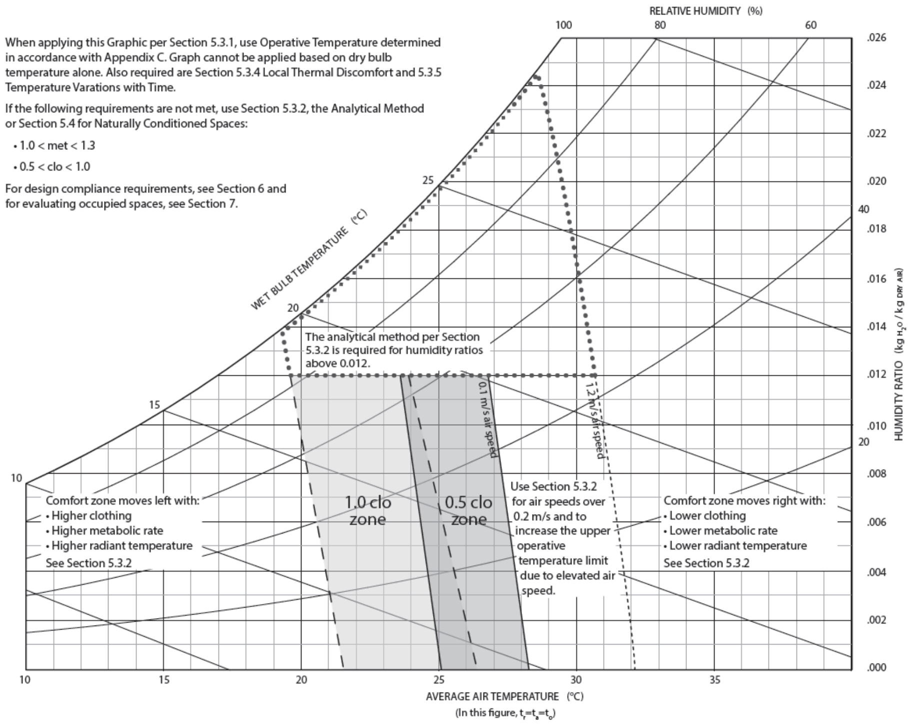

Figure 5.3.1 (SI) Acceptable range of operative temperature and humidity for spaces that meet the criteria specified in Section 5.3.2.

Figure 2. Acceptable range of operative temperature and humidity for spaces (ASHRAE Std 55 Figure 5.3.2 [4])

It should be noted that the standard's maximum allowable temperature ranges are wider than are used in most commercial buildings with central HVAC. In practice, the typical commercial building thermostat range is between 0 and 2.5K, as illustrated in Figure 1. The standards' range based on +/-0.5 PMV extends 3-4K at 40% RH, depending on the clothing insulation.

One might think that current practice is choosing a 'Class A' standard with a narrower PMV range (ISO 7730 has a +/- 0.2PMV range in its Class A), but this is not correct. Most of the narrowing is eliminating the upper temperatures, so that buildings are using the winter part of the comfort zone both summer and winter. Mean indoor temperatures are cooler in summer than in winter [10], and though there exists a preponderance of overheating complaints in winter, the overcooling in summer is a much greater effect. Overcooling is occurring even in tropical zones such as Singapore and Hong Kong. The narrow cool zone appears to result from limitations in central air systems' ability to respond to partial heat and humidity loads.

Air movement: Within a room, air movement can raise its comfortable temperature by increasing the heat removed from the occupants' skin. Within-room air-moving features like ceiling fans or PCS may supplement the ambient conditions provided by HVAC.

ASHRAE Standard 55 Figure 5.3.3 (Figure 3 in this paper) presents the temperatures that may be assumed comfortable under air movement from fans and natural ventilation. The light grey zone shows temperatures where ambient air motion provides acceptable comfort regardless of occupant input. In the cooler temperatures and higher speeds of the dark grey zone, override control of the air movement must be made available to small groups of occupants. The temperature rise enabled by non-controlled air movement is as much as 3.5K (from 27 to 30.5ºC for 0.5clo).

Occupant-controlled room air movement to some extent underlies the wider range of comfortable temperatures predicted by the Adaptive Method, an empirically-based comfort zone for naturally ventilated and free-running buildings, in which the temperature zone is 7K wide. Several adaptive comfort behaviors contribute to the wider zone. Among these, cooling by air movement is likely a significant contributor, although it has been difficult to establish from field studies exactly how this works.

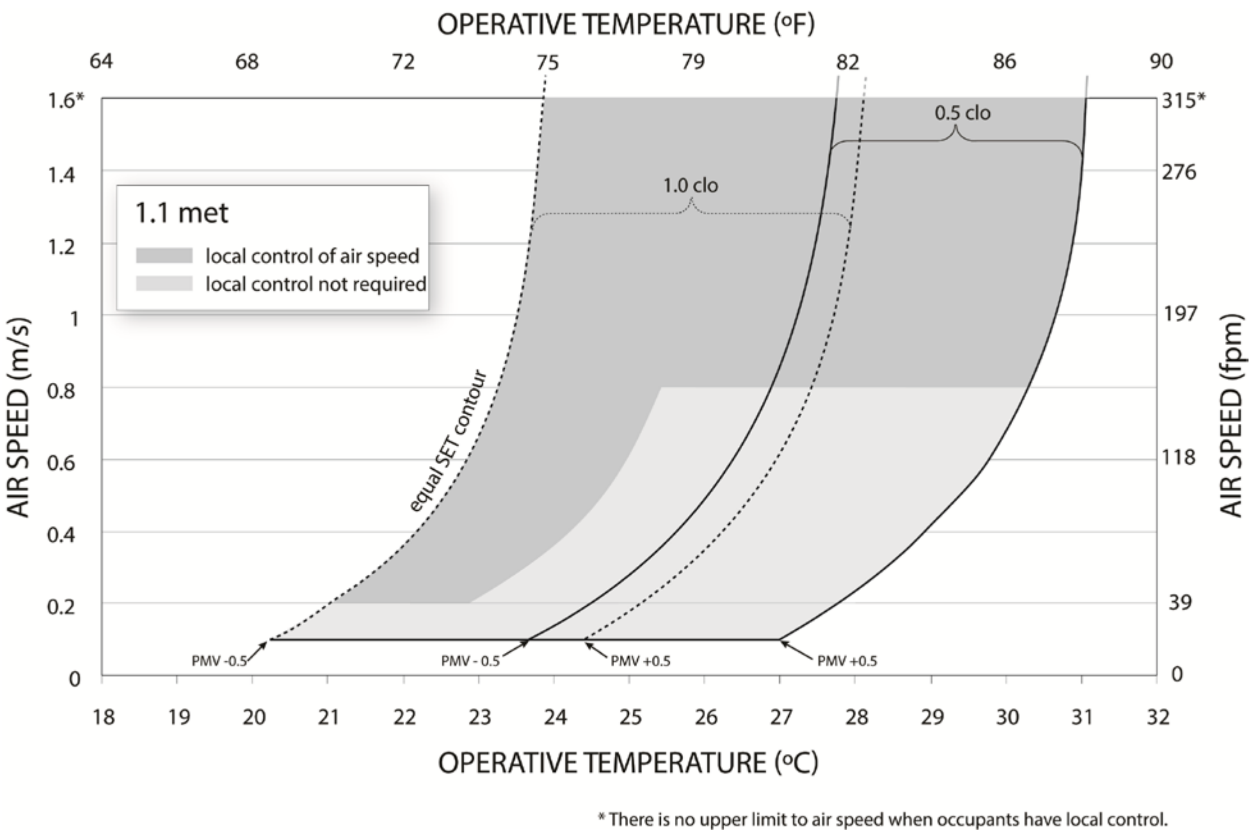

Figure 3. Acceptable range of operative temperature and air speeds for comfort (Std 55, Figure 5.3.3 [4])

Before discussing the local conditioning of individual occupants, one needs to address the fact that occupants are not stationary within the occupied zone, and air movement is inherently not uniformly distributed across space. PCS and ceiling fans may be concentrated at occupants' workstations, and may not cover all the spaces an occupant might visit or pass through during the day. It is necessary to evaluate whether an occupant's visits to spaces not served by air movement may cause discomfort. There are many design factors (ambient temperature, extent of non-served spaces, transit or stationary, length of expected stay, the nature of activities in a space, and the subject's metabolic level while there). These are addressed by some PCS studies [11, 12, 13] that have interspersed their subjects' time at the workstation with break periods in the ambient at elevated exercise levels representing standing, walking, and stair-climbing. These studies have shown that occupants are quite tolerant of thermal excursions, and that the environment at the workstation dominates their comfort perception.

Personal conditioning of occupants

Pertinent scales PEC and PCS systems heat, cool, or ventilate their users locally. 'Locally' applies to a range of scales. At the largest, it distinguishes the microenvironment of the user from that of the ambient room or zone conditions provided by the building's HVAC system. The microenvironment may be viewed as having uniform conditions throughout, and the user within it experiencing a 'whole-body' response. However, the microenvironment is usually not uniform, and the particular segments and sub-segments of the human body are affected differently within that microenvironment. For example, the body's segments include feet, face or hands, and its subsegments include the soles, cheek, and finger. The person will experience local responses to the environments that surround and interact with these segments and subsegments.

Models of comfort: Figures 2 and 3 from ASHRAE Std 55 are based on two whole-body heat balance models, PMV and SET, which do not differentiate body segments, or even the proportions of the body that are covered, or not covered, by clothing. These models are long-established for evaluating uniform steady-state environments near neutral, but are less suited for evaluating non-uniform environments that occur around the human body with PCS. In these the response of the occupant is more complex and more dynamic. Much of the thermal and perceptional effectiveness of PCS springs from this complexity.

Multi-segment physiology/heat balance models have been used to predict variation in skin temperatures and heat fluxes occurring on different segments of the body under non-uniform conditions [14, 15, 16]. These models incorporate the effects of the body's morphology and its vasomotor/sudomotor control. The typical number of body segments addressed is sixteen to twenty-four. This level of segment detail, though an improvement over the single segment models used in standards, may still be insufficient to characterize heat transfer caused by smaller contact areas found in PCS, such as a chair seat, or jets of wind on face or neck.

The functioning of PCS (and PEC and TAC) depends on more than body heat transfer. The above physiological outcomes must be converted to thermal sensation and comfort for both local body segments and the whole body. This involves the individual segments' neurophysiological sensitivity to thermal stimuli psychology, and also how the local sensations are integrated in the brain to produce an overall sense of temperature and comfort. The models of Zhang [17, 18, 19, 20] attempt this integration.

Fundamental psychophysiological basis for PCS systems: The integration process may be grounded in the concept of *alliesthesia*. The term was coined by Cabanac [21] for his premise that hedonic, or pleasurable, sensations are generated by the restoration of a bodily stress toward a neutral interior condition, and conversely that an unpleasant sensation results from disturbing the neutral condition. Alliesthesia confers natural selection benefit to organisms by encouraging appropriate adaptive behavior. The original work focused exclusively on transient effects (temperature, hunger, thirst, sex) and might be termed '*temporal alliesthesia*'. In its thermal embodiment, when a less-than-comfortable warm or cold body received a thermal stimulus in the desirable direction, it could produce an observed overshoot of pleasure that exceeds that of a neutral condition [22, 23, 24, 25]. The physiological mechanism for this ‘overshoot’ originates from the dynamic responsiveness and positioning of thermoreceptors in the skin [26, 27]. The brain processes the firing rates of warm and cool-sensing neurons to provide the perceived pleasure effect. Temporal alliesthesia has some importance to PCS because PCS systems inherently involve local control of fast-acting thermal stimuli, and there may be functional benefit in harvesting thermal overshoot [28, 29, 30].

More important to practical PCS is the concept of *spatial alliesthesia*, which can persist over time in steady state conditions. Here the body experiences non-neutral thermal conditions in its various body parts that bridge the opposite sides of a neutral temperature. Certain combinations of body part temperatures can produce a pleasure sensation greater than that of uniform whole-body neutrality [30]. Spatial alliesthesia is a relatively new concept, embodied in the above models of local thermal sensation and comfort [17, 18, 19, 20]. The concept has been recently summarized in [29].

The Zhang comfort models are as yet unique, rationally quantifying comfort and sensations of body parts and the whole body as a function of differences in temperature across the body’s skin surface. They rely on the displacement of the body’s global skin temperature from a neutral temperature setpoint [31], which itself varies unnoticed within a neutral thermoregulatory zone [20]. The sensitivity of each body part to warm and cool temperature displacements also varies. The hand and feet are most sensitive to cool discomfort in cool environments, particularly to the discomfort caused by vasoconstriction [25, 32] . The head is most sensitive to warm discomfort in warm environments. The torso is sensitive to both heating and cooling.

In these models, both negative and positive alliesthesia determine how temperature and comfort perceptions coming from all body parts are integrated. Comfort follows a ‘complaint’ process. Uncomfortable body segments (with negative alliesthesia) ‘complain’ (are noticed) and then dominate the signals from other segments in creating overall comfort perception [19, 24, 25]. PCS can reverse this negative signal to a positive one by applying heating or cooling to the uncomfortable segment. This suggests a scenario that makes PCS very efficient within a range of normal indoor temperatures and clothing. The discomfort from a whole-body thermal imbalance becomes sensible at a local body part (e.g., feet or head). Only a small amount of energy is needed to heat or cool this body part to restore comfort, and in the process provide positive spatial alliesthesia (since the restoration process puts the local part on the opposite side of neutrality from the overall body). The body’s own adjustment of its neutral average skin temperature varies across a range of 1.3K, assuring that overall thermal balance can be maintained across an ambient range of approximately 3K [24].

Mapping PCS heat transfer onto the body

The model developments above suggest that, to create the strongest impact, PCS shall be designed to target the dominant uncomfortable body segments. Cooling the head and upper body is effective in warm and neutral environments. Warming the feet and lower body is effective in cool environments. The torso may be either heated or cooled. It has relatively large surface areas for heat transfer to the body’s core, but is sensitive to large temperature gradients, especially in cooling. The hands/wrists may also be heated or cooled. Their surface area does not permit much heat transfer, but the prevention of vasoconstriction in the cold is important for maintaining overall comfort.

Most existing PCS systems follow these rules, even if they were intuitively arrived at. Most of them exclusively cool the head or warm the feet, or do either or both with the trunk and the upper extremities.

Physically, PCS systems rely on radiation and warm contact surfaces to warm the body; and air movement and cool contact surfaces to cool the body. Convective heating is not efficient because even though moving warm air may transfer sensible heat to the skin, it augments evaporative heat loss from the skin. Personal space heaters are inherently inefficient for this reason, requiring high wattages for a given effect, even if they are applied very close to the person. We exclude them from PCS designation.

Radiant cooling does not occur at the personal level. Chilled ceiling panels serve wider work areas, are controlled as part of the HVAC system, and are slow-acting. They are also excluded from PCS designation.

The literature does not describe body-segment-specific features of PCS in any detail. Very few skin temperatures are reported. The local air speeds provided by PCS are rarely mapped on the body, or the affected areas quantified, or the proportion of clothing on the affected area. A ceiling fan compared to a small desk fan will affect different areas of skin, with different skin sensitivities within that area, and different proportions clothed. None of these measures are quantified in the existing literature. A similar situation exists for radiant and conductive PCS systems.

But we can in many cases extract from the literature common values for the PCS effectiveness at providing *whole-body* comfort. Some studies also cast light on alliesthesia from PCS - whether the non-uniform PCS systems are providing *greater* comfort than the neutral uniform condition such as provided by HVAC alone.

Types of PCS systems

PCS can be generalized as follows.

- Head/face/upper body local air jets. This includes desk fans, small USB fans, nozzles and slot diffusers in desks and workstation partitions. Flows are usually frontal or from the side. Specific PCS products incorporating these features included the 'Personal Environmental Module (PEM)', 'ClimaDesk', and the Exhausto personal ventilation system; none of these are still in production.
- Overhead (ceiling) fans. These provide a vertical airstream under the fan, converting to a lateral stream outside the air jet. A wide variety of fans are commercially available. Their power efficiency and acoustical quality has been greatly improved in recent years due to improvements to their motors (now often brushless direct-current) and fan blade designs.
- Side large-area air flows (including window ventilation). Large box fans produce such bulk airflow, typically seen in industrial, gymnasium, or lobby settings. Natural airflow through windows or open designs may resemble such flows.
- Chairs, heated or cooled; or ventilated. Chairs have been heated using electric resistance heating elements in the seat surface, the warm side of thermoelectric devices, or with warm water tubes. Chairs have been cooled using isothermal air convection through or behind the heat surface, contact surfaces connected directly to the cool side of thermoelectric devices, and through cooled water tubes. Most commercial examples to date have been in the automotive industry, where cooling is convective using cooled air from thermoelectric devices or the automobile's central HVAC.

- Footwarmers, legwarmers, kneehole radiant panels. The lower extremities (feet and legs) can be heated by radiant sources (panels or focused sources such as reflector bulbs), or less efficiently by conductive pads under the feet.

Only a few integrated PCS systems have been commercialized thus far, and almost none are on the market now. Much of the testing of PCS has been done in laboratories, of prototype designs developed by the researchers.

Very few studies of PCS have reported the wattage of the devices tested, and in the few cases where they have, the wattage reported is no longer relevant because of recent improvements to fans and fan motors [33].

There has not been much overlap of automobile comfort research with the development of PCS for buildings.

Objectives

This paper reviews the literature on human subject and manikin tests for evidence about the comparative comfort performance of PCS. It assembles and evaluates data from (mostly) laboratory studies performed over many years in order to:

- quantify the thermal comfort levels that have been found from particular types of PCS
- suggest appropriate temperature setpoint ranges that are possible when PCS is included in a building
- examine evidence of alliesthesia—whether the satisfaction with non-uniform PCS may exceed that of the neutral uniform condition traditionally considered ideal
- inform the design of future PCS

This review is not intended to describe the physical characteristics of the published PCS systems in detail, since this information can be obtained from the original references if desired. The systems' energy (electricity) consumption is also not described, due to the absence of relevant data as mentioned above.

Comparing the systems' comfort performance requires establishing a common metric, applicable to the different classes of PCS across the range of possible ambient environments. This is described below.

Method of determining corrective power

We here introduce the term *corrective power* (CP) to quantify the extent to which a PCS can "correct" a warm or cool ambient temperature toward neutral. The "power" refers to the temperature-correcting capability (strength) of the system, not the electrical wattage it draws. The units are in temperature. CP is defined as difference between two ambient temperatures at which the same thermal sensation is achieved - one with no PCS (the reference condition), and one with PCS in use. For example, if subjects voted a neutral thermal sensation at a particular combination of warm air temperature and air movement, and also voted neutral sensation with a lower air temperature in still air (the usual reference condition in such studies), then the temperature difference is the CP, which will have a negative value. Heating PCS provides positive values of CP by correcting temperatures below the traditional neutral to be comfortable.

For a human subject study to be included in the review, it had to be necessary for its CP to be determined. There had to be a reference case without PCS in which the same sensation was observed as in the PCS tests. In some studies no equivalence was shown but a close inequality allowed a lower limit to be established for the CP. But many papers that measured only preferred levels of air movement could not be used to establish equivalence. Quite a few nice studies could not be included, including some from this paper's authors! However, those papers are listed at the end of the references list.

CP can also be expressed in terms of comfort votes (CP-C) or thermal sensation votes (CP-S) from the subjects' survey votes, quantified in the scale units of their voting scale (described below). CP-C and CP-S quantify the comfort and sensation differences between occupants with PCS and occupants without PCS (the reference condition).

CP can also be determined from electrical manikin tests. In these, CP is determined by directly measuring the Equivalent Homogeneous Temperature (EHT) with and without PCS. The difference is the CP in Kelvin. EHT is a commonly used metric in manikin testing, defined as the uniform ambient temperature at which the manikin's dry heat loss is equal to that under an actual nonuniform environment (in this case the PCS environment).

The CP measured by a manikin is different from the CP obtained by human subject tests. The cooling effect perceived by people is not linearly related with EHT. The differences in cooling and heating effect between a manikin and human are in two areas.

1) Heating and cooling different body parts produces different results physiologically and psychologically in human. For example, cooling head and warming feet create bigger comfort effect than heating head and cooling feet, because people are sensitive to head warming and cool feet discomfort [24, 25]. The heightened sensitivity to different body parts cooling and heating is associated with spatial alliesthesia, but a manikin does not inherently distinguish between body parts. Therefore it underestimates whole body CP.
2) Humans evaporate moisture from the skin, which is present even when there is no obvious sweating. Air movement (such as fans) increases both convective and evaporative cooling. A dry-surface manikin therefore under-estimates the CP caused by air movement.

Description of the tables

The review is summarized in five tables for the different types of PCS. Forty one studies are included.

Table 1. Air jets on upper body—cases cover a range of areas, from that of the face to that of the upper half of the body (14 studies)

Table 2. Vertical airflow on whole body (ceiling fan, 4 studies)

Table 3. Uniform horizontal airflow on whole body (large fan or window, 5 studies)

Table 4. Heating PCS (footwarmers/legwarmers, and heated/cooled chairs, 12 studies)

Table 5. Manikin tests (6 studies)

The review found more literature on cooling the body rather than on heating. The cooling is mostly through air movement or conductive contact surfaces. Heating tends to be radiant or through contact surfaces.

For each study a thumbnail sketch of the test setup indicates the physical characteristics of the PCS as studied. The parameters included in the tables are intended to provide information for the design and implementation of PCS. For a given set of ambient and PCS conditions, the thermal comfort levels for a given type of PCS should be quantifiable. Each study was mined for the *physical* variables: ambient temperature (T), RH, air velocity (V), supply temperature (T_{supply}). Some papers measured velocity and temperature at the outlets of the PCS, others measured it near the subjects' body surface. The *subjective* measures are sensation and comfort. From these variables the CP was determined. CP is described in Kelvin (K), the standard way of expressing temperature differences on the Centigrade scale. The CP-S and CP-C are described in sensation and comfort units, respectively.

Most published papers have used the 7-point ASHRAE sensation scale in their studies. If a study used a different scale (e.g. 9-point scale including 'very hot' and 'very cold'), it is noted in the table. The comfort scales are not standardized. The most commonly used comfort scales are 'comfortable, slightly uncomfortable, uncomfortable, very uncomfortable', described in the tables as the 4-point-comfort scale (0 to -3). In this scale we evaluate 'comfort' as the value ≥ -0.5. Another scale treats comfort and discomfort symmetrically, ranging between 'very comfortable' to 'very uncomfortable' with a break in the middle at 'just comfortable' and 'just uncomfortable' (+4 to -4). This is described in the tables as the 9-point comfort scale, with positive indicating comfortable and negative uncomfortable.

When humidity was a variable in a study, and effective temperature (ET^*) was provided, CP is presented in the table in terms of ET^*. If ET^* was not provided we used the air temperature.

When equal thermal sensation is not available, a minimum CP can sometimes be estimated from the sensation values given. For example, if without fan at 26ºC the sensation was 0.5, and with fan at 28ºC the sensation was 0, the CP is presented by >|-2K|.

Because very few studies measured the detailed local temperatures provided by PCS on the skin, there are no such data reported in the tables. If studies measured the local sensation/comfort responses to the PCS, the local results are included in the tables.

Results

Summary of CP values in the five tables

The tables in the Appendix provide a general overview of the CP capability of each of the major types of PCS systems in terms of ambient air temperature, thermal sensation, and comfort. They also provide a generalization of the velocity or the heating levels that provided comfort under a wide range of ambient conditions in these studies. The performance of individual systems within a type can be examined and compared with that of other systems in the type.

The results are all for stable conditions. Transient responses were presented in a few studies, but only as examples from which we could not determine a CP. Because the transient advantages of PCS are not accounted for, the review may provide a conservative picture of their benefits.

In general, the higher the ambient air temperature, the bigger the cooling CP observed; the cooler the ambient, the higher the heating CP.

Table 1: cooling by frontal air jets

From the 14 studies of frontal air jets, the following generalities were observed. At 26ºC and 27ºC, low levels of air movement between 0.36 - 0.6 m/s created a CP of -1K to -3K. At 28ºC, low air movement around 0.4 – 0.6 m/s created a CP of -2K to -3K or more. This means that at ambient temperatures equal or lower than 28ºC, air movement below 0.6 m/s can 'correct' the ambient to a still-air equivalent of 25ºC or 26ºC. Comfort is maintained, and sensation is within ±0.5 of neutral (0).

At 30ºC ambient temperature, air speeds must be 0.8 – 1 m/s or higher to create a CP of -2K to -4K, making the equivalent ambient temperature 26 to 28ºC. Comfort can be maintained within ±0.5 scale units of neutral, sometimes to within ±0.1.

When the ambient is 32ºC, a high level of air speed (up to 2 m/s) is needed to maintain comfort. Above 32ºC, isothermal convection alone is not able to maintain comfort, and the air jet requires some cooling. Lowering the jet air temperature at the skin surface by 2-5K provides an extra –2 to -3K CP, to about -4 to -7.

Unlike sensation, not every study surveyed comfort perceptions. In general, the CP-S is bigger than the CP-C.

Tables 2 and 3: cooling by ceiling fan and uniform airflows

Cooling by ceiling fans and large-area box fans covering all directions provide similar effects, and are therefore summarized together here. These devices' CP is stronger than for the frontal air jets. At lower ambient temperature (26ºC, 27ºC) and a low air speed of 0.25 – 0.6 m/s, CP was -3K. At 28ºC ambient temperature, CP can be as great as -4K. Generally, CP is about -1K – 2K stronger than the frontal air jet within this temperature and air speed range. At the higher speed of 1 m/s, the CP can be -4K to -7K. The ceiling fan can provide comfort up to 33ºC ambient temperature. The warmest ambient condition tested using uniform airflow was 31.5ºC and 80% RH (Tanabe), when thermal sensation was 0.48, comfort was -1.12 (using the 4-point comfort scale).

Table 4: cooling by chairs; heating by chairs or footwarmers/legwarmers

Seven studies were of various cooled chair designs, six of various heated chair designs, and five of devices that heat the lower extremities. Chair cooling studies in the literature provide CP values ranging between -2K to -5K. Heating by chairs is very effective, creating CP values as high as 7K – 10K. Heating of the feet through footwarmer, legwarmer, or wrist/palm-warmers yielded CP values from 2K (in a field study) to 6 – 10K (lab studies)

Table 5: manikin tests

Manikin tests underpredict actual human CP results for the reasons described above. For the whole body, cooling CP is mostly less than -1K for the velocity ranges studied (below 1 m/s). The table also provides local body-segment CP values, which are much larger, -4K to -8K for cooling. For heating, whole body heating CP is between 2K to 5K, and local heating CP is as high as 7.5K.

Comfortable ambient temperature ranges possible with PCS

Figure 4 summarizes the range of conditions rated as comfortable with PCS in the literature reviewed. They are superposed on the ASHRAE elevated air speed figure, because most of the cooling studies used air movement.

Frontal air jets, ceiling fans, and uniform airflow are all included, with the studies' associated ambient temperatures. Each symbol in the figure represents one test condition. Air speed from frontal air jets (represented by the blue circles) can be higher than the speeds from ceiling fans (green crosses) or uniform airflow (green rectangles) at lower ambient temperatures (below 28ºC). It can be as high as 1.4 m/s at 27ºC and 28ºC. Air speeds between 0.25 – 1 m/s from ceiling fans are seen to provide comfort up to 32ºC ambient temperatures.

The heating PCS devices (chairs, foot and leg warmers) have a CP of 7K – 10K from neutral. Heating PCS extends the comfort zone down to 14ºC [34] and 16ºC [12, 35] ambient temperatures, as shown by the red squares in the figure.

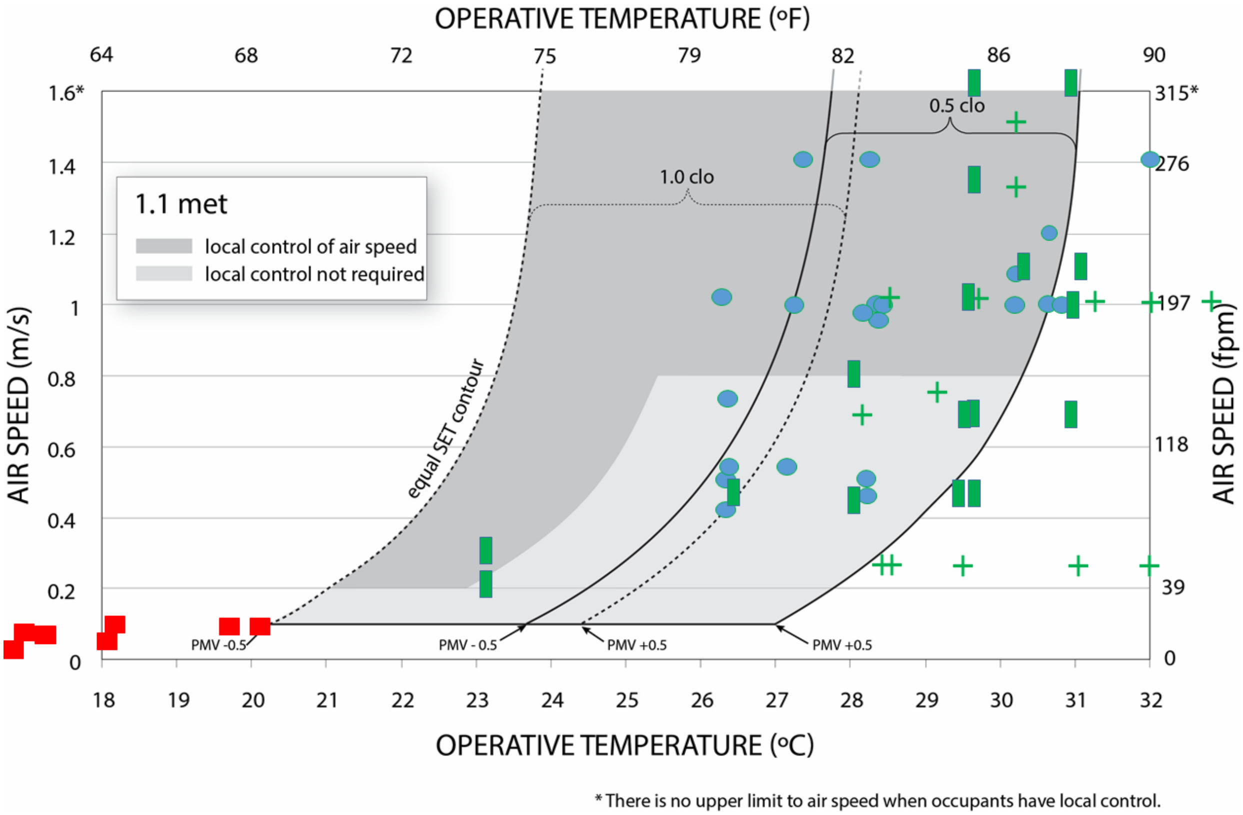

Figure 4. Test conditions providing comfort superposed on ASHRAE Standard 55 airspeed figure. (Symbols are described below)

Figure 5 represents simplified ranges of temperature in which comfort is achievable with PCS. The cooling side is based on frontal air jets whose CP values are conservative compared to those of ceiling fans and uniform air flow. The heating range is based on all footwarmers, legwarmers, and heated chairs.

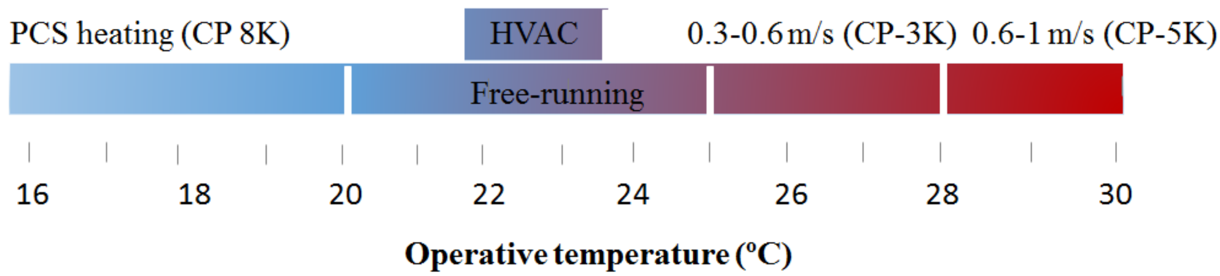

Figure 5. Comfortable temperature ranges provided by PCS

Evidence of alliesthesia

There are 13 human subject studies that reported the percentage of subjects satisfied with thermal comfort in their test conditions, both with and without PCS present. The satisfaction rates are presented in Figure 6, circular dots representing conditions with PCS, and squares without PCS. The 13 colors distinguish the 13 studies.

Across each pair of test conditions, the satisfaction rate with PCS is higher than the satisfaction rate without PCS. One can see that the circles are always located higher than the squares for a given condition.

Seven studies provided satisfaction rate under their measured *neutral* condition without PCS. This value is the presumed ideal for HVAC. These rates are found in the middle of the chart (square symbols between the ambient temperatures 22.0 – 26.3ºC, within the red ellipse.) With PCS, satisfaction rates higher than those under these neutral temperatures are observed in many studies up to 28.5ºC, and down to 16ºC in Taub’s [36] and Y.Zhang’s [37] studies. This result may be a demonstration of spatial alliesthesia, in which comfort in non-uniform environments is greater than in uniform neutral environments without local heating or cooling.

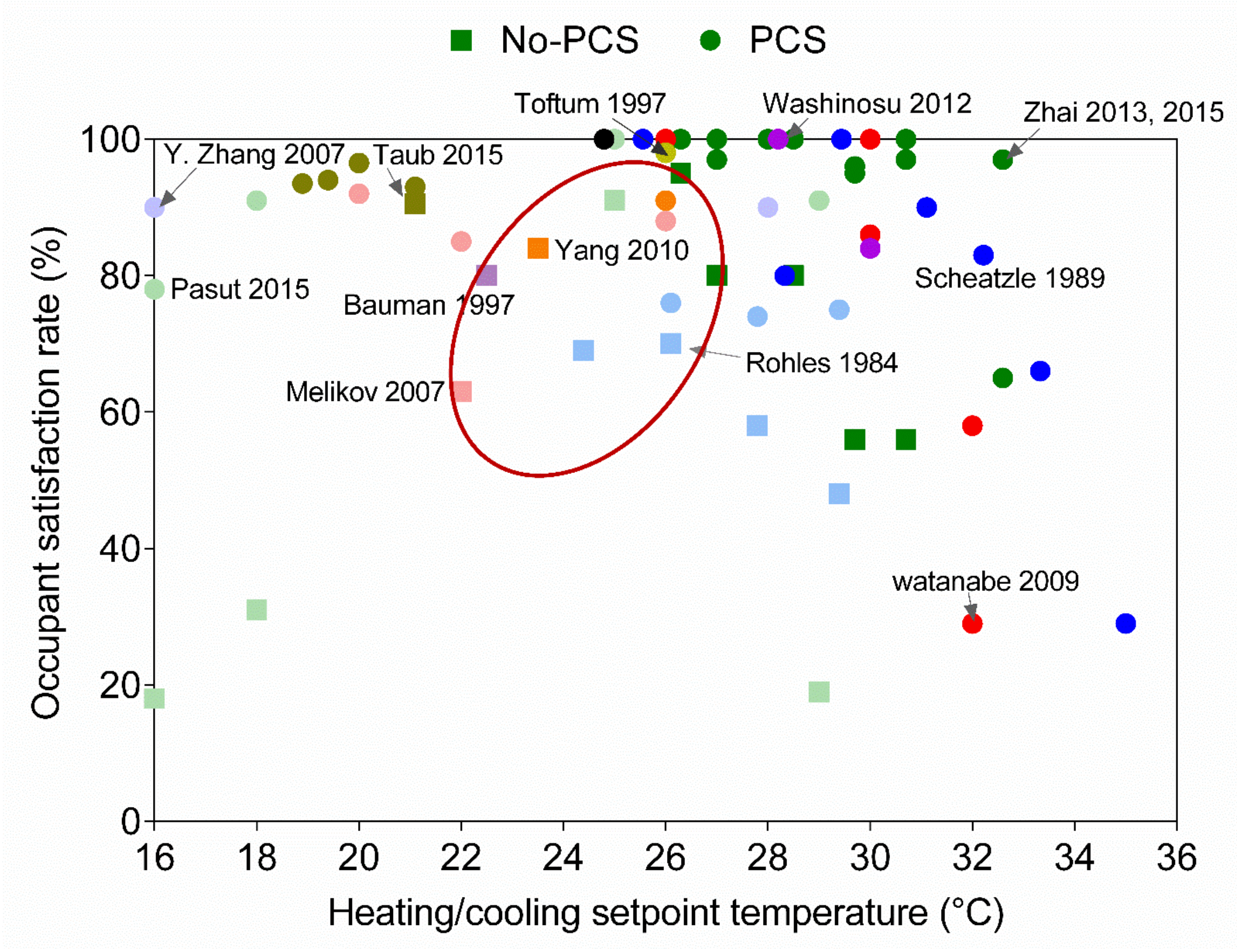

Figure 6. Higher comfort rates achieved at warmer- or cooler-than-neutral ambient conditions (neutral conditions shown as squares in ellipse)

Energy saving and subjective thermal comfort

Referring back to Figure 1, one may ask how comfort is maintained when the setpoint range is expanded. Figure 7 combines the satisfaction results with PCS (round dots in Figure 6) with the Figure 1 chart of energy-savings. It shows that the satisfaction rate is well above 80% (the ASHRAE Standard 55 target) under the widest range of expanded setpoints given in Figure 1. The green lines between the dots are from piece-wise regression fits of the measured data. It shows that, for these studies, a comfort 'lid' completely covers the energy 'cup' so that the full range of simulated energy savings is possible without loss of comfort.

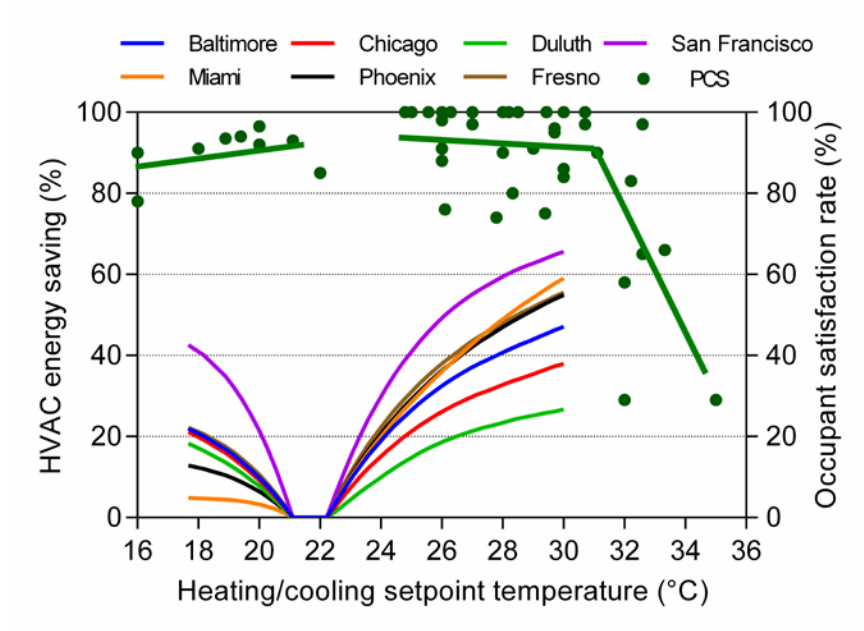

Figure 7 Energy saving (left legend) and occupant satisfaction (right legend) over expanded setpoints (‘*cup + lid*’ *diagram*)

Discussion

Comparison of cooling from fans in field studies in NV buildings. In NV buildings, the measured average velocity tends to be low, typically less than 0.2 m/s. The measured thermal sensations indicate a larger corrective power in such buildings than such airspeed would warrant, which has been for some time an unsolved mystery. Data from ASHRAE database I [38] and a large study of a NV building [39, 40] all found that 0.2 m/s speed corresponded to 1K – 2K air temperature increase (CP 1K – 2 K with 0.2 m/s average air speed). Such CP values are greater than values obtained for large area fans at 0.2 m/s (Table 2 and 3), with one exception (see Table 2 in Appendix).

The alliesthesia model might present a partial answer to this. The indoor air speed in NV buildings typically fluctuates at low frequencies, perceived as intermittent gusts. Comfort perception may be more influenced by the resulting dynamic changes in rate of cooling than by the steady cooling at average speed, producing a transient form of alliesthesia. If this is the case, using the CP from Table 2 and 3 to evaluate NV building design may produce a conservative estimate of the actual cooling effect.

Adoption of PCS. Given the performance improvements offered by PCS, the reader may wonder why there is so little PCS commercially available. The recent arrival of efficient personal fans is the only exception to this, and even these are only beginning to be employed as an integrated part of building HVAC control. (The mandatory HVAC curtailments following the Japanese earthquake appear to have spurred fan use—this might count as an indirect form of PCS integration). There appear to be many reasons for the lack of adoption. A large one is that the cost of PCS is typically borne by the tenant while the energy savings accrue to the landlord. Another is that the focus was for a long time on personal ventilation, requiring prohibitively complex and expensive hookup to the central HVAC system or to the outdoors. Radiant heating systems were poorly designed and inefficient.

The discovery that well-designed PCS systems could work at low wattages using only room air permits a radical lowering of price and (for chairs especially) the potential for cordless battery operation. In addition, all PCS systems can now be fitted with internet connectivity with which these decentralized devices can directly inform the central HVAC system about their local thermal conditions, occupancy, and the occupant's chosen control settings. The software systems to perform this integration - even in retrofits - is now beginning to appear in the marketplace. With these new developments the future for PCS in buildings is bright, offering tremendous opportunity to save energy while improving individual's comfort.

Conclusion

This paper proposes the term 'personal comfort system' (PCS) to refer to systems that locally condition the occupant independent of the HVAC system. Examples are provided from a review of the literature. The paper evaluates those PCS systems whose published human subject and manikin studies allow their cooling and heating effects to be represented as corrective power (CP) values, expressed in Kelvin. As an offset to normal ambient room temperature, the CP allows building engineers and operators to modify temperature setpoints and control sequences when PCS is included in their designs. The paper also provides expected sensation and comfort levels associated with certain PCS test conditions. It provides examples of comfort levels associated with energy-saving ambient control, in which PCS allows the comfort to remain equivalent to, and in some cases better than, that of neutral ambient control.

The CP possible from PCS and from enhanced air movement enables very substantial energy savings to be had by relaxing zone temperature setpoints and reducing HVAC intensity. These can exceed 30% of a building's total HVAC energy. Conversely, the CP allows larger fractions of the occupancy to be satisfied with the interior environment; approaching 100%. This may be possible even coincident with relaxed zone temperatures, though these tradeoffs are only now being investigated in field studies. Field studies of PCS that quantify both comfort and energy are essential for encouraging PCS adoption in buildings.

The paper also summarizes the fundamental physiological and psychophysical basis underlying PCS comfort, and a brief description of how this may be rationally modeled in the future. Very little of the current literature contains information about comfort at the segment (e.g., foot or face) level, though this is clearly an important component of the success of these systems. In addition there is almost no literature on the sub-segment level of comfort, such as pertaining to very localized spots of heat transfer to and from the body. The alliesthesia model suggests that the ultimate efficiency of PCS systems will depend on refining such details to match the psychophysiological needs of the body, and that this is clearly an important area of research for the future.

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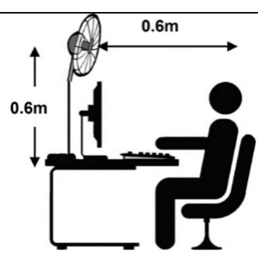
Appendix

Table 1. Air jets on upper body

1.Zhai et al. 2013 [13] Floor fan 16 subjects	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
	28	60	0.5 (avg., Occ. control)	28	.15	1.9	-.59	.85	>|-2|
		80	0.8 (avg., Occ. control)		.5	1.8	-.8	1.34	-2.7
	30	60	1.1 (avg., Occ. control)	30	.45	1.3	-1.22	1.66	-3.7
		80	1.3 (avg., occ. Control)		1	0.4	-1.15	1.81	>|-2.9|

1) Reference condition data from Zhai et al. 2015. These are two parallel studies, one for ceiling fan, one for floor fan, with the same subjects.
2) CP uses ET* because RH is a variable; T_{supply} for circulating fans equals $T_{ambient}$.
3) CP, CP-S and CP-C are stronger when temperature is high. This is because air movement provides more cooling as skin wettedness increases.
4) 9-point comfort scale

2.Huang et al. 2013[41] Frontal desk fan 30 subjects	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
	30	40-50	0.6	30	.7	-.65	-.8	.35	-2
			1.0		.5	-.5	-1	.5	-2
			1.5		.1	-.4	-1.4	.6	>|-2|
			2		0	-.4	-1.5	.6	>|-2|
			1.0 (avg., Occ		.1	-.2	-1.4	.8	>|-2|

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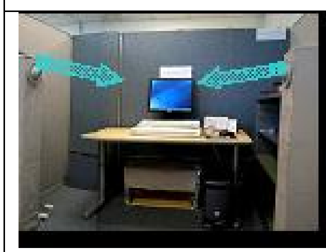
<tr><td></td><td></td><td></td><td>control)</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>32</td><td></td><td>0.6</td><td>32</td><td>1.5</td><td>-1.2</td><td>-.5</td><td>.2</td><td>-2</td></tr>
<tr><td></td><td></td><td></td><td>1.0</td><td></td><td>1</td><td>-.9</td><td>-1</td><td>.5</td><td>>|-2|</td></tr>
<tr><td></td><td></td><td></td><td>1.5</td><td></td><td>.75</td><td>-.7</td><td>-1.25</td><td>.7</td><td>>|-2|</td></tr>
<tr><td></td><td></td><td></td><td>2</td><td></td><td>.5</td><td>-.8</td><td>-1.5</td><td>.6</td><td>-4</td></tr>
<tr><td></td><td></td><td></td><td>1.6 (avg., Occ control)</td><td></td><td>.5</td><td>.5</td><td>-1.5</td><td>.9</td><td>-4</td></tr>
<tr><td></td><td>34</td><td></td><td>0.6</td><td>34</td><td>1.8</td><td>-1.4</td><td>-.2</td><td>.3</td><td>>|-2|</td></tr>
<tr><td></td><td></td><td></td><td>1.0</td><td></td><td>1.3</td><td>-1.1</td><td>-.7</td><td>.6</td><td>>|-4|</td></tr>
<tr><td></td><td></td><td></td><td>1.5</td><td></td><td>1.2</td><td>-1.1</td><td>-.8</td><td>.6</td><td>>|-4|</td></tr>
<tr><td></td><td></td><td></td><td>2</td><td></td><td>1.2</td><td>-1</td><td>-.8</td><td>.7</td><td>>|-4|</td></tr>
<tr><td></td><td></td><td></td><td>1.9 (avg., Occ control)</td><td></td><td>.9</td><td>-.7</td><td>-1.1</td><td>1</td><td>>|-4|</td></tr>
</table>

1) Occupant control provides cooler sensation and higher comfort than the equivalent fixed air speeds.
2) The incremental cooling by increasing air speed is less at the higher speeds.
3) 4-point comfort scale

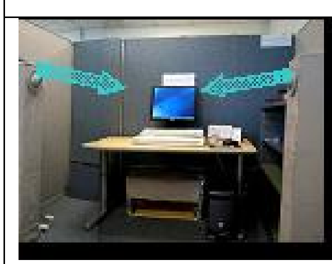
3. Cui et al. 2013[42], Hua et al. 2012[43] Fan simulating natural wind (SNW) or constant mechanical wind (CMW) 21 subjects	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	*****	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
	28-CMW	40	1	28	w	0.42	-.32	-0.48	.25	-2
					r	0.28	-.34	-0.38	.1	-2
	28-SNW				w	0.27	-0.48	-0.63	.09	-2
					r	0.14	-0.42	-0.52	0	-2
	30-			30	w	0.99	-0.77	na	na	-2

	CM W				r 0.86	-0.63	na	na	-2
	30-SNW				w 0.81	-0.71	na	na	>|-2|
					r 0.56	-0.5	na	na	>|-2|

1) * w= office type work (typing, addition), r=rest
2) There is no test on 30C without wind. Therefore, CP-S and CP-C are not able to be calculated at 30C.
3) 4-point comfort scale

4. Arens et al. 2011 [11] Opposing air jets 18 subjects	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
	28	50	1		0.5	1.5	-1.2	1.8	>|-3|

1) Reference condition to calculate CP based on Zhang 2010, same setup
2) 9-point comfort scale, "+" means comfortable, "-" means uncomfortable. The higher the value, the better the comfort. Comfort values range between ±4, value 4 means "very comfortable", and value "-4" means "very uncomfortable".

5. Zhang et al. 2010 [44] Opposing air jets 18 subjects	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
	28	40	1	28	0.31	1.41	-1.0	1.04	-3
			Occ. control (velocity not available)		-0.19	1.92	-1.5	1.65	-3
	30		1	24/28	0.77	0.89	-1.2	.52	~-5
			Occ. control (velocity not available)		0.73	0.98	-1.2	.61	~-5

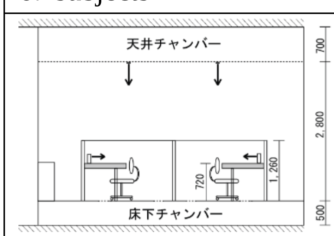
1) "~-5" means that sensation values (0.77, 0.73) with PCS is almost equivalent to the reference condition

(sensation 0.68)

2) Supply air temperature 24/28 (ºC) means that the temperature at the outlet is 24ºC, and it became 28ºC around subjects after traveling 0.6m.
3) 9-point comfort scale, "+" means comfortable, "-" means uncomfortable

6. Bin Yang et al. 2010[45] Ceiling jet 32 subjects	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	***Sensation whole/face***	***Comfort % comfortable***	***CP-S whole /face***	***CP-C***	**CP (K) whole/face**
	26	na	.36	26	0.3/.25	77	-.7/-.5	na	>|-2.5|
				23.5	0/-.25	88	-1/-1		
				21	-0.25/-.8	94	-1.25/-1.55		
			.55	26	0.4/0	84	-.6/-.75		
				23.5	-0.1/-.3	97	-1.1/-1.05		
				21	-0.6/-.9	94	-1.6/-1.65		
			.76	26	0/-.25	91	-1/-1		
				23.5	-0.5/-1	88	-1.5/-1.75		
				21	-1/-1.25	79	-2/-2		

1) Air speeds were measured near the subjects but exact measurement locations not specified.
2) Comfort was presented as % dissatisfied, not be able to draw CP-C

7. Takemasa et al. 2009 [46] Ceiling mounted air jet 67 subjects	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
	27	na	Occ control (0.3-0.5 m/s)	27	-.1	-.3	-.7	.4	>|-1|
				23	-.5	-.4	-1.1	.3	
				19	-.5	-.2	-1.1	.5	
	28			28	-.1	-.5	-.7	.4	-2
				24	-.3	-.4	-1	.5	>|-2|
				20	-.3	-.4	-1	.6	>|-2|

1) The results from ceiling air jet and desk-mounted air jet are same for the CP values, so only results for ceiling air jet included.
2) Lower supply air temperature for both types of air jets didn't make big difference. For ceiling jet, air travels over a distance before reaching people, mixed while traveling. For the desk-mounted air jet, people chose smaller air flow, so the lowering supply air temperature reduced its impact on

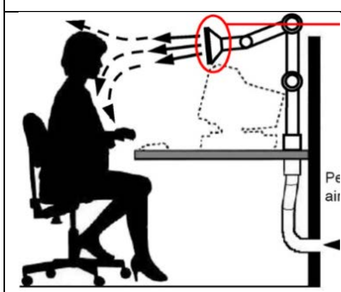
subjective perceptions.
3) 4-point comfort scale.

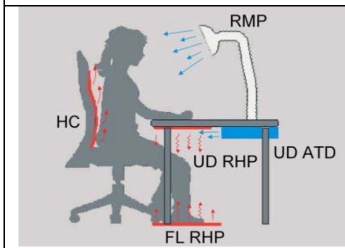
8. Atthajariyakul et al. 2008 [47] Desk fan 15 subjects	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s)**	**T_{supply} (°C)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
	26	60-80	0.5	26	-.2		-.5		~-1
			1		-.3		-.6		~-1
			1.5		-.9		-1.2		>|-1|
			2		-1.4		-1.7		>|-1|
	27	65-80	0.5	27	.13		-.27		>|-1|
			1		-.13		-.53		>|-1|
			1.5		-.4		-.8		-2
			2		-.8		-1.2		>|-2|
	28	70-80	0.5	28	.5		-.4		>|-1|
			1		0		-.9		>|-2|
			1.5		-.3		-1.2		~-3
			2		-.5		-1.4		>|-3|
1) The lowest ambient temperature tested is 25C. Therefore, for 26C tests, the CP can only be presented at >|-1| when sensation with air movement was cooler than the sensation at 25C without desk fan									
9. Y. Zhang et al. 2007, 2005[48, 49] Local airflow 30 male subjects	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s)**	**T_{supply} (°C)**	***Sensation whole/local***	***Comfort***	***CP-S whole /local***	***CP-C***	**CP (K) *whole/local***
Face cooling (0.5m from outlet)	32	40	1	22	-.23/-.6	na	-1.05/-1.4	na	~-4
	35			22	.16/-.6	.5/-.2	-1.26/-	NA	~-7

							2		
Chest cooling (0.2m from outlet) 	32			22	-.06/-1	na	-.8/-1.8	na	~-4
	35			22	.07/-.8	0.15/-.6 (overcooling discomfort)	-1.26/-2.1	0.2	~-7
Back cooling (0.2m from outlet) 	32			22	-.06/-.8	na	-.8/-1.8	na	~-4
	35			22	.58/-.6	0.15/-.4 (overcooling discomfort)	-.98/-2	0.2	~-7

1) When the body parts are 0.2m away from the outlet of the local cooling source (chest and back), the supply air temperature didn't increase while traveling from the outlet to the body; when the body part is 0.5m away from the outlet of the local cooling source (face), the supply air temperature increased about 3K from the temperature measured 0.1m away from the outlet (T0.1m= 23ºC, T_{target}=26ºC, $T_{ambient}$ = 35ºC). When $T_{ambient}$ = 27ºC, Ts_{upply} = 23ºC, T_{target} = 24ºC, 1K increase.
2) When supply air temperature was 28ºC or 25ºC, there was no equivalent sensation available to draw CP. At high ambient temperatures tested (32ºC, 35ºC), cooling air (22ºC in these tests) is needed to provide enough cooling.
3) Thermal comfort uses a 3-point scale ranging between ±1 ; 1 means "very comfortable", and "−1" means "very uncomfortable". Its scale units are 0.25 times those of the 9-point comfort scale, which ranges between.
4) At 35ºC when applying 22ºC local cooling air to chest and back, reduced comfort was due to overcooling; face cooling didn't cause overcooling discomfort. There was no data presented in the thesis about 32ºC ambient applying 22ºC local cooling air.

10. Amai et al. 2007 [50] Four terminal devices:	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**

a)3DU, b) PEM, c) TU isotermal air, d) RCU, blow air to the back 24 subjects									
	28	50	Occ. control (velocity not available)	Occ. control (temperature not available)	-0.45	-0.5	>|-.8|	-0.2	>|-2|
1) The 4 PCS systems showed little difference, so they are presented as combined results. 2) 4-point comfort scale									
11. Sun Wei et al. 2007[51], Tham et al. 2007[52] **Air jet** **24 subjects**	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	***Sensation whole/face***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K) whole/face**
	26	40-55	0.4	26/high Tu	-.2/-.5	na	-0.6/-.8	na	>|-2.5|
			0.8	26/low Tu	-.6/-1	na	-1/-1.3	na	>|-2.5|
			0.4	23.5/high Tu	-1/-1	na	-0.6/-.8	na	>|-2.5|
			0.8	23.5/low Tu	-.6/-1.2	na	-1/-1.4	na	>|-2.5|
1) CP is slightly conservative because reference condition is not still air but 3 L/s, 0.1 m/s (near face, high turbulence intensity, Tu). 2) There are 6 air speeds (0.1–1 m/s) and high and low Tu. Only two air speeds (middle and maximum) and their associated Tu levels are included. 3) Supply air temperature 23.5 °C and 26 °C created smaller difference when the air speed is higher (0.8 m/s), bigger difference when the air speed is lower (0.4 m/s). 4) Whole-body CP-S is calculated based on the regression provided in the paper, using facial sensation to get the whole body sensation									
12. Melikov et al. 2007 [53] Round movable panel (RMP) and under desk air terminal device (UD	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K) *whole/face***

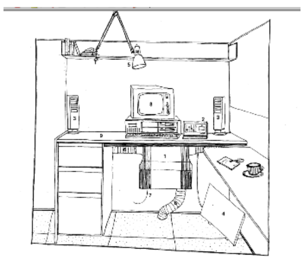
ATD) 48 subjects									
	26	na	RMP 12 L/s, UD ATD 2, 5 L/s (0.22 – 0.56 m/s at outlet)	20	.6	.7			>|-4|

1) CP was calculated based on thermal acceptability, because no equal sensations were achieved allowing to get CP. Reference condition is 22 °C, sensation 0 (neutral), sensations with PCS at 20 °C, 22 °C, 26 °C are between 0.5 and 0.65 (between neutral and slightly warm). However, higher acceptability was achieved with PCS (0.7–0.8) compar ed with the reference condition of 22 °C without PCS (0.45). Based on higher acceptability, we received CP as −4 (difference between 26 °C and 22 °C).
2) No comfort votes available. The value under comfort is based on acceptability vote: 3-point acceptability scale, +0 (just acceptable) to 1 (clearly acceptable); -0 (just unacceptable to -1 (clearly unacceptable)

13. Kaczmarczyk et al. 2005 [54] Five air jet types 24 subjects	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s)**	**T_{supply} (°C)**	***Sensation whole/face***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K) *whole/face***
 (a) HDG + VDG HDG+VDG	26	na	Occ. control (velocity not available)	20	.1/.1	.3	-1.2	.25	>|-3|
 (b) RMP RMP				20	.1/-.3	.35	-1.2	.3	>|-3|
 (c) MP MP				20	.05/-.3	.35	-1.25	.3	>|-3|
 (d) Headset Headset				26	.8/.1	.25	-.5	.2	na

 RMP+HDG				20	.15/-.2	.35	-1.15	.3	>|-3|

1) No comfort votes available. The value under comfort is based on acceptability vote: 3-point acceptability scale, +0 (just acceptable) to 1 (clearly acceptable); -0 (just unacceptable to -1 (clearly unacceptable)

14. Bauman et al. 1997, 1998 [6, 7]	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	***Sensation***	***Comfort % comfortable***	***CP-S***	***CP-C***	**CP (K)**
PEM Field 54 subjects with PEM, 60 control group no PEM 	24.9	~43	Occ. control	na	**0**	**100**	-1.8		-2

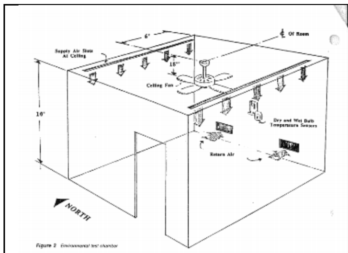
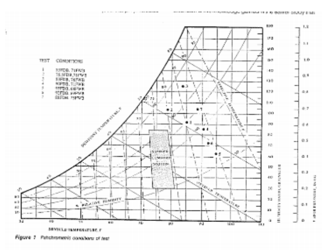
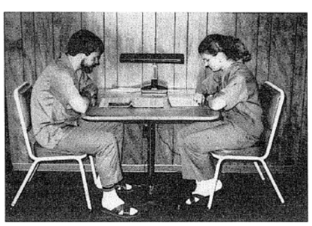
1) The field study was done in three buildings. The CP (−2 K) is based on the study in one building where the ambient temperature could be raised significantly higher when PEMs were installed.
2) Percentage of comfortable subjects in the column “Comfort”

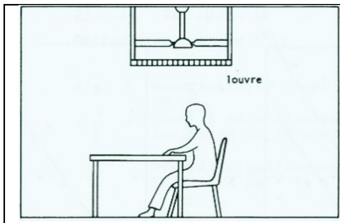
Table 2. Vertical airflow on whole body (ceiling fan)

1. Zhai et al. 2015[55] 16 subjects	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
	28	60	.7	28	.17	1.92	-.57	.87	>|-2|
			.85		.03	2.07	-.71	1.02	>|-2|
			1.2		-.12	2.13	-.86	1.08	>|-2|
			.8*		.1	2.03	-.64	.98	>|-2|
		80	0.85		.4	1.8	-.9	1.34	>|-2|
			1.2		.1	1.69	-1.2	1.23	>|-2|
			1.6		.05	1.54	-1.25	1.08	>|-2|
			1*		.23	1.64	-1.07	1.18	>|-2|
	30	60	0.85	30	.74	1.16	-.93	1.52	|-2|
			1.2		.52	1.6	-1.15	1.96	>|-2|
			1.6		.37	1.9	-1.3	2.26	>|-2|
			1.3*		.48	1.77	-1.19	2.13	>|-2|
		80	1.2		.81	1.1	1.34	2.51	>|-2|
			1.6		.47	1.6	-1.68	3.01	|4|
			1.8		.53	1.36	-1.62	2.77	|4|
			1.3*		.69	1.36	-1.46	2.77	>|2|

1) * Woosh mode" of ceiling fan operation, air speed varies.
2) CP-S and CP-C are larger when the room ambient temperature is higher, because air movement benefits the most in warm environments.
3) Compared with Zhai 2013, two similar test conditions, the comfort results are better with ceiling fans than the floor fans. For example, at effective ambient temperature ET 32.6ºC, 1.2 m/s near face from floor fan was able to maintain occupants thermal satisfaction rate at 65%, but it was 94% with ceiling fan.
4) At ambient ET bigger or equal then 29.7ºC, air speed tested 1.2, 1.6, 1.8 m/s didn't make big differences regarding the thermal acceptability rate.

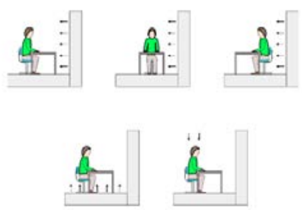
2. Scheatzle et al. 1989[56] 96 subjects	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	***Sensation***	***Comfort % comfortable***	***CP-S***	***CP-C***	**CP (K)**
	25.5	69	0.24	25.5	-1.1	81	-1.1	na	>|-0.5|
	28.4	73		28.4	0	63	-1.5		>|-2.9|

	29.4	50		29.4	0.5	63	-0.5		<|-3.9|
	31	50		31	-0.3	69	-1.4		>|-5.5|
	32	39		32	0.1	70	-0.9		-6.5
	33	32		33	0.7	25	+0.6		>|-3.6|
	35	24		35	1.5	0%	-2.3		>|-3|
	25.5	69	1.02	25.5	-2	>80%	-2.1		>|-0.5|
	28.4	73		28.4	-0.4		-1.5		>|-2.9|
	29.4	50		29.4	-0.5		-1.5		>|-3.9|
	31	50		31	-0.4		-2.2		>|-5.5|
	32	39		32	-0.2		-1.8		>|-6.5|
	33	32		33	0	66	-2.1		|-7.5|
	35	24		35	1.1	29	-1.3		|-6.6|
1) Sensation scale: 9-point scale 2) Comfort scale: 9-point scale, but with a complicated way of calculating 7 bi-polar adjective-pairs ; same scale as used by Rohles 1983 3) Percentage of comfortable subjects for the column "Comfort"									
3. Rohles et al. 1983[57] 256 subjects	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	***Sensation***	***Comfort % comfortable***	***CP-S***	***CP-C***	**CP (K)**
	26	50	.15	26	-0.3	76			>|-2|
	28		.25	28	-0.3	74			>|-4|
	29		.46-1	29	-0.1	75			-5K
1) Reference condition, 24.4C, 50% RH, 69% subjects comfortable 2) Sensation scale: 9-point scale, 3) Comfort scale: 9-point scale, but with a complicated way of calculati ng 7 bi-polar adjective-pairs. 4) Percentage of comfortable subjects for the column "Comf"									
4. McIntyre et al. 1978 [58] 11 subjects	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
	24	50	Occ. control : 0.18	24	0.6	1			>|-2|
	26		Occ. control	26	0.8	0.9			>|-4|

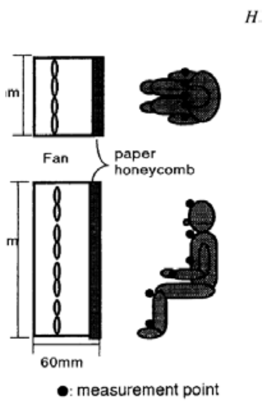
			: 0.74						
	28		Occ. control : 0.94	28	1.2	0.5			>|-6|

1) Male and female were separately analyzed in the paper. Male used fan in all tested conditions, therefore no reference condition allowing the CP be drawn. Therefore, the CP is presented for female only.
2) CP was determined based on equal or higher pleasantness scale. (converted to 7-point scale, + means pleasant and negative mean unpleasant).

Table 3. Uniform airflow on whole body (large fan or window)

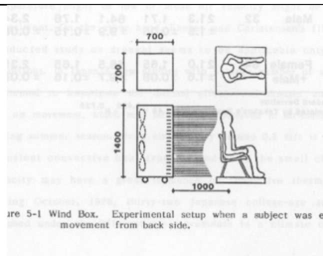
<table>
<tr><th>1. Toftum et al. 1997 [59]</th><th>$T_{ambient}$ (°C)</th><th>RH (%)</th><th>V (m/s)</th><th>T_{supply} (°C)</th><th>Sensation</th><th>Comfort % comfortable</th><th>CP-S</th><th>CP-C</th><th>CP (K)</th></tr>
<tr><td rowspan="4">40 subjects
</td><td rowspan="3">23</td><td rowspan="4"></td><td>.2</td><td></td><td>-.2</td><td></td><td>-.4</td><td></td><td>-3</td></tr>
<tr><td>.3</td><td></td><td>-.4</td><td></td><td>-.6</td><td></td><td>>|-3|</td></tr>
<tr><td>.4</td><td></td><td>-.6</td><td></td><td>-.8</td><td></td><td>>|-3|</td></tr>
<tr><td>26</td><td>.4</td><td></td><td>0</td><td>97</td><td>-.4</td><td></td><td>-3</td></tr>
</table>

1) CP values are same for different directions, therefore, combined test conditions together.
2) Front cooling has the most comfortable results at tested conditions (less overcooling)

2. Kubo et al. 1997[60]	$T_{ambient}$ (°C)	RH (%)	V (m/s)	T_{supply} (°C)	*Sensation vote*	*Comfort vote*	*CP-S*	*CP-C*	CP (K)
55 subjects for this test condition 	30	30	Occ. control (1.1)	30	-0.2	1.2	-1.5	0.7	-4

1) There are other tests conditions. Only this one allows CP to be drawn.

3. Tanabe et al. 1988 [61] 64 subjects	$T_{ambient}$ (°C)	RH (%)	V (m/s)	T_{supply} (°C)	*Sensation vote*	*Comfort vote*	*CP-S*	*CP-C*	CP (K)
	27.8	50	.44	27	0.44		-0.3		-0.3
			.71		0.71		-0.6		-0.6

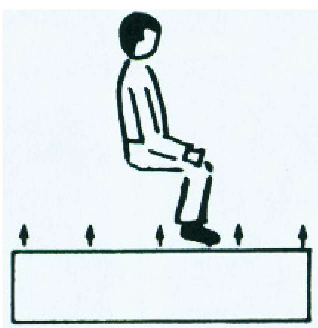
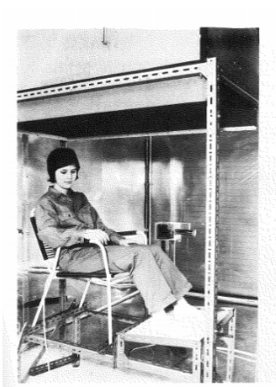
			1.03		1.03		-0.8		-0.8
			1.34		1.34		-1.3		-1.3
			1.63		1.63		-1.5		-1.5
	29.6	50	.44	29	0.5		-0.6		-1.2
Constant flow			.71		0.3		-0.8		-2.3
			1.03		-0.1		-1.2		-3.4
			1.34		-0.1		-1.2		-3.4
			1.63		-0.1		-1.2		-3.4
	28.8	60	.44	29	0.2		-0.6		-1.8
			.71		-0.2		-1		-2.7
			1.03		-0.7		-1.5		-4.4
			1.34		-0.7		-1.5		-4.4
			1.63		-1.1		-1.9		-5.8
	31.1	80	.44		0.8		-0.7		-2
			.71		0.3		-1.2		-4
			1.03		0.3		-1.2		-4
			1.34		0		-1.5		-4.7
			1.63		-0.05		-1.55		-4.9
Fluctuating air movement 64 subjects	27.9	50	1 sin(10)	27.9	-0.5		-0.9		-2.7
			1.02 sin(30)		-0.65		-1.05		-3.6
			1.03 sin(60)		-0.57		-0.97		-3.4
			0.73 sinmax		-0.43		-0.83		-2.6
			1.04 const		-0.38		-0.78		-2.5
			1 random		-0.20		-0.60		-2
			1.04		-0.36		-0.76		-2.4

			pulse						
	29.7	50	1.18 sin(10)	29.7	-0.5		-1.4		-4.5
			1.24 sin(30)		-0.27		-1.17		-4.1
			1.24 sin(60)		-0.47		-1.37		-4.4
			0.83 sinmax		-0.1		-1		-3.5
			1.22 const		0.32		-.58		-2.4
			1 .20 random		0.14		-.76		-3
			1.18 pulse		0.25		-.65		-2.8
	29.1	80	1.39 sin(10)	29.1	-0.48		-1.28		-3.8
			1.40 sin(30)		-0.64		-1.44		-4.8
			1.39 sin(60)		-0.83		-1.63		-5
			1.02 sinmax		-0.6		-1.4		-4.6
			1.39 const		0.19		-.61		-2.4
			1.47 random		-0.22		-1.02		-3
			1.41 pulse		-0.26		-1.06		-3.4
	31.5	50	1.57 sin(10)	31.5	0.2		-1.4		-3.8
			1.59 sin(30)		0.08		-1.52		-4.6
			1.58 sin(60)		0.14		-1.46		-4.4
			1.16 sinmax		0.17		-1.43		-4.3
			1.58 const		0.57		-1.03		-3.3
			1 =.60		0.3		-1.3		-4.1

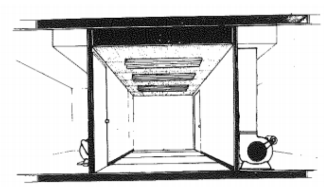
			random						
			1.59 pulse		0.48		-1.12		-3.7
Simulating AC space (not high air temperature)/32 subjects	26.3	12.8 humidity ratio	0.16 (TI=0.39)		-0.2		-0.2		-0.6
			0.22 (TI=0.37)		-0.2		-0.2		-0.6
			0.29 (TI=0.38)		**-0.2**		-0.2		**-0.6**
			0.52 (TI=0.28)		**-0.7**		-0.7		**-2**
			0.21 (TI=0,.69) fluctuated)		**-0.34**		-.34		**-1**

,

1) Tanabe did three sets of studies: Constant air movement ; fluctuat ing air movement compared with constant air speed; air movement on air-conditioned space (ambient air temperature not high, 26.3 °C).

4. Fanger et al. 1974 [62]	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
Uniform air from 5 directions: front, side, back, above, below 4 subjects   Air from above	27.7		0.8		0	na	na	na	-2.3

1) The results are similar from different directions, so they are averaged here.
2) Other CP cited by this study: 4.3K (Fanger 1968), 2K (Olesen 1972), 2.4K (Rohles 1974)

5. Rohles et al. 1974 [63]	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s)**	**T_{supply} (°C)**	***Sensation***	***Comfort % comfortable***	***CP-S***	***CP-C***	**CP (K)**
Perforated ceiling 180 subjects 	29.5		0.8	29.5	0.6	na	na	na	~-3.6

1) Sensation scale: 7-point scale, except "0" means "comfortable", not "neutral".
2) Reference condition sensation was 0.3 at 25.9 °C at 0.2 m/s, and the sensation at 0.8 m/s and 29.5 °C is 0.5. That is why the CP is about "~" −3.6. The value is conservative since the reference condition is not still air.
3) Higher comfort was received at 29.5C when air movement is 0.8 m/s than at the reference condition (25.8C at 0.2 m/s).
4) Other CP cited by this study: 0.4 m/s: 2.1K, 0.8 m/s: 2.8K (Morse 1967); 0.4 m/s: 1.3K, 0.8 m/s 1.9K (Fanger 1970); 0.4 m/s: 1.3K, 0.8 m/s 2.2K (Houghten 1924); 0.8 m/s: 2K (Olesen 1972).

Table 4. Heating PCS and heated/cooled chairs

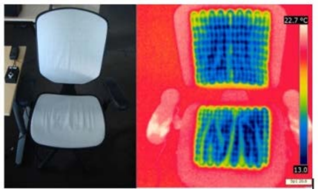
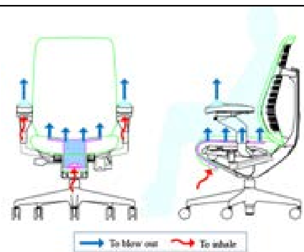
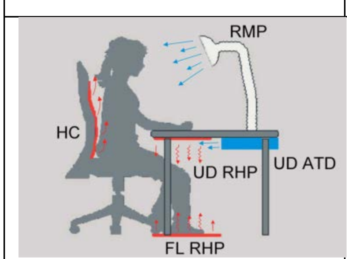
1. Zhang 201 5 Field study [36] Footwarmer 12 subjects	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s)**	**T_{supply} (°C)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
	20	na	na	na	-.25	1.7	-.25	.2	1.1
	19.4				-.4	1.6	-.4	.1	1.7
	18.9				-.9	1.5	-.9	0	2.2

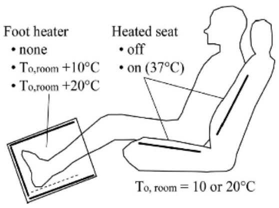
1) The average footwarmer wattage: 11W (20C room ambient temperature), 21W (18.9C room ambient temperature).
2) CP is determined based on equal thermal comfort
3) 9-point sensation scale. In heating condition, negative CP-S means that the sensation wasn't warmed up to the neutral reference condition.
4) 9-point comfort scale

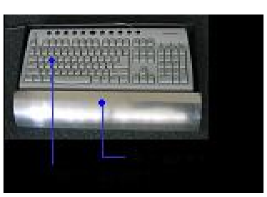
2. Pasut 2014 [35] **Heated/cooled chair** 23 subjects	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s)**	**T_{supply} (°C)**	Seat & clo	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
	16	50	0	Occ. Control, values na	C	-1	1	1	2.5	2
					no-C	-1	1.5	1	3	2
					no-C+clo	0	1.5	2	3	9**
	18				C	0	2	1	2.3	7
					no-C	0	2	1	2.3	7
	29		Occ. Control, values na	29	chair+small fan	0.2	2	-2.5	4.2	-4

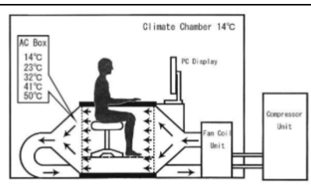
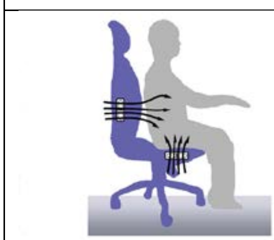
1) ** Reference neutral condition (25 °C) is from another study done by the author (Pasut 2012). The two studies are very similar except that the two heated/cooled chairs are different
2) The small usb fan used in 29C test condition was very small, 2W
3) "C" refers to the chair with a cover, "no-C" refers to the chair without cover, "clo" refers to the test condition when subjects were allowed to add additional clothing.

3. Pasut 2012 [12] TE heated/cooled chair	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s)**	**T_{supply} (°C)** (chair surfaces	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**

30 subjects				temperature)					
	16	50	0	Occ. control, values not available	0	1.5	2	3.1	~9
	18				0	2.2	1	2.4	~7
	29				0.5	.5	-2	1.6	~-4K
1) 9-point sensation scale 2) 9-point comfort									
4. Washinosu 2012 [64] Ventilated seat 20 subjects	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s) Max. flowrate (m^3/h)**	**T_{supply} (°C)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
	30	50	40	30	0.2	0.4	-2.2	2.3	>|-2|
1) 7-point comfort scale: -3 (very uncomfortable), -2 (uncomfortable), -1 (slightly uncomfortable), 0 (neutral), 1 (slightly comfortable), 2 (comfortable), 3 (very comfortable)									
5. Melikov 2007 [53] Convective heating chair (HC), Under-desk radiant heating panel (UD RHP), Floor radiant heating panel (FL RHP) 48 subjects	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s)**	**T_{supply} (°C)** (surfaces temperature for radiant heating panel)	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
	20	na	na	HC: up to 45, UD RHP: up to 47 FL RHP: 40	0.5	0.8			>2
1) With PCS, the sensation at 20C is 0.5. Reference condition at 22C, the sensation is 0. Therefore, CP >2. 2) No comfort votes available. The value under comfort is based on acceptability vote: 3-point acceptability scale, +0 (just acceptable) to 1 (clearly acceptable); -0 (just unacceptable to -1 (clearly unacceptable)									
6. Oi 2011[65]	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s)**	**T_{supply} (°C)** (surfaces	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**

Heated seat and footwarmer box 8 subjects 				temperature for seat or footwarmer box air)					
Heated seat	10	50	0	37	***-1.3***	***-0.8***	0.7	0.8	3
	20				***1***	***0.3***	0.8	-0.3	
footwarmer	10			20	-1.5	***-1.3***	0.5	0.5	3K
				30	***-1.3***	***0.2***	0.7	-0.4	
	20			30	***0.5***	***-1***	0.3	0.8	
				40	***0.9***	***0.2***	0.7	-0.4	
Heated seat+footwarmer	10			Tseat=37 Tfootwarmer=20	***-1***	***-0.5***	1	1.3	6K
				Tseat=37 Tfootwarmer=30	***-0.5***	***0.1***	1.5	1.7	
	20			Tseat=37 Tfootwarmer=30	***1.1***	***0.3***	0.9	-0.3	
				Tseat=37 Tfootwarmer=40	***1.1***	***0***	0.9	-0.6	

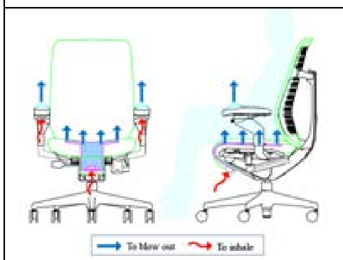
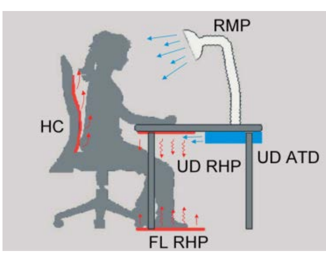
7. Zhang 2010 [44] Heated keyboard and footwarmer 18 subjects	$\mathbf{T_{ambient}}$ **(ºC)**	**RH (%)**	**V (m/s)**	$\mathbf{T_{supply}}$ **(ºC)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
Heated keyboard  Footwarmer	18	40	na	na	-.2	1.1	.3	.8	~6.5

									
1) Hand warmer wasn't controlled well, as a result less people used the heated keyboard. So most heating came from the footwarmer 2) 9-point sensation scale; 9-point comfort scale									
8. Enomoto 2009 [34] Leg heating box 8 male subjects	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s)**	**T_{supply} (°C)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
 Figure 1. Sketch of the air-conditioning box	14	na	na	32	-.2	0	na	na	10
				41	.1	0			
1) Assuming the neutral condition ambient air temperature 24C									
9. Watanabe 2009 [66] Ventilated chair (bottom + back) 7 male subjects	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s) Flowrate (L/s)**	**T_{supply} (°C)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
  	27.9	48.7	19.2	27.9	0	0.8	-0.2	0	~-2
1) Two sizes of fans are installed: 31.9 L/s at 100 V and 4.8 L/s at 100 V. The small -sized fan creates									

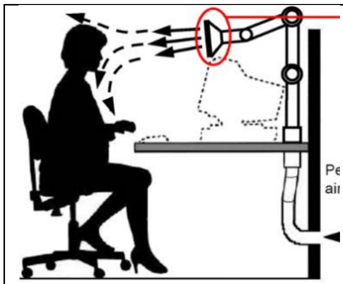
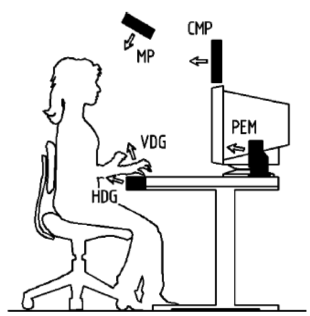
asmall cooling effect, not included in the table. 2) 5-point comfort scale: 2 (comfortable), 1 (slightly comfortable), 0 (neither comfortable nor uncomfortable), -1 (slightly uncomfortable, -2 (uncomfortable) 3) Chair was not able to maintain comfort at 30 °C and 32 °C ambient temperatures, no CP could be drawn, so not included.									
10. Zhang 2007 [37] Heated/cooled seat 24 subjects 	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s)**	**T_{supply} (°C)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)**
Heated chair	15, 18, 22	40	na	25, 31, 37, 44	na	.4	na	na	9.3*
Cooled chair	25, 28, 35, 45			18, 20, 25,	na	.4	na	na	-6.3
1) CP are close for different ambient/seat conditions, so they are presented together 2) *Using acceptability votes 3) 9-point sensation scale; 9-point comfort scale 4) Paper didn't provide comfort votes. The value under comfort is based on acceptability vote: 3-point acceptability scale, +0 (just acceptable) to 1 (clearly acceptable); -0 (just unacceptable to -1 (clearly unacceptable)									
11. Nobe 2004 [67] Ventilated seat 16 subjects	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s)**	**T_{supply} (°C)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K) Whole/ back**

	28	50	na	28	0.2	-.7	-0.5		-2
1) 4-point comfort scale									
12. Brooks 1999 [68] heated seat (encapsulated carbonized fabric) 8 subjects	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)** Surf. Temp.	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K) Whole/ back**
	5	40	<0.2	Occ. control (18-55)	-0.9	-2	1.7	1	10
	10				0.3	-.3	2.4	1.2	>10
	15				0.8	-.3	1.5	.2	>5
	20 + 5C wall				0.95	0	0.65	0	na
1) 4-point comfort scale									

Table 5. Manikin tests

1. Washinosu 2012 [64] Ventilated seat	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s) Max. flowrate (M3/h)**	**T_{supply} (ºC)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K) *whole/head***
	28	50	40	28					-1/-4.5
2. Watanabe 2010 [69] Air jet cooling, contact surface and radiation heating 	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC)** (surfaces temperature for radiant heating panel)	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K) *whole/face***
Heating: Convective heating chair (HC)	20	na	na	41					5.2
Under-desk radiant heating panel (UD RHP)				31.9, 44.6					2.8
Floor radiant heating panel (FL RHP)				40					2.1
All three				31.9, 40, 41, 44.6					5.9

Cooling: Front round movable panel (RMP) and under desk air terminal device (UD ATD – air out from front)	26		UD ATD 0.22 – 0.56 m/s at outlet	20					-0.8/ -2.1 to -8.1 at different l/m
1) There is another sets of heating tests at 22C, the results are not included in the table.									
3. Bin Yang 2009 [70] Ceiling air jets	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s)**	**T_{supply} (°C)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)** whole/face
	23.5	na	.24	23.5					na/-1.1
			.39						na/-2.5
			.61						na/-3.8
			.8						-1.9/-5.3
			.24	21					-.3/-1
			.39						-.6/-2.5
			.61						-1/-4.3
			.8						-2/-6
	26		.24	26					na/-0.6
			.39						na /-1.7
			.61						na /-2.6
			.8						-1.6/-3.9
			.24	23.5					na/-.7
			.39						na/-2
			.61						na/-3.4
			.8						-1.7/-4
1) Some CP data for the whole-body are not presented in their paper, therefore not available.									
4. Sun Wei 2007 [51], Tham 2007 [52] **Air jet**	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s)**	**T_{supply} (°C)** *	***Sensation whole/face***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K) whole/face**

	23.5	40-55	0.4	23.5	h					-.2/-5
				23.5	l					-.4/-8
			0.8	21	h					-.7/-6.5
				21	l					-.9/-10
	26		0.4	26	h					-.5/-4
				26	l					-.5/-4
			0.8	23.5	h					-.8/-6
				23.5	l					-1/-8
1) * turbulence intensity, h= high, l=low										
5. Melikov 2002 [71] Five air jet types 	**$T_{ambient}$ (°C)**	**RH (%)**	**V (m/s) Flowrate leaving the nozzle (L/s)**	**T_{supply} (°C)**		***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K) *Whole/head***
HDG: horizontal desk grill	20	30	5	20						-.4/-.8
	26		5							-.9/-.7
VDG: vertical desk grill	20		10							-.8/-3.9
	26		10							-1.1/-6
PEM: personal environment module	20		10							-.8/-3.1
	26		10							-1/-3.1
CMP: computer monitor panel	20		20							-.4/-3.1
	26		20							-1/-3.6
MP: movable panel	20		20							-.6/-2.5

	26		20						-1.8/-4.2
6. Tsuzuki 1999 [72] three air jet types	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)** **Flowrate leaving the nozzle (L/s)**	**T_{supply} (ºC)**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)** ***Whole/biggest local***
Underfloor task air module (TAM)	25.9	na	85	19					-5.1/-10 (forearm)
ClimaDesk (CDESK)	25.1		7.1	18.3					-1.3/-2.5 (chest)
Personal environment module (PEM)	25.2		71	19.5					-7.1/-17 (head)
			35.4	18.8					-4.3/-8 (lower leg)
7. Tsuzuki 1999 [72] Radiation panels	**$T_{ambient}$ (ºC)**	**RH (%)**	**V (m/s)**	**T_{supply} (ºC) Surface Temp.**	***Sensation vote***	***Comfort vote***	***CP-S***	***CP-C***	**CP (K)** ***Whole/biggest local***
ClimaDesk (CDESK) (under desk)	19.9	na	na	50					2/3.5 (thigh)
Personal environment module (PEM) (on floor)	20.5			na					2.2/7.5 (lower leg)

An additional twenty eight papers were reviewed but did not include the information necessary to calculate CP. These papers are listed in the references [73-100].