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3 Comfort considerations in Net ZEBs: theory and design

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3.1 Introduction

A primary goal of buildings is to provide shelter, a space to live and engage in activities, and to facilitate provision of a comfortable environment. In the context of net-zero energy buildings (Net ZEBs), this means they should efficiently provide a comfortable environment while meeting the net-zero energy target. While comfort was once considered something that occupants passively tolerate, more recent research has recognized that occupants adapt themselves and their environment in order to improve comfort (de Dear and Brager, 1998). For this reason, comfort is tightly linked to energy performance; if occupants are not provided with comfortable conditions, they often adapt in the most convenient and responsive way rather than in energy conserving ways (Cole and Brown, 2009). Therefore, comfort should be critically assessed throughout the design and operation of Net ZEBs.

This chapter focuses on the three main categories of occupant comfort in buildings (thermal, visual, and acoustic) and indoor air quality (IAQ). These domains are all linked to each other and energy performance and must be incorporated into design as such, as shown in Figure 3.1. For instance, in naturally ventilated buildings, occupants are often faced with making compromises between acoustic comfort (noise from outside), thermal comfort (a cooling sensation from moving air or by introducing cooler outdoor air), and indoor air quality (fresh outdoor air).

Conventionally, thermal comfort has been considered a function of four environmental variables (air temperature, mean radiant temperature, relative humidity, and air speed) and two personal variables (metabolic activity and clothing level). Using an energy balance of the human body, comfort levels are predicted based on laboratory-based experiments and occupant ratings of comfort. A newer approach, known as adaptive thermal comfort, acknowledges that occupants tend to attempt to control the indoor environmental variables to restore comfort. Adaptive comfort models generally predict lower energy use as long as convenient, responsive, and effective means for occupants to improve their environment are available (e.g., operable windows).

Perspectives on visual comfort have also evolved recently due to renewed emphasis on daylighting as an important approach to reducing energy use for Net ZEBs, daylight's importance to health and well-being (Veitch, 2011), and the predominant use of vertically oriented computer monitors (as opposed to deskwork). Visual comfort is affected by window size, position, and type, and interior geometry and finishes. Daylight glare can be controlled using fixed shading (e.g., overhangs and fixed louvers) and dynamic shading devices (e.g., blinds).

Acoustic comfort is often neglected during the design of standard and Net ZEBs because it can conflict with good daylighting and natural ventilation design. Recent reports of postoccupancy evaluation of low-energy buildings have revealed that they generally

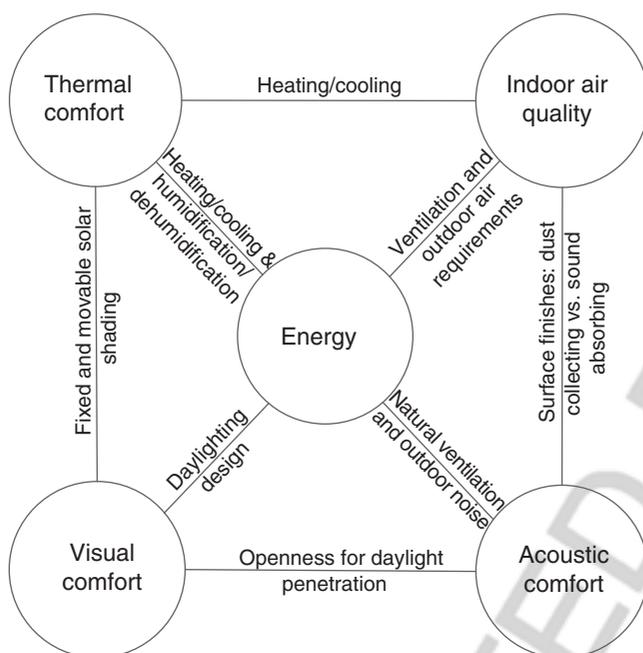


Fig. 3.1 Interactions between forms of comfort and building energy use with examples

score high for all categories of occupant satisfaction except for acoustic quality and privacy (Abbaszadeh *et al.*, 2006; Newsham *et al.*, 2013). Acoustic comfort is directly linked to health and productivity (Crook and Langdon, 1974; Leaman and Bordass, 2000; Veitch, 1990). Furthermore, poor acoustic quality can compromise energy-conserving strategies like natural ventilation because occupants are faced with choosing between thermal comfort and having a quiet indoor environment.

Indoor air quality refers to the health and comfort-related properties of building air. Modern buildings tend to have high concentrations of occupants and materials that can compromise healthy IAQ unless sufficient solutions are implemented. While IAQ is typically good in new Net ZEBs and other high-performance buildings due to the emphasis on IAQ in many green building standards, the high concentration of synthetic materials presents a challenge.

As described in detail in this chapter, occupant comfort is complex and subtle; seemingly minor localized discomfort can adversely affect the perceived indoor environment. The objective of this chapter is to identify and quantify major sources of comfort.

3.2 Thermal comfort

In order to assess the operational performance of a building and to provide a quantification of thermal discomfort, reliable methods to evaluate the long-term general thermal comfort conditions in a building are required. Net ZEBs are characterized by a

notable reduction of energy required for space conditioning. But, such energy reduction should not compromise the quality of their indoor thermal environment.

In this section, a brief description of the two thermal comfort approaches accepted worldwide is reported, and a method to rate long-term thermal discomfort in a building is presented. Finally, two examples of the application of a thermal comfort assessment are introduced.

3.2.1 Explicit thermal comfort objectives in net ZEBs

Traditionally, the end-uses related to indoor environment control (heating, cooling, and ventilation) were dominant in the annual energy balance of a building (both residential and commercial) and constituted more than 50% of the total required primary energy (Pérez-Lombard *et al.*, 2008). Therefore, a strategy to reach the zero energy target consists of reducing the energy required for space heating and cooling as much as possible. However, in the words of the European standard EN 15251: “An energy declaration without a declaration related to the indoor environment makes no sense. Therefore, there is a need for specifying criteria for the indoor environment for design, energy calculations, performance and operation of buildings” (CEN, 2007). Thus, the specification of thermal comfort objectives that a building must achieve is a prerequisite for its design. Such objectives shall be explicitly included as an integral part of the definition of a Net ZEB and need to be quantitatively defined through reliable and explicit methods.

3.2.2 Principles of thermal comfort

Thermal comfort is usually used to indicate that an occupant of a building does not feel too hot or too cold in a given thermal environment. The concept has drawn the attention of a number of scientists and doctors and it has been defined according to three approaches: a physiological, a psychological, and an approach based on the heat-balance of the human body (also called the rational approach).

- In the physiological approach, the thermal perception of an individual is due to the action of nervous impulses that start from thermal receptors in the skin and reach the hypothalamus. “Comfort, in this sense, is defined as the minimum rate of nervous signals from these receptors” (Höppe, 2002); therefore, it is a state in which no pulses occur in an individual to correct the environment by his/her behavior (Hensen, 1991).
- In the psychological approach, thermal comfort is “that condition of mind which expresses satisfaction with the thermal environment” (International Organization for Standardization (ISO, 2005)). This definition is reported in the international standard ISO 7730. A similar definition is reported in the ASHRAE Standard 55; although the ASHRAE definition highlights the subjective character of such a concept by adding to the previous definition the sentence “[. . .] and is assessed by subjective evaluation” (ANSI/ASHRAE, 2010).
- In the heat-balance approach, thermal sensation is related to the heat balance of the human body with its surroundings. Thermal comfort is that condition in which heat fluxes leaving the human body balance those incoming and the skin temperature and the sweat rate are within specified ranges depending on metabolic activity (Höppe, 2002).

In summary, the term thermal comfort is used to provide information about the thermal state of an individual within a given thermal environment. However, thermal comfort is not a single quantity that can be directly measured; its assessment is complex. Over time, a number of models and metrics have been proposed in the literature to quantify what thermal comfort is by predicting optimal environmental conditions or by assessing the predictable thermal stress caused to an individual given certain environmental conditions. Among all the proposed models, two main families have been used to describe the human thermal response in moderate environments: (i) the rational (or heat-balance) and (ii) the adaptive comfort models. These models have been used to develop standards that will be introduced later.

3.2.2.1 A comfort model based on the heat-balance of the human body

The heat-balance comfort model was mainly developed by Fanger and was derived by analyzing surveys carried out on Danish students exposed to steady-state conditions in controlled climate chambers for a 3 h period in winter at sea level, and by modeling the heat balance of the human body using a steady-state heat transfer model (Fanger, 1970). Fanger's experiments showed that (i) skin wetness mainly indicates warm discomfort and mean skin temperature is strongly related to cold discomfort, (ii) skin wetness and mean skin temperature are both functions of activity level, and (iii) thermal dissatisfaction may be due to discomfort of the human body as a whole (general discomfort) or to the involuntary heating or cooling of one particular part of the body (local discomfort) (Djongyang, Tchinda, and Njomo, 2010). Specifically, the steady-state heat transfer model proposed by Fanger to describe thermal comfort requires that no local discomfort exist and that the human body be in heat balance. It also assumes that mean skin temperature and skin wetness may fluctuate as a consequence of the action of the thermoregulatory system of the human body. But such fluctuations should remain within specified limits.

Heat balance of the human body

Summarizing the work of Fanger (1970) and Olesen (1982), the heat balance between an individual and their environment can be expressed, per unit of body surface area, by the equation

$$S = M \pm W \pm L_{\text{cond}} \pm L_{\text{conv}} \pm L_{\text{rad}} - E_{\text{evap}} - E_{\text{res}} \quad [\text{W m}^{-2}] \quad (3.1)$$

where S is the instantaneous energy balance of the human body, M is its metabolic rate, W is its external work, L_{cond} is the sensible heat loss by conduction due to contact of skin with solid objects, L_{conv} is the sensible heat loss by convection from the outer surfaces of the clothed body to air, L_{rad} is the sensible heat loss by radiation from the outer surfaces of the clothed body to all surfaces of the environment viewed by the body, E_{evap} is the latent heat loss by evaporation (sweating and moisture diffusion) from the skin, and E_{res} is the total (sensible plus latent) heat loss by respiration. E_{evap} and E_{res} , if present, act to reduce the internal energy of the human body and are each negative values; the remaining heat fluxes on the right-hand side of Eq. (3.1) can be added or removed from a person (where addition is positive).

Assuming that the thermoregulatory system acts to prevent an increase of internal energy of the human body (so that $S = 0$) and that the heat loss for conduction with solids

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is negligible ($L_{\text{cond}} = 0$) and since L_{conv} and L_{rad} depend both on clothing, Eq. (3.1) can be rewritten as

$$M \pm W - E_{\text{evap}} - E_{\text{res}} = \pm L_{\text{cloth}} = \pm L_{\text{conv}} \pm L_{\text{rad}} \quad [\text{W m}^{-2}] \quad (3.2)$$

where

- Values of M for typical activities are reported in Table B.1 of ISO 7730;
- W is defined as the amount of energy that a human body absorbs or dissipated as a consequence of external loads. The human body is not an efficient thermal engine and its external mechanical efficiency, μ , defined as the ratio between the external work and the metabolic activity, $\mu = W/M$, is lower than 20% (Butera, 1998);
- E_{evap} is comprised of both heat loss by water vapor diffusion through the skin, (E_{diff}) – which is a function of skin temperature (t_{skin}) and the water vapor pressure in the ambient air ($p_{\text{v,a}}$) – and heat loss due to the evaporation of sweat on the skin (E_{sweat})

$$E_{\text{diff}} = 3.05 \cdot 10^{-3} (256 \cdot t_{\text{skin}} - 3373 - p_{\text{v,a}}) \quad [\text{W m}^{-2}] \quad (3.3)$$

$$t_{\text{skin}} = 35.7 - 0.0275(M - W) \quad [^{\circ}\text{C}] \quad (3.4)$$

$$E_{\text{sweat}} = 0.42(M - W - 58.15) \quad [\text{W m}^{-2}] \quad (3.5)$$

- E_{res} is given by

$$E_{\text{res}} = 1.72 \cdot 10^{-5} M (5867 - p_{\text{v,a}}) \quad (3.6)$$

- L_{cloth} is sensible heat loss by conduction due to skin contact with clothing. In Eq. (3.7) t_{cloth} is the clothing surface temperature and t_{a} is the ambient air temperature. The values of thermal insulation for typical clothing ensembles (I_{cloth}) are reported in Table C.1 of ISO 7730 and the values of thermal insulation for garments (I_{clu}) in Table C.1 of ISO 7730.

$$L_{\text{cloth}} = \frac{t_{\text{skin}} - t_{\text{cloth}}}{0.155 \cdot I_{\text{cloth}}} \quad (3.7)$$

$$\begin{aligned} t_{\text{cloth}} = & 35.7 - 0.028(M - W) - 0.155 I_{\text{cloth}} \cdot \\ & \cdot \{ (M - W) - 3.05 \cdot 10^{-3} [5733 - 6.99(M - W) - p_{\text{v,a}}] + \\ & - 0.42[(M - W) - 58.15] - 1.7 \cdot 10^{-5} M (5867 - p_{\text{v,a}}) + \\ & - 0.0014 M (34 - t_{\text{a}}) \} \end{aligned} \quad (3.8)$$

$$I_{\text{cloth}} = 0.161 + 0.835 \sum_i I_{\text{clu}, i} \quad (3.9)$$

- L_{conv} is a function of the convective heat transfer coefficient (h_{conv}), which depends on the regime of convection around the body, the clothing area factor (f_{cloth}) and the difference between the clothing superficial temperature (T_{cloth}) and the ambient air

temperature (T_a)

$$L_{\text{conv}} = f_{\text{cloth}} h_{\text{conv}} (T_{\text{cloth}} - T_a)$$

$$h_{\text{conv}} = \begin{cases} 2.38(T_{\text{cloth}} - T)^{0.25} \Leftarrow \text{Natural convection} \\ 12.1\sqrt{v_{\text{air}}} \Leftarrow \text{Forced convection} \end{cases} \quad (3.10)$$

- L_{rad} depends on the effective radiation area of the human body, which depends on its shape, and on clothing insulation. For general purposes, it is used to approximate the effective radiation area of the human body. The term T_{MRT} is the mean radiant temperature, which is the “uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual nonuniform space” (ANSI/ASHRAE, 2010).

$$L_{\text{rad}} = 3.95 \cdot 10^{-8} f_{\text{cloth}} [(T_{\text{cloth}} + 273.15)^4 - (T_{\text{mr}} + 273.15)^4]$$

$$f_{\text{cloth}} = \begin{cases} 1.00 + 0.2 I_{\text{cloth}} \Leftarrow I_{\text{cloth}} \leq 0.5 \text{ clo} \\ 1.05 + 0.1 I_{\text{cloth}} \Leftarrow I_{\text{cloth}} > 0.5 \text{ clo} \end{cases} \quad (3.11)$$

In order to estimate the body area of an individual upon which these equations are based, the DuBois area (A_{DB}) can be calculated. It is a function of body weight (w_b) and height (h_b) (Du Bois and Du Bois, 1989):

$$A_{\text{DB}} = 0.20247 w_b^{0.425} h_b^{0.725} \quad [\text{m}^2] \quad (3.12)$$

The thermal comfort equation

Inserting Eqs. ((3.3)–(3.6), (3.10), (3.11)), in Eq. (3.2) yields the so-called *thermal comfort equation*

$$\begin{aligned} \{(M - W) - 3.05 \cdot 10^{-3} [5733 - 6.99(M - W) - p_{v,a}] + \\ - 0.42[(M - W) - 58.15] - 1.72 \cdot 10^{-5} M [5867 - p_{v,a}] + \\ - 1.4 \cdot 10^{-3} M (T_{\text{ex}} - T_a)\} = \{3.95 \cdot 10^{-8} f_{\text{cloth}} [(T_{\text{cloth}} + 273.15)^4 + \\ - (T_{\text{mr}} + 273.15)^4] + \\ + f_{\text{cloth}} h_{\text{conv}} (T_{\text{cloth}} - T_a)\} \end{aligned} \quad (3.13)$$

This equation describes the heat balance of the human body and depends on four environmental variables (air temperature, mean radiant temperature, velocity, and humidity of ambient air) and on two personal variables (metabolic activity and clothing insulation). This equation permits the calculation of the comfortable operative temperature, for which the heat fluxes through the human body are balanced. Operative temperature is defined as “the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment” (ANSI/ASHRAE, 2010). It is defined as follows:

$$T_{\text{op}} = \frac{h_r T_{\text{MRT}} + h_{\text{conv}} T_a}{h_r + h_{\text{conv}}} \quad (3.14)$$

where T_{op} is the operative temperature, h_r is the radiative heat transfer coefficient, and T_{MRT} is the mean radiant temperature of the surroundings of the occupant(s). These heat transfer coefficients are often assumed to be equal in magnitude, which may be a reasonable assumption for typical conditions and slow-moving air. The operative temperature produces the “neutralization” of the aforementioned heat flows through the human body and, according to the rational approach for defining thermal comfort, it is the theoretical comfort temperature given a specific metabolic activity, clothing, air humidity, and velocity. For this reason, it is also called the neutral temperature and the thermal sensation corresponding to the condition when heat flows are balanced is called neutral sensation or neutrality.

Fanger’s predicted mean vote and predicted percentage dissatisfied

The thermal comfort equation allows calculating sets of the exact values of the aforementioned variables for which the heat fluxes leaving the human body balance those entering. However, in reality such variables could be outside the range of values that is acceptable for Eq. (3.11). Therefore, in order to assess indoor environments, Fanger proposed two indices: the *Predicted mean vote* (PMV) and the *Predicted percentage dissatisfied* (PPD). PMV is an analytical index derived from the thermal comfort equation and tuned using approximately 1300 surveys:

$$\begin{aligned} \text{PMV} = & (0.303e^{-0.036M} + 0.028) \{ (M - W) - 3.05 \cdot 10^{-3} [5733 - 6.99(M - W) - p_{v,a}] + \\ & -0.42[(M - W) - 58.15] - 1.72 \cdot 10^{-5} M [5867 - p_{v,a}] - 1.4 \cdot 10^{-3} M (T_{ex} - T_a) + \\ & -3.95 \cdot 10^{-8} f_{cloth} [(T_{cloth} + 273.15)^4 - (T_{mr} + 273.15)^4] - f_{cloth} h_{conv} (T_{cloth} - T_a) \} \end{aligned} \quad (3.15)$$

which allows us to estimate the mean value of the thermal sensation votes of a large group of people expressed according to the ASHRAE seven-point scale of thermal sensation (Table 3.1).

Although PMV is derived for steady-state conditions, it can also be applied with an acceptable approximation if PMV is within the range $[-2, +2]$ and the aforementioned variables describe small fluctuations within the following intervals (International Organization for Standardization (ISO, 2005)):

- Metabolic activity: $M \in [0.8, 4.0]$ met
- Clothing insulation: $I_{cloth} \in [0.0, 2.0]$ clo
- Ambient air temperature: $T_a \in [10.0, 30.0]$ °C
- Mean radiant temperature: $T_{MRT} \in [10.0, 40.0]$ °C
- Air speed: $v_a \in [0.0, 1.0]$ m s⁻¹
- Ambient vapor pressure: $p_{v,a} \in [0, 2700]$ Pa

Table 3.1 ASHRAE seven-point scale of thermal sensation

Question	How do you feel at this time?						
Descriptor	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Numerical	−3	−2	−1	0	+1	+2	+3

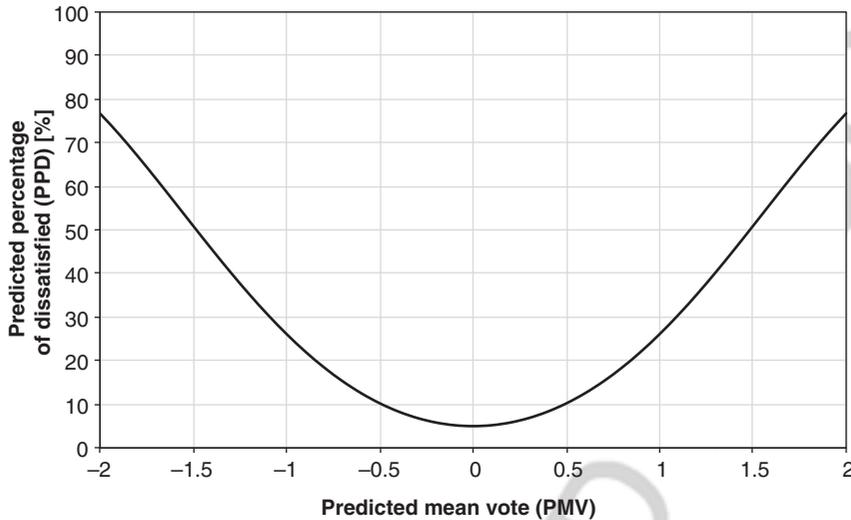


Fig. 3.2 PPD as a function of PMV

PPD is an index that predicts the percentage of people who are expected to feel uncomfortable if exposed to given environmental conditions and according to given metabolic activity rate and clothing. It is a function of PMV and the so-called *PMV/PPD equation* is

$$\text{PPD} = 100 - 95 \exp[-(0.03353 \text{ PMV}^4 + 0.2179 \text{ PMV}^2)] \in [5, 77] \quad (3.16)$$

subject to $\text{PMV} \in [-2, +2]$

PPD can be plotted as a function of PMV (Figure 3.2). The rational model is often called the *PMV/PPD model*.

Local thermal discomfort

The thermal comfort equation can only be applied to the whole human body. However, a heat or cold stress acting only on one particular part of the body may also cause thermal discomfort. Local thermal discomfort is caused by excessive draughts, vertical air temperature gradients, radiant temperature asymmetry, and by physical contact with objects at high or low floor temperatures, among others.

In order to predict the likelihood of local thermal discomfort, a number of equations have been proposed and relate parameters describing the local discomfort phenomena with PPD. Threshold values are also suggested together with the equations and can be found in a number of existing standards and guidelines, such as ISO 7730 (International Organization for Standardization (ISO), 2005), CR 1752 (CEN, 1998), and ASHRAE 55 (ANSI/ASHRAE, 2010).

Limitations of the heat-balance model

After the introduction of the rational model by Fanger, numerous studies supported it, (e.g., Parsons (2002)) or validated it (e.g., Humphreys and Nicol (2002)), or proposed

modified formulations (e.g., Araújo and Araújo (1999); Mayer (1997); Xavier and Lamberts (2000); Yoon, Sohn, and Cho (1999)) or extensions (e.g., Lin and Deng (2007); Ole Fanger and Toftum (2002)), or highlighted its limitations (e.g., Croome, Gan, and Awbi (1993); Howell and Kennedy (1979); Humphreys and Hancock (2007)) and discrepancies (e.g., Benton, Bauman, and Fountain, (1990); Doherty and Arens (1988)). The main shortcomings of the Fanger model are: (i) people are considered *passive sensors* of the thermal environment, instead of active individuals who adapt their activity, clothing ensemble, and the customization opportunities of the building (operability of the windows, doors and solar shadings, or modification of set-points, etc.); (ii) that Fanger did not identify adaptation opportunities other than the modification of clothing ensemble; therefore, his model does not account for climatic differences and types of buildings, and is the same throughout the world; (iii) thermal neutrality may not necessarily represent the optimal condition for a significant number of individuals since it does not account for psychological and cultural aspects; specifically (iv) thermal preferences are very asymmetrical around neutrality and, in some cases, people preferred non-neutral conditions; and consequently (v) that the assumption that the interval $[-1, +1]$ of the ASHRAE thermal sensation scale represents comfortable conditions may not universally reflect the preference for a large sample of people.

3.2.2.2 The adaptive comfort models

Since the rational model was developed from studies in controlled climate chambers and it assumes steady-state conditions, the rational model is not reliable if applied to free-running (i.e., naturally ventilated) buildings according to some researchers. This is because it only partly takes into account human thermal adaptation to the indoor environment and other nonthermal factors, such as *personal factors* (age, sex, culture, economic status, etc.), *psychological factors* (thermal preference, thermal expectation, personal attitude, etc.), and *interaction with the environment* (visual and acoustic perception, air quality level) (de Dear and Brager, 1998; La Gennusa *et al.*, 2010; Nicol and Humphreys, 2002). Instead, “if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” (Nicol and Humphreys, 2002), since “[. . .] people [. . .] are not inert recipients of the environment, but interact with it to optimize their conditions” (Humphreys, 1994).

From the aforementioned research, the theoretical basis of adaptive comfort models is the concept of adaptation, which “might be interpreted broadly as the gradual diminution of the organism’s response to repeated environmental stimulation” (de Dear and Brager, 1998). Adaptation manifests itself in three ways: physiological, psychological, and behavioral (Figures 3.3 and 3.4).

Physiological adaptation

Physiological adaptation can be considered as the set of all the changes used by the human thermoregulatory system to maintain constant the body internal temperature around a value of 37 ± 0.5 °C, in order to prevent damage to important organs. Physiological adaptation is usually separated into two items: *genetic adaptation*, which involves an adaptive opportunity being passed from a generation to the next, and *acclimatization*, which manifests itself within one generation; the former could be

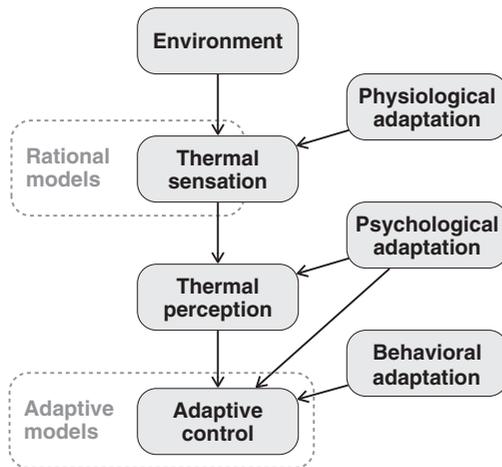


Fig. 3.3 Mechanisms organized by thermal comfort models

considered as a result of a long-term adaptation to one given thermal environment, and the latter as a short-term adaptation that happens within hours to months.

Psychological adaptation

Psychological adaptation can be considered as an altered perception of a given thermal environment, caused by an individual's thermal history and expectation. It is related to the habituation of an individual to a given thermal condition, since if an individual is repeatedly exposed to a certain thermal stimulus, his/her perception of the thermal stress, such as his/her expectation, diminishes. According to this, psychological adaptation is difficult to evaluate. It also depends on the adaptive opportunities that an individual can use to customize the indoor environment, since an individual attempts to tolerate, up to a certain degree, uncomfortable conditions if they can control them (Paciuk, 1989).

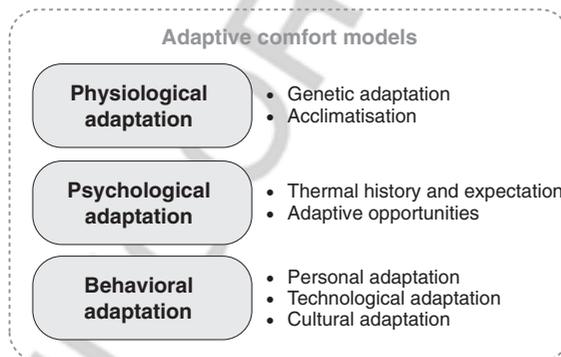


Fig. 3.4 Adaptive opportunities organized by adaptive comfort models

Behavioral adaptation

Behavioral adaptation can be considered as the set of all those activities that are, voluntarily or involuntarily, implemented by an individual in order to modify the amount of energy and mass exchanges between his/her body and the surrounding thermal environment. Behavioral adaptation is usually classified into three types of action: *personal*, for example, removing one garment; *technological*, for example, modifying the set-point temperature of the thermal plant system, opening a window, or operating a shading device; and *cultural*, for example, resting during the hottest hours of summer days.

Bases and formulations of the adaptive comfort models

The models based on the heat balance of the human body were developed using climate chambers. The adaptive models, however, were derived from the statistical analysis of data from field studies of people in real buildings, for example, de Dear, Brager, and Cooper (1997) and Nicol and McCartney (2001). Humphreys (1978) and Auliciems (1981) demonstrated that, specifically in buildings in free-floating mode, the neutral temperatures are mostly linked to the outdoor temperatures, rather than to the indoor conditions as assumed by the rational model. The rational models are deterministic models; instead the adaptive models are derived from a black-box approach and relate indoor neutral temperatures to outdoor temperatures, by linear regression analysis. For this reason, the canonical equation of adaptive models is

$$T_{\text{comfort}} = a \cdot f(T_{\text{ext}}) + b \quad (3.17)$$

Many adaptive approaches have been presented in the literature over the years and a number of them are summarized in Table 3.2.

Limitations of the adaptive models

One of the main limitations of adaptive models is that since they focus only on (operative) temperature, they neglect the effect of the other indoor environmental variables, such as air velocity and humidity. In particular, the increase of the average air velocity around the body increases convective heat exchange (ANSI/ASHRAE, 1982; Nicol, 2004).

In the rational model, the effect of humidity on human thermal perception is not negligible in the case of high air temperatures. According to Nicol (2004), high levels of relative humidity reduces the acceptability range around the theoretical comfort temperature. However, this revision is not yet implemented in the current adaptive comfort models.

3.2.2.3 Standards regarding thermal comfort

The ANSI/ASHRAE introduced the Fanger model in the ASHRAE Standard 55 for the first time in 1982 (ANSI/ASHRAE, 1982) and it was revised in 1992 (ANSI/ASHRAE, 1992), in 2004 (ANSI/ASHRAE, 2004), and in 2010 (ANSI/ASHRAE, 2010). The main modifications dealt with the upper limit for humidity in the comfort zone (based on the 10% dissatisfaction criterion). And the 1992 version introduced the diagram to estimate the temperature rise for comfort purposes as a function of air velocity produced by devices under direct control of occupants.

Table 3.2 Terms of the canonical equation of adaptive models according to several studies

Author and year	a	$f(T_{\text{ext}})$	b	Range of applicability
(CEN, 2007)	0.33 ^{a)}	Exponentially weighted running mean outdoor air temperature	18.8 ^{a)}	$f(T_{\text{ext}}) \in [10, 30] \text{ } ^\circ\text{C}$
(ANSI/ASHRAE, 2004)	0.31 ^{a)}	Monthly mean outdoor air temperature	17.8 ^{a)}	$f(T_{\text{ext}}) \in [10, 33.5] \text{ } ^\circ\text{C}$
(Fato, Martellotta, and Chiancarella, 2004)	0.315 ^{c)} 0.34 ^{a)}	Exponentially weighted running mean outdoor air temperature	17.82 ^{c)} 17.63 ^{a)}	$f(T_{\text{ext}}) \in [5, 30] \text{ } ^\circ\text{C}$
(Nicol and McCartney, 2001) ¹⁾	0.302 ^{a)}	Exponentially weighted running mean outdoor air temperature	19.39 ^{a)}	$f(T_{\text{ext}}) > 10 \text{ } ^\circ\text{C}$
(Humphreys and Nicol, 2000)	0.54 ^{a)}	Monthly mean outdoor air temperature	13.5 ^{a)}	$f(T_{\text{ext}}) \in [10, 30] \text{ } ^\circ\text{C}$
(Nicol <i>et al.</i> , 1999)	0.36 ^{c)}	Historical monthly mean outdoor temperature	18.5 ^{c)}	$f(T_{\text{ext}}) \in [5, 35] \text{ } ^\circ\text{C}$
(de Dear and Brager, 1998)	0.255 ^{a)} 0.04 ^{b)}	Monthly mean outdoor effective temperature (ET^*)	18.9 ^{a)} 22.6 ^{b)}	$f(T_{\text{ext}}) \in [5, 32] \text{ } ^\circ\text{C}$
(Nicol and Roaf, 1996)	0.38 ^{b)}	Monthly mean outdoor air temperature of the previous month	17.0 ^{b)}	$f(T_{\text{ext}}) \in (5, 35) \text{ } ^\circ\text{C}$
(Nicol and Humphreys, 1995)	0.534 ^{b)}	Exponentially weighted running mean outdoor air temperature	12.9 ^{b)}	N.d.
(Auliciems and de Dear, 1986)	0.31 ^{a)}	Running mean of the preceding fortnight	17.6 ^{a)}	N.d.
(Humphreys, 1978)	0.534 ^{a)}	Monthly mean outdoor air temperature	11.9 ^{a)}	N.d.

a) Model exclusively developed for free-floating and naturally ventilated buildings.

b) Model exclusively developed for air-conditioned buildings.

c) Model developed for all types of buildings (naturally ventilated, mixed mode, conditioned).

1) During the SCATs project, specific values of a and b were derived for the participating countries (France, Greece, Portugal, Sweden and UK).

Table 3.3 Acceptability classes in ASHRAE 55

ASHRAE 55 class	Scope	PPD (%)	Fanger PMV	Adaptive DT_{op} (K)
90%	To be used when a higher standard of thermal comfort is desired	≤ 10	$-0.5 \leq PMV \leq +0.5$	± 2.5
80%	To be used for typical applications and when other information is not available	≤ 20	$-0.85 \leq PMV \leq +0.85$	± 3.5

The adaptive comfort model, as proposed in ASHRAE Standard 55 (ANSI/ASHRAE, 2004, 2010), presents two acceptability classes: the 80% acceptability class, which is normative, and the 90% acceptability class, which is informative. Their scopes are reported in Table 3.3.

The target comfort class has to be chosen on the basis of the level of thermal acceptability required in a building and whether very low variations of indoor environmental variables are required, (e.g., in the case of sensitive or unhealthy occupants).

The model developed by Nicol and Humphreys (2002) has been more recently included in the European standards EN 15251 (CEN, 2007); hence, it is sometimes referred to as the European adaptive comfort model. EN 15251 proposes four comfort categories, which are called I, II, III, IV, and are defined according to the ranges of PMV proposed by ISO 7730, but, in this case, the standard provides a description of the scope for every category (Table 3.4).

Again, the target comfort category has to be chosen on the basis of the application – new building or refurbishment – and whether very low variations of indoor environmental conditions are required.

3.2.3 Long-term evaluation of thermal discomfort in buildings

In order to assess the thermal comfort performance of a building, a concise relationship between simulated or actual indoor hygrothermal conditions provided by a building, and occupants' expectation needs to be formulated. The thermal comfort models offer methodologies to calculate optimal predicted indoor conditions and provide ranges of the physical parameters of the indoor environment, which should be perceived as comfortable by a larger group of people. However, such optimal predicted indoor conditions are in the shape of time series values; hence, they allow for visualizing the dynamic performance of a building with respect to set-point comfort conditions, but they do not provide an overall picture of its comfort performance.

Table 3.4 Thermal comfort categories and acceptability ranges according to EN 15251

EN 15251 category	Description	Fanger		Adaptive
		PPD (%)	PMV	DT_{op} (K)
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons	≤ 6	$-0.2 \leq PMV \leq +0.2$	± 2
II	Normal level of expectation and should be used for new buildings and renovations	≤ 10	$-0.5 \leq PMV \leq +0.5$	± 3
III	An acceptable, moderate level of expectation and may be used for existing buildings	≤ 15	$-0.7 \leq PMV \leq +0.7$	± 4
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year	> 15	$PMV < -0.7$ and $PMV > 0.7$	

A number of metrics for assessing human thermal response to climatic conditions or thermal stress have been proposed in the literature over the past decades. Several researchers have used terms such as *discomfort index*, *stress index*, or *heat index* to identify the (expected or actual) human thermal perception of the thermal environment to which an individual or a group of individuals is exposed. More recently, a new type of *discomfort index* has been proposed in scientific literature, standards, and guidelines. The new type allows for describing the long-term thermal discomfort in a building and for predicting uncomfortable phenomena in a concise way; in particular summer overheating. Most of these new indices summarize the thermal performance of a building in a single value. They are called *long-term discomfort indices* and their ranking capability was evaluated by Carlucci (2013).

3.2.3.1 Background

The Chartered Institution of Building Services Engineers (CIBSE) introduced some overheating criteria based on the dry-resultant temperature (CIBSE, 2002) that for low air velocity can be approximated with the mean of air and radiant temperatures of a certain thermal zone. In 2005, ISO 7730 proposed five methods developed upon the Fanger comfort model. More recently, in 2007, EN 15251 reposed three of

the ISO-7730 indices and extended their use also to the adaptive comfort model, if compatible. Nicol *et al.* (2009) introduced an *Overheating risk* index, which is derived from the statistical analysis of the measured data collected in free-running buildings during the SCATs Project (Nicol and McCartney, 2001). Robinson and Haldi (2008) also proposed an *Overheating risk* index based on the analogy between human thermal comfort perception and an electric capacitor. Often *degree-hours* are also used to estimate heating or cooling loads, but with different base temperatures. More recently, Borgeson and Brager (2011) used a particular weighted degree-hour index, called Exceedance_M, which weighs discomfort hours by hourly average occupancy in a specified zone of a building. Carlucci and Pagliano (2012) reviewed 16 long-term discomfort indices. Carlucci (2013) deemed that none of these fully satisfied the needs for assessing long-term thermal comfort in a building; hence, they developed a new index called Long-term Percentage of Dissatisfied (LPD). It improves upon previous work by establishing an index for evaluating over a long-term the general comfort conditions in a building. According to the nomenclature introduced in Carlucci and Pagliano (2012), it is a symmetric and comfort-model-based index, not depending on comfort categories, and it is applicable to both summer and winter assessments. Its analytical expression accounts for hourly predicted Likelihood of Dissatisfied, which is calculated for each zone of a building. The hourly predicted Likelihood of Dissatisfied is weighted, each time step, for the number of people inside the zone during the current time step, and is normalized over the total number of people inside the building, and over the total occupied period during the seasonal calculation period. The equation for calculating LPD is

$$LPD(p, LD) = \frac{\sum_{t=1}^{t_f} \sum_{z=1}^Z (p_{z,t} \cdot LD_{z,t} \cdot h_t)}{\sum_{t=1}^{t_f} \sum_{z=1}^Z (p_{z,t} \cdot h_t)} \quad (3.18)$$

where t is the index for the time step of the calculation period, t_f is the last progressive time step of the calculation period, z is the index number for the zones of a building, Z is the number of the zones, $p_{z,t}$ is the zone occupancy at a certain time step, $LD_{z,t}$ is the Likelihood of Dissatisfied inside a certain zone at a certain time step and h_t is the duration of a calculation time step (by default 1 h). This index can be used to quantify thermal discomfort during cold periods, warm periods, or the whole year. Its formulations depend on (i) the chosen comfort model, (ii) the calculation period, and (iii) the type of discomfort.

3.2.3.2 The likelihood of dissatisfied

A Likelihood of Dissatisfied is a mathematical relationship that estimates the severity of the deviations from a theoretical thermal comfort objective, given certain outdoor and indoor conditions at a specified time and space location. They are, therefore, short-term (local) discomfort indices. Since the theoretical thermal comfort objective depends on the reference comfort model, three different Likelihoods of Dissatisfied shall be identified; each of them based on one of the comfort models. Carlucci (2013) shows that the *Average PPD* (<PPD>) and the *Nicol et al.'s Overheating Risk* (NaOR) are useful indices for the following reasons: (i) they aim to predict the percentage of

dissatisfied occupants in an environment by accounting for the nonlinear relationship between indoor conditions and human thermal sensation, and (ii) they provide similar long-term ranking assessment, although they are based on the Fanger and on the European adaptive models, respectively.

Regarding the ASHRAE adaptive model, Carlucci (2013) proposes the new *ASHRAE Likelihood of Dissatisfied*, which has been developed only for naturally ventilated buildings by analyzing the data recorded in the ASHRAE RP-884. This short-term index is comparable with the previous two indices.

Average PPD

Average PPD ($\langle \text{PPD} \rangle$) consists of calculating the mean PPD over the occupied hours within a given calculation period. It is an index based on the rational comfort model, but it does not depend on comfort categories. As currently defined, it could be used for assessing discomfort caused by overheating and overcooling. Its most important feature is that it accounts for the actual discomfort stress assessed through the PPD, according to the Fanger comfort model, without introducing a discontinuity as the indices based on comfort categories. It can be used for comfort optimization procedures and for comparing the thermal comfort performance of different buildings. However, since it relies only on the Fanger model, it is less suitable for the design of naturally ventilated buildings.

Nicol *et al.*'s overheating risk

Nicol *et al.* (2009) introduced an index (called here NaOR) to assess the summer overheating risk and proposes that thermal discomfort is not related to a specified temperature threshold, but to the difference between the actual operative temperature and the EN adaptive comfort temperature. It was derived from the analysis of comfort questionnaires collected in European naturally ventilated office buildings during the SCATs Project and takes into account that some people may feel uncomfortable even at the theoretical comfort temperature. In order to calculate NaOR, when the theoretical comfort temperature is exceeded, for each hour in a specified period, the offset from theoretical comfort temperature is recorded and a weighting factor is calculated. The weighting factor shows the nonlinear relationship between thermal discomfort and the deviation from the theoretical comfort temperature (Eq. (3.16)) (Nicol *et al.*, 2009). The authors derived the likelihood of overheating from a logistic regression analysis. The index predicts the percentage of individuals, $P(\Delta\theta_{\text{op}})$, voting +2 or +3, respectively warm or hot, on the ASHRAE thermal comfort scale (Table 3.1):

$$P(\Delta\theta_{\text{op}}) \equiv \frac{\exp(0.4734 \cdot \Delta\theta_{\text{op}} - 2.607)}{1 + \exp(0.4734 \cdot \Delta\theta_{\text{op}} - 2.607)} \in [0.069, 1) \quad (3.19)$$

where $\Delta\theta_{\text{op}}$ is the absolute value of the difference between the indoor operative temperature and the optimal comfort temperature calculated accordingly to the European adaptive model. NaOR was derived from the EN 15251 adaptive comfort model and it is not related to comfort categories. It is an asymmetric index, which aims at predicting overheating phenomena and it is not suitable for mechanically cooled buildings.

Ashrae likelihood of dissatisfied

An index for estimating the likelihood of thermal discomfort with respect to the ASHRAE adaptive model is missing in the literature; thus, it was necessary to build a new analytical function, called *ASHRAE Likelihood of Dissatisfied* (ALD), which has been determined via a logistic regression analysis performed on the data collected in the ASHRAE RP-884 database. Its final expression is

$$\text{ALD}(\Delta\theta_{\text{op}}) = \frac{\exp(0.008 \Delta\theta_{\text{op}}^2 + 0.406 \Delta\theta_{\text{op}} - 3.050)}{1 + \exp(0.008 \Delta\theta_{\text{op}}^2 + 0.406 \Delta\theta_{\text{op}} - 3.050)} \in [0.05, 1.00] \quad (3.20)$$

where $\Delta\theta_{\text{op}}$ is the absolute value of the difference between the indoor operative temperature and the optimal comfort temperature calculated accordingly to the ASHRAE adaptive model.

Comparison of the selected likelihood of dissatisfied

In order to provide a graphical comparison among the three selected likelihood distributions, it is necessary to present them in a form where they have the same input variable, for example, the operative temperature. Hence, for the distribution based on the Fanger model, a selection of PMV values has to be translated in operative temperatures by making some arbitrary assumptions. In this case we assume that the dry-bulb air temperature is equal to the mean radiant temperature (hence equal to the operative temperature), indoor relative humidity is equal to 50%, air velocity amounts to 0.1 m s^{-1} , metabolic activity is 1.2 met, the external work is zero met, and clothing resistance is 0.5 clo in summer, and 1.0 clo in winter. According to these assumptions, there are two likelihood distributions derivable for the Fanger model: one for summer and one for winter. The four likelihood distributions show quite similar trends (Carlucci, 2013), although there are a number of differences among them:

- Their scopes: the Fanger ones apply to mechanically conditioned buildings, while the Adaptive ones apply to free-floating buildings.
- The datasets where they were derived from: data recorded in thermal chamber (Fanger, 1970), SCATs Project (Nicol and McCartney, 2001), and ASHRAE RP-884 (de Dear, 1998).
- The methods used for deriving them: Griffiths's method (Griffiths, 1990) and binning of sample data method (de Dear, Brager, and Cooper, 1997).
- The values of their theoretical comfort temperatures are different.

3.2.3.3 Applications of the long-term (thermal) discomfort indices

Two possible uses of the long-term discomfort indices are introduced here and are applied in the following sections.

Thermal assessment of buildings

The basis of a long-term discomfort index is that it is a single value, which aims to estimate the overall predicted percentage of dissatisfied people inside the whole building over a given period. Therefore, LPD can be used to assess the quality of a building

Table 3.5 Proposal for thresholds to be used with the Long-term Percentage of Dissatisfied

Type of building	Version of LPD	Threshold for LPD	
		80% acceptability	90% acceptability
Conditioned	Fanger	LPD \leq 30%	LPD \leq 17%
Free-floating	Adaptive (both European and American)	LPD \leq 20%	LPD \leq 10%

(envelope and mechanical systems) in providing thermal comfort and to identify if there are differences in its winter or summer performance during the optimization of a new building or during the operational ranking of an existing building. The long-term discomfort index based on an adaptive comfort model (NaOR for the European adaptive model and ALD for the ASHRAE adaptive comfort model) is suggested for free-floating buildings and one based on the Fanger comfort model (Average PPD) is suggested for conditioned buildings.

Although the statement of discomfort thresholds or comfort categories is a challenging issue and it is also a subject of debates (Alfano, d'Ambrosio, and Riccio, 2001; Arens *et al.*, 2010), there are two assumed thermal discomfort levels: a standard level corresponding to 80% of acceptability (or equally, to 20% of dissatisfaction) and a level corresponding to a 90% of acceptability (or equally, to a 10% of dissatisfaction). Under this assumption, some acceptability thresholds could be suggested for the long-term discomfort indices in the adaptive and Fanger versions (Table 3.5).

Building optimization as minimization of thermal discomfort

Since long-term discomfort indices allow comfort to be assessed from building simulation, they can be used within multiobjective optimization problems. Thus, the optimization problem results in a bi-objective optimization.

$$\min_{x \in X} F = \begin{cases} \text{LPD}_{\text{summer}}(x^*) \\ \text{LPD}_{\text{winter}}(x^*) \end{cases} \quad \text{for } x^* \in X \quad (3.21)$$

An example of this optimization approach is presented in Section 5.4.

This section on thermal comfort has discussed traditional thermal comfort models, adaptive thermal comfort, and finally long-term thermal comfort indices and their application. The following sections discuss visual and acoustic comfort and indoor air quality.

3.3 Daylight and visual comfort

3.3.1 Introduction

Occupants clearly prefer having windows in their working environment as a means of illumination and view to the outdoors (Boyce, Hunter, and Howlett, 2003). Moreover, daylight and views have a positive effect on occupants' health, well-being, and

productivity (Farley and Veitch, 2001; Veitch and Galasiu, 2012). In addition, the presence of windows or skylights on buildings may have a positive effect on retailing (Heschong, Wright, and Okura, 2002). Finally, windows can provide useful passive solar gains and provide a means, if operable, for occupants to introduce fresh outdoor air into the space and increase local air speeds. All case studies in Chapter 7, and particularly ENERPOS and NREL RSF, demonstrate the driving role that daylighting should play in buildings and their design process.

Despite the architectural, comfort, energy, and functional benefits of glazing, it often adds to construction costs and may increase space conditioning energy if not designed carefully. Glazing typically has lower thermal resistance than opaque wall or roof constructions and can cause unwanted solar gains – particularly in cooling-dominated climates and/or buildings that have high internal gains (e.g., densely occupied office buildings).

Modestly sized windows with fixed shading devices are the preferred configuration to simultaneously optimize energy performance and occupant comfort. Façades with more than a 60% window-to-wall ratio should be avoided, as they tend to cause thermal and visual discomfort due to excess daylight and solar gains. Fixed shading devices function best for south-facing façades and do not perform well for non-south-facing façades; nor do they offer privacy or the ability to darken a space (e.g., for presentations or sleeping). Because of this lack of flexibility, dynamic shading systems have gained popularity as a means to complement fixed shading. The three-section façade concept (Tzempelikos and Athienitis, 2003) allows fenestration system properties to be tailored to the particular function of the façade at different heights above the floor. A three-section façade (Figure 3.5) consists of: (i) a bottom (spandrel) section, which is opaque (e.g., insulated wall) as it would contribute little to daylighting (LBNL, 1997), (ii) a middle

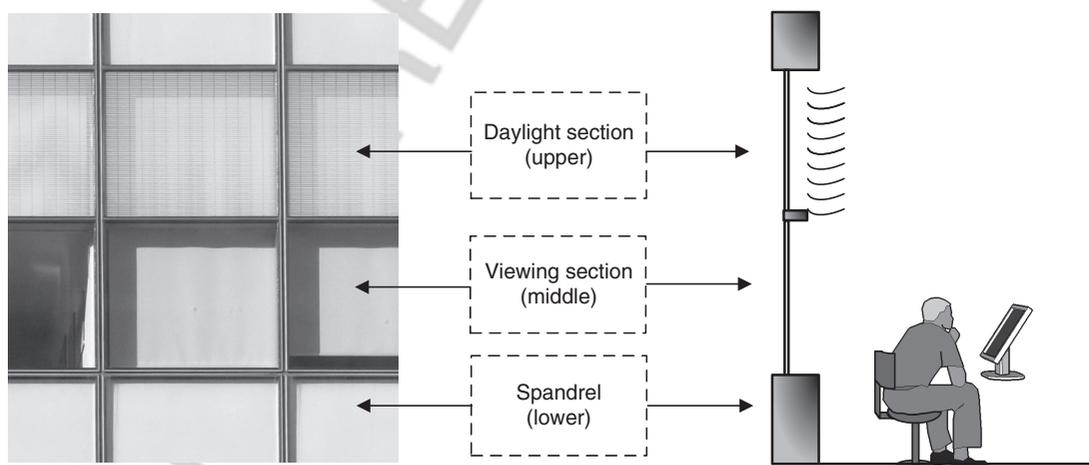


Fig. 3.5 Three-section façade concept and three-section façade of the Engineering, Computer Science and Visual Arts Integrated Complex (EV) at Concordia University, Montreal, Canada

(viewing) section, which normally extends from the workplane (0.8 m above the floor) to about 1.5–2.0 m above the floor and allows views to the outdoors, and (iii) a top (daylight) section, which has the primary function of admitting daylight deep into the space while protecting occupants from glare and direct solar radiation. When applied to shallow buildings, three-section façades can be optimized to reduce electric lighting and maximize natural ventilation (e.g., see the ENERPOS and NREL RSF case studies in Chapter 7). In addition, it has been shown that occupants prefer shallow (no more than 15 or 20 m wall to wall) over deep buildings, due to daylight availability, views to the outdoors, and natural ventilation potential (Leaman and Bordass, 2005). However, in order to fully realize the energy savings from daylighting, manual or automated lighting controls must allow for it to be properly integrated as a complement to electric lighting.

This section provides an overview of visual comfort issues with emphasis on their quantification, including illuminance- and luminance-based metrics.

3.3.2 Adaptation luminance

For the eye to be able to function well, it has to adapt to the prevailing luminance conditions (adaptation luminance) by constricting and dilating the iris (Rea, 2002). Adaptation to varying transient luminance takes some time (seconds to minutes, depending on the magnitude of the luminance shift) and varies through the period of a task, either because of the eye movement from one point to another or due to daylight variation (Osterhaus, 2009). If high contrast conditions are present, the eye stresses to adapt, which translates to feelings of annoyance (discomfort glare). Hence, the luminance ratio between the visual task, its adjacent surroundings, and more distant surfaces is recognized as a major, if not the most important, determinant for a glare-free environment (ISO, 2006). Depending on the environment, the luminance levels might significantly vary from one viewpoint to another. However, recommendations (– Table 3.6) can be followed to ensure that in the case of nonuniform luminance surfaces, visual comfort can be maintained.

In addition, it is more difficult for the eye to adapt when a high luminance source is located at the center of the visual field than on the periphery. Considering that most tasks require the occupant to look straight ahead (e.g., at a computer screen), the preferred orientation of the occupant relative to the window is 90° (Osterhaus, 2005) or an orientation close to this angle. In all cases, having the window, shaded or unshaded,

Table 3.6 Luminance ratio recommendations (Rea, 2002)

Maximum luminance ratios	Description
3 : 1 or 1 : 3	Between visual task and immediate surroundings
10 : 1 or 1 : 10	Between visual task and near surroundings
20 : 1 or 1 : 20	Between visual task and remote surroundings
40 : 1 or 1 : 40	Between visual task and any surface in the field of view

located in front or behind the occupant should be avoided, as it increases the probability of glare (*discomfort glare*, when the occupant faces the window, or *veiling glare* due to the window reflection on the computer screen) occurring.

3.3.3 Illuminance-based performance metrics

Most lighting design standards and metrics rely primarily on illuminance-based levels and provide guidelines mainly for horizontal (workplane) illuminance levels. However, the human eye responds to luminance levels and variations. Moreover, most visual tasks take place on nonhorizontal planes (e.g., a computer screen). Existing daylight metrics based on workplane illuminance and conventional daylight glare metrics have not yielded consistent predictions of daylight glare (Wienold and Christoffersen, 2006). However, useful metrics exist that can be used to influence design decisions toward a luminance-balanced environment.

3.3.3.1 Daylight autonomy and continuous daylight autonomy

Daylight autonomy (DA) indicates the fraction of time when the workplane illuminance meets or exceeds a set threshold (e.g., 500 lux for typical office environments), by daylight alone (Reinhart, Mardaljevic, and Rogers, 2006). The metric can be expressed as a fraction of occupied hours, daylit hours or occupied hours that are daylit, over a given period of time (e.g., a year). For nondimmable (i.e., on/off) electric lighting that is automatically controlled by occupancy and/or a daylight sensor, DA can be directly translated into potential energy savings.

An extension to DA is continuous Daylight Autonomy (DA_{cont}), which indicates the fraction of time when the minimum workplane illuminance requirements are partly or fully met by daylight alone. This is suitable for quantifying the energy savings from automatically dimmable lighting.

$$DA_{\text{cont}} = \sum_{t=1}^n \min \left\{ \frac{E_{\text{daylight}}}{E_{\text{min}}}, 1 \right\} \quad (3.22)$$

where n is the total number of time steps (e.g., hours), E_{min} is the minimum workplane illuminance requirement, and E_{daylight} is the workplane illuminance provided by daylight only, at a given time step t .

3.3.3.2 Useful daylight illuminance

Useful daylight illuminance (UDI) categorizes workplane illuminance levels for typical office spaces, due to daylight only, into three bins as shown in Table 3.7 (Nabil and Mardaljevic, 2006). UDI offers the advantage over DA and DA_{cont} in that it quantifies the duration of high illuminance and thus, may indicate cause for concern from chronic visual discomfort. However, there is some discussion in the research community about whether the thresholds for the bins are appropriate (Mardaljevic, Heschong, and Lee, 2009). All metrics are relatively straightforward to obtain from BPS tools or measurements (e.g., on scale models and full-size mock-ups) and provide an indication of year-round daylight quality for the building design and climate of interest.

Table 3.7 Useful daylight illuminance (UDI) (Nabil and Mardaljevic, 2006)

Workplane illuminance range	Symbol	Implications
<100 lux	$UDI_{<100\text{lux}}$	Fraction of time when daylight is insufficient as the only source of illumination
100 to 2000 lux	$UDI_{100-2000\text{lux}}$	Fraction of time when daylight is sufficient to completely or partially (in the lower part of the range) offset electric lighting
>2000 lux	$UDI_{>2000\text{lux}}$	Fraction of time when daylight is likely associated with visual and/or thermal discomfort

3.3.4 Luminance-based performance metrics

Several luminance-based metrics have been developed through the years to try to predict and quantify glare. However, further research and validation studies are still needed to produce robust luminance metrics that will be able to assess the impact of potential glare sources. Daylight glare probability (DGP) proposed by Wienold and Christoffersen (2006) has shown promising results. DGP is a directional view-dependent metric; thus, the designer should be aware of the possible locations and orientations of the occupants relative to the window as well as the tasks to be performed. Furthermore, DGP allows the impact of interior design and surface finishes to be evaluated.

3.3.4.1 Daylight glare probability

Daylight glare probability, which is based on vertical eye illuminance and glare source luminance, detects glare sources by contrast ratios. DGP uses luminance mapping of a scene generated either by daylighting BPS tools or using high dynamic range (HDR) images (e.g., Figure 3.6). Thus, it can be used for new building designs or retrofits. DGP uses a scale to evaluate glare risk, such that if $DGP < 0.30$ then the glare source is “barely perceptible,” if $0.3 \leq DGP \leq 0.45$ the glare source is “disturbing,” while if $DGP > 0.45$ then glare source is “intolerable.” The DGP is calculated as follows:

$$DGP = 5.87 \cdot 10^{-5} E_v + 9.18 \cdot 10^{-2} \log \left(1 + \sum_i \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} P_i^2} \right) \quad (3.23)$$

The position index (P) located above the line of vision is expressed as

$$\ln P = \left[35.2 - 0.31889\tau - 1.22e^{-2\tau/9} \right] \cdot 10^{-3} \sigma + \left[21 + 0.26667\tau - 0.002963\tau^2 \right] \cdot 10^{-5} \sigma^2 \quad (3.24)$$

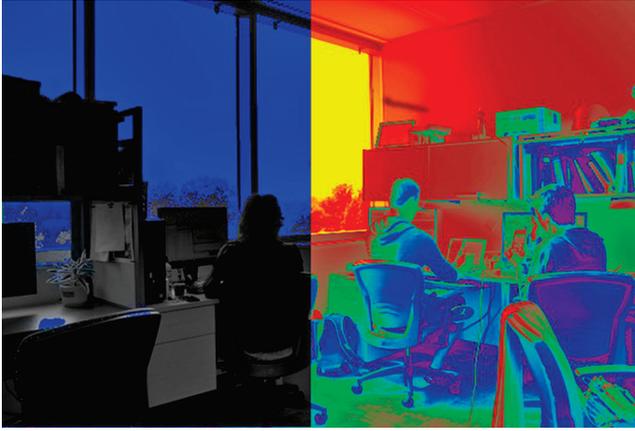


Fig. 3.6 Daylight glare analysis for a shared office space: False color image of high dynamic range (HDR) photograph (right) and glare analysis performed with Evalglare software, where the colored regions indicate sources of daylight glare (left). (Photo courtesy of Brent Huchuk)

while P located below the line of vision is expressed as

$$P = 1 + 0.8 \frac{R}{D} \quad \text{if } R < 0.6D \quad (3.25)$$

$$P = 1 + 1.2 \frac{R}{D} \quad \text{if } R \geq 0.6D \quad (3.26)$$

$$R = (H^2 + Y^2) \quad (3.27)$$

where E_v is the vertical eye illuminance (lux), L_s is the source luminance (cd/m^2), ω_s is the solid angle of the source ($^\circ$), P is the position index, τ is the angle from the vertical of plane containing source and line of sight ($^\circ$), σ is the angle between line of sight and line from eye to source ($^\circ$), D is the distance between eye and plane of source, in the view direction, H is the vertical distance between source and view direction, and Y is the horizontal distance between source and view direction.

3.3.5 Daylight and occupant behavior

The last aspect described in this section is about the interaction between occupants and the daylighting/lighting domain. Dynamic window shading devices are normally installed with the design intent to be temporarily closed to provide privacy and protection from glare, while remaining partly or fully open to exploit daylight and passive solar gains, when needed. However, observations have revealed that occupants tend to be inactive users of shading systems (e.g., blinds and roller shades). The mean rate of shade movement is well below once per day for most office buildings with some shades being never moved (Wymelenberg, 2012). Instead of being highly responsive to daylight conditions, occupants tend to leave their shades in a position that “causes the

least trouble” (Bordass *et al.*, 2001) or minimizes conflict between occupants in shared offices (Cohen *et al.*, 1999), namely, partly or fully closed. This leads to reduced views and unnecessary electric lighting use that ultimately increase energy use relative to what designers predicted. An effective daylight design should create a pleasant, glare-free environment, so as to minimize actions that will reduce daylight admission (Boyce, Hunter, and Howlett, 2003), while exploiting daylight. Good passive and indoor design, such as window geometry, window type, fixed exterior shading, interior design surface reflectances, and strategic furniture layout, can reduce the frequency of closed shades and increase the daylight utilization and view to the outdoors. Moreover, field surveys reveal that occupants value some degree of individual control over the shading devices and windows (Leaman and Bordass, 2005).

3.3.6 Conclusion

This section briefly reviewed the key issues related to visual comfort and how it affects design and energy performance. Common and emerging daylighting and visual comfort metrics were provided, including luminance ratios, daylight autonomy, useful daylight illuminance, and daylight glare probability. The section concluded by describing the important role of occupant behavior and occupant interactions with lights and shading devices. This aspect cannot be ignored as occupants are significantly less active and energy-conserving than designers might expect.

3.4 Acoustic comfort

Acoustic comfort describes the indoor acoustic conditions of a building with regard to providing a healthy and productive environment for occupants. It is critical to properly functioning buildings, yet often neglected during design and in green building standards (Hodgson, 2008). Acoustic comfort has become even more critical because strategies to reduce energy use and improve indoor air quality often directly contradict good acoustic comfort design practices:

- Natural ventilation improves both real and perceived thermal comfort, provides fresh air to supplement or temporarily eliminate the need for mechanical ventilation, and in many climates can completely eliminate the need for mechanical cooling. However, open windows often introduce outdoor noise into the workplace, which is a particular concern in urban areas or beside busy streets (Ghiaus *et al.*, 2006). Furthermore, good cross-ventilation requires an open concept design. However, a lack of partitions between spaces (e.g., cubicles instead of floor-to-ceiling walls) results in higher levels of sound transmission. Thus, distracting conversations and other noises can cause poor occupant concentration and comprehension.
- Deep daylight penetration in a space requires an open concept design, similarly to natural ventilation. Closed offices and other small perimeter spaces, if enclosed, prevent daylight from being able to penetrate to its full potential (about 1.5 to 2.5 times window height for standard windows (Reinhart, 2005) and five to six times window height if advanced reflective systems are in place (Guglielmetti, Pless, and Torcellini, 2010)).
- Exposed thermal mass (e.g., concrete structures) facilitates greater ability to absorb solar gains and regular air temperatures – an important element of low-energy passive

buildings. However, hard smooth surfaces are also poor sound absorbers and can lead to poor acoustic comfort if such surfaces dominate a space.

The strategies to mitigate poor acoustic quality (the so-called ABCs or acoustic design) include absorbing, blocking, and covering noise. Absorbing means the use of strategically placed surfaces (e.g., acoustic ceiling tiles, wall panels, carpeting, furniture, and/or sound-absorbing artwork) to reduce sound transmittance through a space. Blocking requires that the source of sound be isolated (e.g., servers or photocopiers in a separate room). Covering means masking sounds with white noise generators such that individual sounds (e.g., occupant chatter) are indistinguishable. For instance, the NREL RSF (see Chapter 7 for details) uses white noise generators to cover conversations and other sounds. While mechanical ventilation often plays this role, RSF does not use forced-air for heating and cooling, so ventilation rates and the corresponding noise levels are relatively low. Regardless, HVAC systems (e.g., fans and ducts) can be a source of unwanted noise and careful design is important.

As for other forms of occupant comfort, metrics for quantifying acoustic comfort are diverse and complex. Metrics for interior surfaces include sound transmission class (STC), which quantifies a surface's ability to block sound from being transmitted, and noise reduction coefficient (NRC), which defines the fraction of sound that is absorbed upon hitting it. Speech intelligibility index is a measure of how clearly one occupant can hear others and has been used in numerous postoccupancy evaluations of buildings (Hodgson, 2008; Newsham *et al.*, 2013). Ambient noise level, measured in decibels (dB), indicates the magnitude of background noise in a space. A noise criterion (NC) level of between 30 and 40 is acceptable (Hodgson, 2008). Normally, noise levels are based on an A-weighting, which defines the human ear's hearing ability at different frequencies.

3.5 Indoor air quality

Indoor air quality is a measure of the healthiness and comfort of air in buildings. IAQ gained considerable attention during the oil embargos of the 1970s when building operators significantly reduced ventilation rates in an effort to reduce energy use. While this strategy achieved its original objective, it resulted in very poor air quality and many health effects that became known as sick building syndrome (SBS) (Redlich, Sparer, and Cullen, 1997).

Contaminants in the air are normally categorized as gaseous, particulates, or microbial. These vary in harmfulness and at least a dozen official standards impose limits on safe levels, depending on exposure duration (Charles *et al.*, 2005). This brief section provides an overview of IAQ, including some common contaminants and design and operational strategies to mitigate high levels of indoor air contaminants.

The main contaminants of concern or interest include: tobacco smoke, radon, molds, legionella, carbon monoxide, bioeffluents, volatile organic compounds (VOCs), asbestos fibers, ozone, and carbon dioxide. Details on these contaminants and recommended maximum exposure levels can be found in ASHRAE Standard 62.1 (ASHRAE, 2010) and reports by the US EPA (2013). Their origin can be materials and substances that are

indoors, occupants, equipment and HVAC distribution, or the outdoors (e.g., a point source of pollution or from polluted urban environments).

Carbon dioxide is frequently cited as a major source of IAQ problems. However, this is because carbon dioxide is a good indicator of IAQ in occupied buildings and it is considered a *surrogate*. It correlates well with occupancy since occupants are the primary source of CO₂ in most buildings and can be used to approximate the outdoor air supply rate if the occupancy and outdoor CO₂ concentration are known, as follows:

$$C_{\text{CO}_2}(\infty) = \frac{PQ C_{\text{CO}_2\text{o}} + S/V}{Q} \quad (3.28)$$

where $C_{\text{CO}_2}(\infty)$ is the steady state indoor carbon dioxide concentration, P is the fraction of outdoor air in the air supply, Q is the air supply rate, $C_{\text{CO}_2\text{o}}$ is the outdoor carbon dioxide concentration, S is the generation rate of carbon dioxide, and V is the volume of the space. Many ventilation standards (e.g., ASHRAE Standard 62.1 (ASHRAE, 2010)) use a certain allowable carbon dioxide concentration to provide minimum ventilation rates for different space types (e.g., classroom, office, kitchen).

The three main methods to ensure good IAQ are: (1) removal or reduction of source of contaminants, (2) ventilation, or (3) filtration of contaminants. The first approach, to attempt to eliminate the source of contaminants, is the preferred option because it requires no maintenance or operating energy use. Use of low-VOC paints, furniture, and other finishes are also good approaches to achieve this. Careful design of walls and HVAC systems to minimize chronic moisture or sitting water is essential to minimize mold growth and other bioaerosols. Ventilation and filtration cost energy: electrical energy (fans and pumps) and thermal energy (for conditioning supply air) for ventilation and electrical energy to run fans to overcome pressure drops in filters. The thermal energy demands of ventilation can be partly reduced using heat or energy recovery ventilation.

3.6 Conclusion

This chapter examined thermal, visual, and acoustic comfort, and indoor air quality. These elements of indoor environmental quality are critical to the success of Net ZEBs. While indoor conditions were traditionally viewed as being passively endured by occupants, it is now widely accepted that occupants actively adapt their environment and themselves to improve comfort. They normally do so in the most convenient and effective ways and only once a “crisis of discomfort” has occurred (Haigh, 1981). Because these adaptations may have a significant effect on energy use (e.g., window opening on heating or cooling and blind-closing on electric lighting), comfort and energy are tightly linked. As such, maintaining comfort through careful building design and operation should be considered throughout the building life cycle. Readers are encouraged to refer to the case studies of this book (Chapter 7) for examples of occupant comfort and design for comfort; particularly the ENERPOS case study, which owes much of its success to achieving comfortable conditions with very low energy use.

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