Addendum a to
ASHRAE Guideline 10-2023

Public Review Draft

Proposed Addendum a to Guideline 10-2023, Interactions Affecting the Achievement of Acceptable Indoor Environments

First Public Review (February 2024)
(Draft shows Proposed Changes to Current Guideline)

This draft has been recommended for public review by the responsible project committee. To submit a comment on this proposed standard, go to the ASHRAE website at www.ashrae.org/standards-research--technology/public-review-drafts and access the online comment database. The draft is subject to modification until it is approved for publication by the Board of Directors and ANSI. Until this time, the current edition of the standard (as modified by any published addenda on the ASHRAE website) remains in effect. The current edition of any standard may be purchased from the ASHRAE Online Store at www.ashrae.org/bookstore or by calling 404-636-8400 or 1-800-727-4723 (for orders in the U.S. or Canada).

This standard is under continuous maintenance. To propose a change to the current standard, use the change submittal form available on the ASHRAE website, www.ashrae.org.

ASHRAE, 180 Technology Parkway, Peachtree Corners GA 30092

Proposed Addendum a to Guideline 10-2023

FOREWORD

This addendum adds moisture as an Aspect of the four Indoor Environmental Factors to Guideline 10-2023. Edits include the various properties, measurements, effects, and interactions of moisture with the acceptability of the indoor environment, associated definitions (with notes), and References.

Note: In this addendum, changes to the current guideline are indicated in the text by underlining (for additions) and ~~strikethrough~~ (for deletions) unless the instructions specifically mention some other means of indicating the changes.

Addendum a to Guideline 10-2023

Modify Sections 3, 4, 4.1, 4.3, 4.5, 4.8, 5.1.1,5.1.4, 5.2.2, 5.2.4, 5.2.5, 5.2.6, 6.1, 6.2, 6.3.5, 6.6, 9.

3 DEFINITIONS

absolute humidity: the weight of water vapor contained in a unit volume of air, expressed as milligrams of water vapor per cubic centimeter of air.

Note: The measurement of absolute humidity is expressed sensitive to changes with the temperature of air and atmospheric pressure. Specific humidity is a more accurate and useful term for the indoor environment, while absolute humidity is technically correct for chemical processes.

acceptable indoor environment: an environment that is suitable for the purposes of the intended occupancy. ***Note:*** The meaning of acceptability depends on the criteria and the process that is applied to perform the determination. This is influenced by the individuals involved in this process (e.g., occupants, building operators, owners, and visitors) along with relevant health and other standards. These different individuals may render diverse determinations. Acceptability of an indoor environment is the determination of any affected party that the environment is suitable for the purposes of the intended occupancy.

It should be noted that acceptability is not identical to the satisfaction of most or all occupants, which would generally require a somewhat higher level of environmental quality. Ultimately, acceptability is defined by the process used to determine it, as well as by the individuals who make the evaluations, assessments, or judgments that are part of the process. This guideline recognizes that individual acceptability is often dependent on context and on cultural expectations.

acoustical environment: the sound and vibration conditions in a space.

aspect: the components that make up an environmental factor.

condensation: the conversion of water vapor in the air to liquid water on a surface that is at or below the dew point temperature of the surrounding air.

contaminant*: see *pollutant.

dew point temperature*:* the temperature to which the air must be cooled to become 100% saturated with water vapor. Water vapor (humidity) will form condensation on adjacent surfaces that are at or below the dew point temperature of that air.

dry bulb temperature: the ambient temperature of the air as measured by using a normal thermometer freely exposed to the air but shielded from radiation and moisture.

enthalpy: the integrated representation of the dry-bulb and wet-bulb condition of the air that describes the total energy content of the air.

***equilibrium relative humidity*:** the relative humidity of air in contact with a surface when neither air nor surface is gaining or losing energy or moisture.

Note: Full equilibrium between surface and air does not occur in buildings because equilibrium requires a sealed and insulated container that isolates both surface and air from external sources of energy and moisture. But when the surface temperature of building components or furnishing and the dew point temperature of the adjacent air is known with some certainty, converting the dew point of the air to relative humidity with respect the temperature of the surface can be useful for assessing whether a surface might be gaining or losing moisture.

factor: the major features of the indoor environment that affect its acceptability as addressed in this guideline are termed *factors*.

health: the World Health Organization defines *health* as, "... a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity." For the purposes of this document, the term *health* extends to the general category of interactions, whether currently known or unknown, affecting the achievement of acceptable indoor environments.

health risk*:* an *interaction* of the *factors* of the *indoor environment* that decreases below satisfaction the chance of developing a diagnosable disease or a definable hazard.

humidity*:* ~~a generic reference to the collective or inclusive use of relative humidity and specific humidity without differentiation.~~ The presence of water vapor in the air or in a gas. The amount of water vapor in the air can be expressed in at least four different terms, each of them linked to a different way of measuring the humidity.

humidity measurement by:

1. **Specific humidity** is a measure of the weight of water vapor contained in a unit weight of air, expressed as grams/lb / grains of water vapor per lb/kilogram of air.
   Note 1: It is the vertical axis of psychrometric charts and corresponds directly with dew point.
   Note 2: The measurement of specific humidity is not influenced by the temperature of air or atmospheric pressure of the air.
   Note 3: Specific humidity is more relevant to effects on materials rather than to humans.
2. **Dew point condition** is a measure of absolute humidity that is measured by cooling the air until it starts condensing or "dew" forming on a cold surface.
3. ***Absolute humidity*** the weight of water vapor contained in a unit volume of air, expressed as milligrams of water vapor per cubic centimeter of air.
   Note 1: as pressure or drybulb temperatures change, the amount of water vapor in a fixed volume of air changes. At the constant temperature and pressure of "standard CFM" conditions, absolute and specific humidity directly correspond to each other as well as the dew point of the air.
   Note 2: The measurement of absolute humidity measures weight per volume or g/m3 or grains/cfm. HVAC air supply conditions are usually defined in terms of volume per time i.e., (CFM/CMH), it can be used to determine how much water needs to be added or removed to get to target conditions in term of DB/RH.
4. ***relative humidity****:* the amount of water vapor present in air expressed as a percentage of the amount needed for saturation at the same temperature. Abbreviated as RH.
   Note 1: Relative humidity is more relevant to effects on humans, while dew point temperature is more relevant to effects on materials.
   Note 2: The relative humidity as measured in the open air is not the same value as relative humidity when measured near indoor surfaces, unless both the air and the surface in question are at the same temperature.
   Note 3: Extremes of the relative humidity of indoor air can affect perception of comfort. High relative humidity supports growth of biological agents, including disease vectors like viruses. High relative humidity also drives moisture development on cold surfaces. It can also maintain the size of moisture droplets in the air with viruses/bacteria inside of them that are expelled by occupants. Heavier droplets will more quickly fall down. Low relative humidity increases the lifetime of airborne disease vector by quickly reducing the size of droplets. It also adversely affects the human immune system in a number of ways that lead to significant increases in transmission of infectious diseases like the flu.

illumination: non-ionizing radiation in the visible portion of the electromagnetic spectrum.

indoor air quality: the measurable physical, chemical, and biological composition of air in a space compared with reference values for its components, the acceptability of the air to occupants, and the total composition of the air, whether detectable or not.

indoor environment: the conditions that exist inside an enclosed, nonindustrial building intended for human occupancy.

interaction: the combined effect on a building occupant of two or more environmental factors or their aspects.

ionizing radiation: a form of energy that acts by removing electrons from atoms and molecules of materials that include air, water, and living tissue; ionizing radiation can travel unseen and pass through these materials.

moisture: 1. Water vapor in air. 2.Water liquid absorbed or adsorbed into or below the surface of a solid such as the materials or furnishings of a building.

Note 1**:** Moisture is an aspect of the environment that is interactive, individually or collectively, as an influence of the four environmental factors that affect the acceptability of indoor environments. Moisture is active in the air as vapor (enthalpy), in materials as liquid (moisture content), or on surfaces of materials or furnishings (water activity/available water) of the indoor environment. Moisture can be considered a pollutant when excessive in air, in materials, or on surfaces of materials; and potentially considered a health risk when excessive or deficient in air. Water as vapor, liquid, or solid can also contain or distribute dissolved or suspended material as Category 1, 2, or 3 Water, per ANSI-IICRC S500 Professional Water Damage Restoration.

Note 2**:** Moisture accumulation in materials creates favorable conditions for biological growth, including but not limited to the growth of molds on surfaces and growth of disease vectors like viruses and bacteria. Very low moisture conditions on surfaces can lead to extended life of micro biological substances. High surface moisture can lead to adverse surface reactions that increase gaseous pollutants of indoor air and over time can lead to health-relevant building dampness.

Note 3**:** The term "moisture" is routinely used as a generic reference to the collective or inclusive use of relative humidity, specific humidity, moisture content, and water activity without differentiation.

moisture content: the weight of water in a material compared to the dry weight of that material, expressed as a percentage.

Note: Moisture content is a common metric used to assess the risk of excessive moisture accumulation in wood and other cellulosic building materials, including paper-faced gypsum board and acoustic ceiling tile. For building materials, moisture content is generally expressed as a percentage of the material when oven dried. Wood moisture equivalent (WME) is a convenient metric of moisture content because low-cost handheld moisture meters are widely available with that calibration. WME values that imply risk of mold growth on cut wood surfaces also imply risk of mold growth and other adverse effects in the adjacent cellulosic materials and fabrics commonly found in buildings.

non-ionizing radiation: a type of low-energy radiation that does not have enough energy to remove an electron (negative particle) from an atom or molecule; non-ionizing radiation includes visible, infrared, and ultraviolet radiation; microwaves; radio waves; and radiofrequency energy from cell phones.

pollutant: any unwanted environmental component that is present in an occupied building space.

Note: What is "unwanted" will vary with the use of a space and the individual users. For example, loud sound (music, speech, motors, etc.) that interferes with a desired function of a space, such as conversation, a lecture, or other activity with audible content essential to its success, is considered sound pollution (usually referred to as *noise*). However, what may be perceived as noise by one person may be considered desirable by another, as in the case of music, where taste and personal preference differ for loudness (sound intensity). Differences in auditory acuity will also affect perceptions of acoustical conditions as visual acuity, olfactory sensitivity, and tolerance or preference for thermal conditions will affect perceptions of thermal comfort.

Both disability glare (lighting that interferes with occupants' ability to see), discomfort glare (lighting that causes discomfort for the occupants), and color spectrum could be considered undesirable components in the built environment. Here, too, individual preferences can be important. Contaminants in air are commonly referred to as *air pollutants*. No equivalent concept exists for thermal conditions inside buildings, but thermal pollution of water occurs at power plants where cooling water is released into a water body and adversely affects aquatic life.

psychrometric chart: a graphical representation of the thermodynamic properties of air at various conditions.

thermal environment: the combined effect of the temperature, humidity, air movement, and thermal radiation in a space.

visual environment: the combined effect of the spectral distribution, intensity, and direction of the visible electromagnetic energy in a space.

wet bulb temperature: a measure of the enthalpy/energy content of the air, measured air temperature influenced by humidity and other environmental factors.

Note: wet bulb temperature reflects the cooling effect of evaporation of water from a thermometer bulb wrapped in wet muslin, whirled in the air until the thermometer reaches a constant value. Modern digital instruments calculate web bulb temperature from the measured values of temperature and humidity. The wet bulb temperature can also be located on a psychrometric chart.

water activity/available water: the ratio between the water vapor pressure of a surface and the vapor pressure of distilled water at the same temperature, when both are in equilibrium at a constant temperature.

Note: Water activity is abbreviated as aW and is the decimal equivalent of the equilibrium relative humidity at the surface in question. For example, a water activity value of 0.8 is the same as an equilibrium relative humidity of 80%. At high water activity values, moisture at the surface of a material is available to fungus and bacteria to support growth and reproduction.

wood moisture equivalent: the moisture level in any building material as if it were in close contact and in moisture equilibrium with wood, expressed as the equivalent moisture content of wood.

Note: Wood moisture equivalent is abbreviated as WME and can be used directly to establish if materials are in a dry, at risk, or damp condition as the critical percent moisture content thresholds for wood are known. WME is particularly useful not only for direct comparisons but when a material under evaluation is not directly accessible to the moisture meter.

4 INTRODUCTION TO THE FACTORS AND THEIR INTERACTIONS

In order to provide an acceptable indoor environment, it is necessary not only that each aspect of the environment be at a satisfactory level but also that the adverse impact of interactions between these aspects is limited. Four factors—indoor air quality (IAQ), thermal environment, acoustical environment, and visual environment—are widely regarded as the principal categories for classifying or characterizing the acceptability of an indoor environment. Each of these factors includes several separate aspects. For example, within the lighting factor are included the issues of luminance and illuminance levels, color temperature, color rendering ability, gradients or luminance ratios, discomfort glare, and disability glare. The number of possible interactions among the four factors and their several aspects, especially moisture, is therefore very large. This guideline provides a framework based on the limited available knowledge for considering these interactions and draws attention to the ones that are currently considered to be the most important.

Occupant experiences of and responses to the indoor environment may also be strongly affected by a variety of additional considerations that are not considered to be among the four major indoor environmental factors. Although many of these are subjective and are difficult to characterize quantitatively, they may actually dominate individual reactions to a space. These characteristics or factors include, among others, the ergonomics of the workplace; the time of day and season of the year; the occupant density; the proximity of other occupants; privacy and security; spatial qualities (volume, shape); the presence of windows and views to the outdoors; contextual understanding of the space, including logical "wayfinding" and freedom of movement; and the aesthetic qualities and cultural associations of the space. While these considerations are not addressed directly in this guideline, users of the guideline should be aware that one or more of them can have significant or even dominant effects on the acceptability of the indoor environment no matter the characteristics of the factors addressed herein. There is a growing body of literature that addresses these additional considerations, especially in the field of environmental psychology.

4.1 The Four Factors and Building Design.

There can be interactions among the four main factors that were unanticipated during building design or refurbishment. For example, to limit temperature fluctuation and improve the thermal environment, it may be decided to make use of the thermal storage provided by interior surfaces of high thermal capacity (thermal mass), such as exposed masonry ceilings or hard floors which are also susceptible to condensation. But high-capacity materials can be deficient in sound absorption and so produce an unacceptable acoustical environment. If the acoustical engineer then recommends covering these surfaces with sound-absorbent materials, an unsatisfactory thermal environment may result. Materials with increased sound absorption often have increased absorption of moisture which can lead to microbial growth and release of VOCs. Likewise, buildings may be designed to make use of natural ventilation through operable windows both to control indoor temperature and maintain IAQ. If the outdoor environment is excessively noisy, ~~or~~ polluted, or humid, however, people will not open the windows, and both the indoor thermal environment and the air quality will be poor. Design and construction solutions to control one environmental variable may therefore result in problems in another variable.

To further illustrate this, acoustical control is often accomplished with high-surface-area materials ("fleecy" materials such as carpet, fibrous or highly textured ceiling tiles, and textiles) for interiors. This conflicts with what some consider to be the ideal IAQ solution of hard, durable, non-porous surface materials to reduce emissions of volatile organic compounds (VOCs) from the materials and to reduce "sink effects" (adsorption on surfaces) that lead to subsequent secondary emissions. Smooth surfaces are also more easily cleanable. So, if designs are to produce satisfied occupants, solutions to the acoustical environmental problem must account for the IAQ implications, and the air quality solutions must consider the acoustical environmental implications.

IAQ, thermal environment, acoustical environment, and visual environment are all interconnected in the indoor environment. An effective design process integrates the numerous considerations across factors and aspects to produce a total indoor environment acceptable to occupants. Building designers should therefore consider potential conflicts at an early stage of design or refurbishment so that an indoor environment can be provided that is acceptable with regard to all four main factors and their interactions while—in line with ASHRAE policy—making minimal demands on energy and environmental resources.

The combination of architecture and mechanical/electrical design of buildings will normally serve to define the performance of the interior spaces, and it is important to have a high level of occupant satisfaction with the building indoor environmental quality (IEQ) factors. Traditionally, visual aspects of design have been the leading factors in decision making on architecture, and now green performance, climate, and moisture management ~~is~~ are becoming ~~an~~ increasingly influential factors. The challenge is to find compatibility between aesthetic, green, climate, moisture, and other environmental qualities to ensure a healthy, comfortable, and productive environment for the building occupants and users.

Efforts to make buildings more energy efficient often incorporate improved insulation of the envelop, improvements to windows, and reductions in uncontrolled infiltration in the building that leads to tighter buildings with significantly lower cooling and heating loads. As a result, humidity control becomes more important especially in the warm and humid climates typical for the eastern United States. Traditional condensing technologies are designed to primarily remove sensible loads. As a result, DX units often need to reheat highly humid air, especially during unoccupied periods. Absorption based desiccant technologies can improve moisture management in buildings by allowing for moisture removal without cooling down the building and thereby deliver air with lower relative humidity levels of about 50% (70Fdb, 55Fdp).

Occupant satisfaction surveys such as those reported by Huizenga et al. (2006) indicate that normal building design/construction/operation have not been entirely successful relative to occupant satisfaction for several of the primary IEQ factors. This is confirmed by the results of more than 400 building surveys encompassing more than 45,000 building occupants (Brager and Baker 2009), summarized in Figure 1.

As Figure 1 shows, indoor environmental performance is often less than desirable, which suggests that design professionals should pay specific attention to each of the four main factors as well as to their interactions to ensure better performance in future building design.

Studies also show that higher humidity and higher levels of pm2.5 that can significantly impact health do not necessarily reduce occupant reported satisfaction (Allen et al. 2015). Research shows significant links between unplanned, sickness related absenteeism and especially dry conditions during flu periods. Low ventilation is also correlated with reduced decision making quality and other cognitive factors. Even small effects can have a significant impact on performance of people in the space with an impact several times that of the total energy cost (Colton et al. 2014; NRC 2007; Singh et al. 2010).

4.3 Acceptability and Human Adaptability. People are not passive receptors of their environment but interact continuously with it. Given the opportunity, people will adjust themselves to their environment and their environment to themselves. Problems associated with the interactions among the factors and of aspects within each factor can therefore sometimes be circumvented by providing the occupants suitable control over their environment. People then perform their own optimization, balancing one factor against another, as their requirements vary from time to time and from task to task.

For example, consider the thermal environment. The principal aspects within this factor are the temperature of the air, thermal radiation from surrounding surfaces, and the movement of the air and its moisture content (specific humidity), while the principal personal aspects are relative humidity, the thermal insulation of the clothing, the degree of activity, and the physiological status of the individual. Providing control for local air temperature, air movement, or thermal radiation and adequate freedom in the choice of clothing will usually ensure thermal satisfaction. People establish their own optimization, balancing the several aspects of the thermal environment. The balance chosen may differ from person to person and may vary with the time of day or the climate and culture, and it may be that once a satisfactory balance is established, no further adjustments take place. Nevertheless, the awareness that controls are available for use could be important for overall satisfaction.

4.5 Human Response to the Environment: Physiological and Psychological Interactions. The main environmental factors directly affect the human body, and their physiological effects may be perceived by the occupants. How these perceptions are interpreted will affect the acceptability of the environment and may result in physiological responses, whose perceptions and interpretations may further affect the acceptability of the environment. A perception can therefore modify an occupant's interpretation and consequent response to the environment whether or not the perception is correctly attributed to its actual cause.

To illustrate, consider a person who has a headache. People often tend to blame a headache on something that is causing them stress, whether physical or psychological. In fact, headaches can arise from either physical or psychological causes—or from both simultaneously. Headaches can result from glare, eye strain, noise, air contaminants, or thermal conditions, as well as from medical conditions, psychological and social conditions such as anxiety, stressful interpersonal relationships, or stressful work. Stress can exacerbate the effects of almost any environmental factor and cause otherwise normally acceptable environmental conditions to degrade occupant comfort and well-being.

Prior exposure also modifies the human response to the environment. For example, newborn infants react with increased heart rates the first six to eight times they are exposed to a new odorant, but upon subsequent exposures their heart rates remain normal. Time can also modify responses. Humans, upon first being exposed to an odor they find unpleasant, perceive it strongly, but over the course of 15 minutes the intensity generally is perceived as declining. This is an adaptation effect that is not uncommon with odors. In contrast, irritants work the other way around: their effects tend to increase with extended exposure. Thus, a chemical or chemical mixture not found unpleasant, annoying, or irritating upon entry into a space may, after only a short time, become an important parameter that makes the environment less acceptable.

In addition to considering the four main environmental factors—IAQ, thermal environment, acoustical environment, and visual environment—it is necessary, when exploring their effects, to consider the physiological and the psychological dimensions of each. Some authors identify social and institutional factors separately from psychological factors. These factors mediate human responses through psychological mechanisms. For example, occupants' attitudes toward other occupants (employers, supervisors, peers) can create stress that can alter the body's normal reactions to the environment.

A Yale study by Kudo identified links between relative humidity levels indoors and the human respiratory system. The mucus barrier and ciliary clearance of the respiratory system, and the response by T and B cells, protect against infection and more severe disease resulting from the flu. (Kudo, Arundel et al).

It is important to note physiological and psychological factors, for not only are occupants likely to influence their environments by purposeful behavioral adaptations, but there are also responses at a less deliberate level. The body heat, ~~moisture~~ perspiration, and odor emissions from occupants affect the temperature, humidity, and quality of the air; if sound absorption is increased people tend to converse more quietly, further reducing the sound pressure levels. There are certainly characteristics of indoor environments that are appropriate or even desirable for certain occupancy types that may make another occupancy type unacceptable. Loud music or conversation, the odor of alcohol, or other characteristics of a typical night club would be unwelcome in a classroom or office. The preferred temperature for a gymnasium differs from that of a conference room.

4.8 Limits to Reliance on Existing Standards and Previous Guidelines. Because of their combined effects on the diverse population of building occupants, interactions among the factors can sometimes result in unacceptable IEQ even where the design conforms to the standards and guidelines for the four major environmental factors. For example, an odor that may be acceptable when thermal conditions are cool and dry may be annoying or even sickening when thermal conditions are warm and humid but still within the thermal comfort zone. Particles that may not be annoying when relative humidity is at normal levels may be irritating to the eyes or upper respiratory tract when relative humidity is very low.

5.1.1 The PMV Index. The principal aspects of the thermal environment that affect the subjective warmth of the occupant are the temperature, speed, and relative humidity of the air and the thermal radiation exchange between the occupant and the surroundings. The principal "personal" thermal aspects are the level of physical activity and the thermal insulation of the clothing. ASHRAE Standard 55 (ASHRAE 2020a) combines all these aspects in the Predicted Mean Vote (PMV) index, which is a numerical value on a seven-point scale of subjective warmth. The PMV index quantifies the offsetting of one thermal aspect against another, thus incorporating their interactions on the basis of their effect on human heat exchange.

5.1.4 Interaction between Metabolism and Thermal Environment. The metabolic rate is similarly responsive to the thermal environment, for in warm weather people tend to eat less and expend less energy than in cool weather. This interaction is benign, resulting in satisfaction with environments that might otherwise have been unacceptable.

Because it is difficult to evaluate this change in activity level, it tends to be disregarded, and hence subjective warmth is often overestimated in warm environments (see, for example, de Dear and Brager [1998] and Humphreys and Nicol [2002]). It may also be that people in buildings whose interior temperatures vary in harmony with seasonal outdoor temperatures have different qualitative expectations of their environments than those in conventionally air-conditioned buildings. Since 2004, ASHRAE Standard 55 has provided an additional method for use in naturally ventilated office buildings in warm weather. See also European Standard 15251 (EN 2007) and the Chartered Institute of Building Ser-vices Engineers' Guide A, Environmental Design (CIBSE 2006).

The PMV index works best when assessing the effects of the interactions of the various thermal aspects in moderate indoor temperatures with low air movement (Humphreys and Nicol 2002). To assess the effects of the thermal interactions on the acceptability of higher temperatures with substantial air movement, particularly if the relative humidity is high, an alternative index such as the Standard Effective Temperature (SET) index (ASHRAE 2021, Chapter 9) may be preferred. Values of the thermal sensation predicted by either index can be calculated using the CBE Thermal Comfort Tool (CBE 2022). Figure 2 shows paired evaluations for thermal environments drawn from the ASHRAE database of field studies of thermal comfort (de Dear and Brager 1998). Each point represents a separate indoor environment. Those environments assessed as neutral or warmer by either method have been included (0 = neutral, 1 = slightly warm, 2 = warm, 3 = hot). The scatter is attributable to the different quantifications of the interactions by the two indices.

Air movement is included in PMV as an interaction among the thermal factors. Increasing the ventilation rate to improve air quality will often change the pattern and speed of the air currents in the space, which may affect the acceptability of the environment. Natural ventilation as a thermal comfort strategy will impact IAQ. Natural ventilation as an IAQ strategy will impact the thermal environment.

5.2.2 Temperature and Perception of Air Quality. The sense of smell is more acute at warmer temperatures, so both pleasant and unpleasant odors become more perceptible. Substantial research has shown that changes in the thermal environment can cause changes in perceptions of the air quality. Changes in temperature or relative humidity affect human responses to, and perceptions of, the chemical content of the air. Several laboratory studies have found that subjects describe air as more stuffy, odorous, and stale when the air temperature is elevated, the relative humidity is increased, or both (Berglund and Cain 1989; Fang et al. 1998a, 1998b, 1999). This relationship holds true at both low activity levels and at the levels attained when walking or jogging (Berglund and Cain 1989).

Berglund and Cain (1989) investigated the effect on perceived air quality (freshness, stuffiness, and acceptability) of 20 subjects at 2°C, 11°C, and 20°C (36°F, 52°F, and 68°F) dew-point temperatures at air temperatures of 20°C, 24°C, and 27°C (68°F, 75°F, and 81°F) while holding air quality constant. Their results (see Figures 3 through 5) indicate that subjective comfort depends "upon almost all perceptible influences." Temperature and humidity influenced not only thermal comfort but also the "perception of the chemical quality of the air." Contaminant concentrations influenced subjective judgments of air quality, "but in some instances, may actually prove secondary to temperature and humidity." Changes of 0.5°C (1°F) typically "had the same effect" on perceived air quality as changes of 3°C (6°F) in dew point temperature. Temperatures greater than approximately 26°C (79°F) produced significant decrements in perceived IAQ.

Subsequent investigations by Fang et al. (1998a, 1998b, 1999) have confirmed the findings of Berglund and Cain (see Figure 6). One study by these authors (1998a) found that the perception of odor intensity during facial exposure did not change significantly with changing air temperature and humidity. These same researchers (1998a, 1998b, 1999) found a strong effect of temperature and humidity on the acceptability of the air. All of these studies confirmed that acceptability of air linearly increased with decreasing enthalpy of the air.

A 1°C (0.5°F) increase in dry-bulb temperature has approximately the same effect on perception of air quality as a 5% increase in relative humidity (Berglund and Cain 1989; Fang et al. 1998a).

These laboratory-based findings have yet to receive confirmation in the field. Analysis of perceived air quality from respondents in a large year-round study of the environment in offices in France, Greece, Portugal, Sweden, and the United Kingdom found that perceived air quality was related to the subjective thermal state of the respondent rather than to the actual temperature and humidity, the enthalpy of the air, or the concentration of CO_2, an indicator of the outdoor air ventilation rate in relation to total human metabolic activity. Those who successfully adapted thermally to warmer room temperatures did not report deterioration in perceived air quality (Humphreys et al. 2002).

Implications: In summary, in mechanically ventilated spaces, as the temperature becomes uncomfortably warm, people may perceive the IAQ as less acceptable.

5.2.4 Hygro-Thermal Conditions and Biological Contaminants. Thermal conditions strongly affect the potential survival, growth, and distribution of microbial contaminants in indoor environments. Cold surfaces, for example, are susceptible to condensation, which can contribute to microbial growth. The higher the ~~air humidity,~~ dew point temperature the higher the potential water activity (aW) at the surface. ~~, and water activity is, by definition, a strong determinant of the ability of a surface to support microbial growth.~~ At high water activity values, moisture at the surface of a material is available to fungus and bacteria to support growth and reproduction. The water activity level is not measured directly but is a function of the ~~air~~ specific humidity and the moisture content of the material immediately below the surface (Prezant et al. 2008; Harriman et al. 2001).

Providing a comfortable thermal environment may result in pressure differences among various spaces within a building, resulting in migration of gases and particles from one space to another. The movement may be horizontal, vertical, or both. Movement is normally from areas of higher pressure to those of lower pressure. Most mechanically ventilated commercial buildings are designed to be intentionally pressurized relative to the outdoors to prevent unwanted intrusion of unconditioned/contaminated air from outdoors from entering through cracks or other gaps in a building enclosure. Humid outdoor air may enter and condense on interior surfaces, ultimately leading to microbial growth, deterioration of building materials, and occupant health effects.

Indoor air often has higher ~~moisture content (absolute humidity)~~ specific humidity than outdoor air in cold climates. In cold climates, water vapor in heated buildings tends to migrate through the materials of the building envelope toward the outdoors. Moisture migration in the opposite direction can occur when buildings are cooled and dehumidified in warm humid climates. Condensation and elevated specific humidity, ~~of the moisture~~ as it migrates through the envelope assemblies, can result in increased moisture content and water activity of cellulosic materials, resulting in mold growth and decay of building materials (ASHRAE 2020c, ASHRAE 2021b). The increased moisture content of the inaccessible interior materials of the building envelope is described as the wood moisture equivalent (WME) based on that of the interior and exterior assessable materials. ~~Moisture migration in the opposite direction can occur when buildings are cooled and dehumidified in warm humid climates.~~

Implications: Microbial organisms—fungi, bacteria, and viruses—are among some of the most significant contaminants of indoor air (dust mites and especially their feces are also important, although presumably more so in residences than in nonresidential environments). The absence of these organisms at harmful concentrations is a criterion for acceptability. There is a lack of specific guidelines on acceptable or harmful concentrations. ~~It is current practice to compare indoor concentrations to outdoor concentrations and consider indoor levels above outdoor levels as an indicator of a source or amplification site in the building.~~ ~~This~~Microbial amplification is the result of ~~is usually accompanied by~~ excessive moisture in the building, either from leaks or spills or from condensation. Eliminating the moisture source will reduce or eliminate the growth of these organisms indoors. Careful attention to the pressure relationships between a building and the outdoors as well as the differences between spaces is important to avoid unwanted movement of contaminants.

5.2.5 Humidity and Particulate Matter. As the ~~absolute~~ specific humidity of the air decreases (more commonly determined by measuring relative humidity), so do upper respiratory defense mechanisms based on bodily tissue moisture and mucociliary removal action. Particles then may penetrate deeper and stay longer, resulting in increased effects for a given particle concentration. The irritation and discomfort of "dry nose," "dry throat," "itchy nose," and "scratchy throat" feelings, as well as effects on other mucous-membrane-protected surfaces (such as the eye), are potentially exacerbated by low humidity (Wyon 1991) or higher chemical concentrations in the air (Sundell 1994). Also, drier air will result in reduction in airborne particle size and mass of particles generated by exhaled breath, talking, coughing, and sneezing, resulting in longer airborne suspension times and greater likelihood of particles being inhaled (WHO 2009).

5.2.6 heating Equipment and Particulate Matter. The breakdown of dust into finer particles on contact with heating elements may result in more irritation for occupants. There is increasing concern about very small particles because they can penetrate more deeply into the respiratory tract (Institute of Medicine 2000). It is now believed that they may carry chemicals adsorbed on their surfaces and deliver these chemicals to the lung, where they can cross into the bloodstream. Some of the types of chemicals of concern are known or believed to be quite odorous, irritating, or even toxic. As an example of this process, consider the odorous component (gaseous phase chemicals) of cigarette ash residue in an ashtray. The effect of heating particles can also result in the generation of particles made more odorous from partial combustion or singeing effects.

Implications: The designer of a mechanical ventilation system should consider a higher efficiency filter (such as MERV 13) for heated spaces designed for operation at low relative humidity (e.g., <20% RH). MERV is the Minimum Efficiency Reporting Value—a single-number designation derived from the composite curve data product of ASHRAE Standard 52.2, *Method of Testing General Ventilation Air Cleaning Devices for Removal Efficiency by Particle Size* (ASHRAE 2017). The test method determines the minimum efficiency of particulate filters at 12 specific particle size fractions ranging from 0.3 µm, or microns, to 10 µm. The MERV 13 level of efficiency is necessary to control the smaller particles (0.3–1 µm) that impact human health. Refer to Chapter 12, "Air Contaminants," in *ASHRAE Handbook—Fundamentals* (ASHRAE 2021b) and Chapter 28, "Air Cleaners," in *ASHRAE Handbook—HVAC Systems and Equipment* (ASHRAE 2020b) for more fundamental information on gaseous and particulate contaminants.

6.1 interactions. There are usually hundreds of organic compounds in most indoor environments. While none of these individual compounds might exceed concentrations known to cause odor, irritation, or toxicity, in some cases, combinations of chemicals may have adverse effects that are not indicated by their individual properties.

It may be necessary, under normal conditions of temperature and humidity, to modify the operational procedures of the ventilation system to increase ventilation or to modify the system to provide more ventilation to accommodate these interactive effects. If outdoor specific humidity is high, then introducing more outdoor air requires control of the dew point temperature indoors ~~humidity~~ to limit its potential contribution for microbial growth by preventing condensation~~, or~~ and control of relative humidity for ~~to~~ occupant discomfort. In the case of low outdoor ~~air~~ specific humidity, increasing outdoor airflow may result in a very dry environment with various potential effects on occupants and on the electrostatic environment. In very cold climates, bringing in too much outdoor air can result in very dry indoor air and potential eye, skin, and throat irritation (Jaakkola et al. 1991a, 1991b). Finally, if volatile organic compounds (VOCs), inorganic pollutants, or particle concentrations are higher outdoors than indoors, increasing ventilation will increase indoor concentrations of these pollutants.

6.2 Control of Pollutant Sources and Ventilation to Remove Pollutants. Indoor sources of pollutants include occupants, building materials, interior finishes, furnishings, equipment, maintenance products and procedures, and consumer products. Outdoor sources include combustion products, agricultural processes, and exhaust from neighboring buildings and vehicles. These and other factors affect the quality and ~~moisture content~~ specific humidity of the outdoor air, which in turn affect the quality of the indoor air via ventilation and infiltration.

The irritation potential, odor, and toxicity of indoor air vary greatly. It is widespread practice to measure certain characteristics of indoor air in order to infer whether it is healthy or acceptable. But because of potential interactions among the constituents of air and the potential for interactive effects (additive, synergistic, or prophylactic), it is not possible to determine all or even most of the impacts of indoor air directly from measured concentrations. It is evident that there are potentially important chemical compounds and bioaerosols in indoor air that are not measured or measurable. It has also been difficult to correlate low concentrations of many pollutants directly with occupant health effects. Finally, the concentrations of individual chemicals known to cause human health and comfort effects provide little guidance on the effects of the mixtures of hundreds of chemicals usually present in indoor air.

ASHRAE addresses IAQ in Standard 62.1, *Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2019a), and Standard 62.2, *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings* (ASHRAE 2019b). The primary methodology employed in these standards is to establish requirements for ventilation believed adequate to provide what is defined as acceptable IAQ for the majority of adapted occupants of a space or by specifying that a substantial majority of occupants should find the IAQ "acceptable." Thus, ASHRAE Standard 62.1 does not purport that following its requirements provides acceptable IAQ to visitors to a space. This is because visitors may not accept an odor that has become less noticeable—and therefore more acceptable—to occupants who have been in a space for some period of time. The Ventilation Rate Procedure of Standard 62.1 does not include visitors. However, the IAQ Procedure of Standard 62.1 does provide for using the standard for visitors, which is important in certain occupancy types (such as shops).

The requirements of ASHRAE Standards 62.1 and 62.2 also include certain design features intended to avoid or mitigate potential sources of indoor air pollutants. However, Standards 62.1 and 62.2 do not specify the chemical, physical, or biological contents of the indoor air that meet its definition of what is acceptable. Instead, these standards are based on engineering judgment and laboratory and field studies of subjects' evaluations or ratings of air quality in terms of its acceptability based on assumed sources and source strengths as well as various ventilation rates. Clearly, such studies differ from actual field experience in that all factors in the studies except the air quality are held constant. In practice, while IAQ varies, other factors such as thermal conditions, sound and vibration conditions, and illumination may vary as well. Also, such studies are often done with subjects who are reasonably healthy and not known to be particularly sensitive to indoor air pollutants. Furthermore, as other conditions vary, even if ventilation and sources remain the same, contaminant concentrations may vary as well as occupant responses to the perceived air quality or its impacts on human physiology.

6.3.5 Formaldehyde and Other Indoor Air Pollutants. Low-level concentrations of formaldehyde and VOCs not known to cause irritation and other Sick Building Syndrome (SBS) complaints alone often do cause such complaints when present together. More than 80% of the most common indoor air pollutants identified during the late 1970s and early 1980s in buildings and in laboratory studies of emissions from materials were classified by Mølhave (1982) as mucous membrane irritants. This finding can be explained if some compounds act synergistically; it appears plausible if they act in a roughly additive fashion. Note that the VOCs listed by Mølhave as irritants and the concentrations at which they are found have changed dramatically since the original research. Some of the most toxic chemicals are found less commonly, and most of the chemicals are found at lower concentrations than in the 1970s and 1980s (Hodgson and Levin 2003a). Nevertheless, as some chemicals have been eliminated or their concentrations reduced, new chemicals have appeared to replace them functionally in the products from which they were emitted. The concentrations are often lower, but the health implications are unknown.

Implications: Designers should strive to use low-emitting materials in buildings. This is a form of source control and is usually both cost-effective and easily achievable. *Low-emitting materials* refers to products that have been formulated to emit little to no VOCs after installation. Information on low-emitting materials can be found in Objective 5 of *Indoor Air Quality Guide: Best Practices for Design, Construction, and Commissioning* (ASHRAE 2009).

Emissions of VOCs from most materials are strongest when they are new and decrease dramatically over time, but many emissions continue at lower levels for months and even years. Ventilation affects emission rates, and increased ventilation is associated both with higher emissions and with lower airborne concentrations. Extra ventilation during the early life of new materials accelerates the emissions decay process.

Where materials are replaced in existing buildings, the replacement work should be performed during unoccupied periods and with maximum outdoor air ventilation. Designers should recommend that operators run the HVAC system on all outdoor air in order to flush out pollutants prior to new or renovated buildings being occupied. A flush-out typically occurs for four days to a week, although the length of the flush-out depends on the amount of outdoor air that can be supplied and properly conditioned for acceptable indoor <u>thermal</u> temperature, <u>specific humidity, and dew point temperature</u>. ~~and humidity.~~ Flushing out to achieve 100 complete air changes might be a more useful guideline. The number of hours is less important than the total number of air changes after the application of new finishes and before occupancy or re-occupancy. (Tichenor 1996).

6.6 Indoor Air Quality—Acoustical Environment. The primary ways to achieve IAQ include the use of ventilation, either mechanically with equipment or passively through window openings. Mechanical ventilation is often accompanied by the noise of fans, airflow through duct elbows and branches, mixing boxes, dampers, and diffusers or even the sounds of air leakage from the ductwork or other system components. This HVAC noise will generally be dominated by low-frequency sound, which may in extreme cases induce secondary vibration in walls, floors, and other surfaces (in addition to that caused by improperly isolated or mounted equipment). See *Indoor Air Quality Guide: Best Practices for Design, Construction, and Commissioning* (ASHRAE 2009) for a more detailed discussion.

If ventilation equipment is noisy, it may not be used as intended by the designer. For example, teachers tend not to operate noisy unit ventilators in their classrooms, resulting in reduced outdoor air ventilation and increased indoor source pollutants. Home occupants tend not to operate noisy bathroom or kitchen fans, resulting in a buildup of <u>all aspects of</u> moisture, combustion gases, or other products and by-products of activities conducted in the home. Because of this interaction, Standard 62.2 (2019b) requires quiet fans to achieve its IAQ objective.

Passive control of IAQ is often attempted with the use of operable windows. Opening windows to “get some fresh air” may not be an option where noise enters a space from outdoors. In busy urban areas or areas adjacent to highways, railways, airports, playgrounds, or factories, the ambient noise levels can deter people from opening windows. But it should be recognized that the primary purpose of a window is to let daylight in while providing visual relief by making it possible for occupants to see outside. It is not necessary to use operable windows to allow outdoor air entry; an acoustical plenum or acoustical louvers can be used in conjunction with a window (above, below, or to the side) to allow outdoor air entry without allowing noise to enter.

---

9. REFERENCES AND BIBLIOGRAPHY

The following sources were either cited in this guideline or consulted by the project committee in the preparation of this guideline.

Abraham, M.H., R. Sanchez-Moreno, J.E. Cometto-Muniz, and W.S. Cain. 2007. "A Quantitative Structure– Activity Analysis on the Relative Sensitivity of the Olfactory and the Nasal Trigeminal Chemosensory Systems." *Chemical Senses* 32(7):711–19.

Apte, M.G., I.S.H. Buchanan, and M.J. Mendell. 2007. "Outdoor Ozone and Building Related Symptoms in the BASE Study." Lawrence Berkeley National Laboratory Report 62419 (February 21).

Arens, E., M.A. Humphreys, R. de Dear, and H. Zhang. 2010. "Are 'Class A' Temperature Requirements Realistic or Desirable?" *Building and Environment* 45(1):4–10.

Arundel AV et al. Indirect health effects of relative humidity in indoor environments. Environ Health Perspect. 1986 Mar;65:351-61. doi: 10.1289/ehp.8665351. PMID: 3709462; PMCID: PMC1474709. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1474709/)

ASA. 2020. ANSI/ASA S12.60 Part 1-2010 (R2020), *Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools*. Melville, NY: Acoustical Society of America.

ASHRAE. 2009. *Indoor Air Quality Guide: Best Practices for Design, Construction, and Commissioning*. Peachtree Corners, GA: ASHRAE.

ASHRAE. 2017. ANSI/ASHRAE Standard 52.2, *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*. Peachtree Corners, GA: ASHRAE.

ASHRAE. 2019a. ANSI/ASHRAE Standard 62.1, *Ventilation for Acceptable Indoor Air Quality*. Peachtree Corners, GA: ASHRAE.

ASHRAE. 2019b. ANSI/ASHRAE Standard 62.2, *Ventilation and Acceptable Indoor Air Quality in LowRise Residential Buildings*. Peachtree Corners, GA: ASHRAE.

ASHRAE. 2019c. *ASHRAE Handbook—HVAC Applications*. Peachtree Corners, GA: ASHRAE.

ASHRAE. 2020a. ANSI/ASHRAE Standard 55, *Thermal Environmental Conditions for Human Occupancy*. Peachtree Corners, GA: ASHRAE.

ASHRAE. 2020b. *ASHRAE Handbook—HVAC Systems and Equipment*. Peachtree Corners, GA: ASHRAE.

ASHRAE 2020c. ASHRAE MTG *Damp Buildings, Human Health, and HVAC Design.*

ASHRAE. 2021a. *ASHRAE Handbook—Fundamentals*. Peachtree Corners, GA: ASHRAE.

ASHRAE. 2021b. ASHRAE Position document: *Limiting Indoor Mold and Dampness in Buildings*.

ASHRAE. 2022. *Position Document on Indoor Carbon Dioxide*. Peachtree Corners, GA: ASHRAE. www.ashrae.org/file%20library/about/position%20documents/pd_indoorcarbondioxide_2022.pdf.

Bailey, S.M., U.S. Udoh, M.E. Young. 2014. Circadian regulation of metabolism. *J Endorinol.* 222(2):R75–96.

Baker, D.B. 1989. “Social and Organizational Factors in Office Building-Associated Illness.” In *Occupational Medicine: State of the Art Reviews,* vol. 4*, Problem Buildings: Building Associated Illness and the Sick Building Syndrome*, pp. 607–25. eds. J.E. Cone and M.J. Hodgson. Philadelphia: Hanley & Belfus.

Bakó-Biró, Z., P. Wargocki, C.J. Weschler, and P.O. Bakó-Biró. 2004. “Effects of Pollution from Personal Computers on Perceived Air Quality, SBS Symptoms and Productivity in Offices.” *Indoor Air* 13:178–87. Bekö, G., G. Clausen, and C.J. Weschler. 2007. “Further Studies of Oxidation Processes on Filter Surfaces: Evidence for Oxidation Products and the Influence of Time in Service.” *Atmospheric Environment* 41:5202–12.

Bekö, G., G. Clausen, and C.J. Weschler. 2008. “Sensory Pollution from Bag Filters, Carbon Filters and Combinations.” *Indoor Air* 18:27–36.

Berglund, L.G., and W.S. Cain. 1989. “Perceived Air Quality and the Thermal Environment.” *IAQ 89, The Human Equation: Health and Comfort*, pp. 93–99.

Berglund, B., and T. Lindvall. 1990. “Sensory Criteria for Healthy Buildings.” *Indoor Air ’90: Proceedings of the Fifth International Conference on Indoor Air Quality and Climate* 5:65–79.

Bingham, E., and H.L. Falk. 1969. “Environmental Carcinogens: the Modifying Effect of Cocarcinogens on Threshold Response.” *Archives of Environmental Health* 19:641–61.

Bluyssen, P.M., O. Fernandes, E. Groes, G. Clausen, P.O. Fanger, O. Valbjorn, C.A. Bernhard, and C.A. Roulet. 1996. “European Indoor Air Quality Audit Project in 56 Office Buildings.” *Indoor Air* 6:221–38.

Boyce, P.R., J.A.Veitch, G.R. Newsham, C.C. Jones, J. Heerwagen, M. Myer, and C.M. Hunter. 2006. “Occupant Use of Switching and Dimming Controls in Offices.” *Lighting Research and Technology* 38(4):358–78.

Brager, G.S., and L. Baker. 2009. “Occupant Satisfaction in Mixed-Mode Buildings.” *Building Research & Information* 37(4):369–80.

Cain, W. S. 2002. “The Construct of Comfort: A Framework for Research.” *Indoor Air 2002: Proceedings of the Ninth International Conference on Indoor Air Quality and Climate* 2:12–20.

Cain, W.S., and R. Schmidt. 2009. “Can We Trust Odor Databases? Example of tand n-Butyl Acetate.” *Atmospheric Environment* 43:2591–601.

CBE. 2022. CBE Thermal Comfort Tool. University of California-Berkeley, Center for the Built Environment. comfort.cbe.berkeley.edu.

CIBSE. 2006. *Guide A, Environmental Design*. London: Chartered Institute of Building Services Engineers. Cometto-Muñiz, J.E., and W.S. Cain. 1994. “Perception of Odor and Nasal Pungency from Homologous Series of Volatile Organic Compounds.” *Indoor Air* 4:140–45.

de Dear, R.J., and G.S. Brager. 1998. “Developing an Adaptive Model of Thermal Comfort and Preference.” *ASHRAE Transactions* 104(1):145–67.

Devos, M., F. Patte, J. Rouault, P. Laffort, and L.J. van Gemert. 1990. *Standardized Human Olfactory Thresholds*. Oxford: IRL Press at Oxford University Press.

Dravnieks, A., and H.J. O’Neill. 1979. “Annoyance Potentials of Air Pollution Odors.” *American Industrial Hygiene Association Journal* 40:85–95.

EN. 2007. European Standard 15251, *Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics*.

Fang, L., G. Clausen, and P.O. Fanger. 1998a. “Impact of Temperature and Humidity on the Perception of Indoor Air Quality.” *Indoor Air* 8:80–90.

Fang, L., G. Clausen, and P.O. Fanger. 1998b. “Impact of Temperature and Humidity on Perception of Indoor Air Quality During Immediate and Longer Whole-Body Exposures.” *Indoor Air* 8:276–84.

Fang, L., P. Wargocki, T. Witterseh, G. Clausen, and P.O. Fanger. 1999. “Field Study on the Impact of Temperature, Humidity and Ventilation on Perceived Air Quality.” *Indoor Air ’99: Proceedings of the Eighth International Conference on Indoor Air Quality and Climate* 2:107–12.

Fountain, M.E., and C. Huizenga. 1996. “A Thermal Comfort Prediction Tool.” *ASHRAE Journal* 38(9):39–42. Hatori, M., and S. Panda. 2010. The emerging roles of melanopsin in behavioral adaptation to light. *Trends Mol. Med*. 16(10):435–46.

Harriman, L., G. Brundrett, and R. Kittler. 2001. *Humidity Control Design Guide for Commercial and Institutional Buildings*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Heschong, L. 1979. *Thermal Delight in Architecture*. Cambridge: MIT Press.

Heschong, L. 2021. *Visual Delight in Architecture: Daylight Vision, and View*. Milton Park, UK: Routledge. Heschong Mahone Group. 2003. “Windows and Offices: A Study of Office Worker Performance and the Indoor Environment: Technical Report.” California Energy Commission Report P500-03-082-A-9.

Hinkle, L.E., and W.C. Loring. 1977. *The Effect of the Man-Made Environment on Health and Behavior* (DHEW Publication No. CDC 77-8318.) Atlanta: Centers for Disease Control, Public Health Service. Hodgson, A.T., and H. Levin. 2003a. "Volatile Organic Compounds in Indoor Air: A Review of Concentrations Measured in North America since 1990." LBNL Report 51715. Berkeley: Lawrence Berkeley National Laboratory.

Hodgson, A.T., and H. Levin. 2003b. "Classification of Measured Indoor Volatile Organic Compounds Based on Noncancer Health and Comfort Considerations." LBNL Report 53308. Berkeley: Lawrence Berkeley National Laboratory.

Hodgson, M.J., E. Permar, G. Squire, W. Cagney, A. Allen, and D.K. Parkinson. 1987. "Vibration as a Cause of 'Tight Building Syndrome' Symptoms." *Indoor Air '87:Proceedings of the Fourth International Conference on Indoor Air Quality and Climate* 2:449–53.

Huizenga, C., S. Abbaszadeh, L. Zagreus, and E. Arens. 2006. "Air Quality and Thermal Comfort in Office Buildings: Results of a Large Indoor Environmental Quality Survey." *Proceedings of Healthy Buildings 2006* 3:393–97.

Humphreys, M.A., and J.F. Nicol. 2002. "The Validity of ISOPMV for Predicting Comfort Votes in EveryDay Thermal Environments." *Energy and Buildings* 34:667–84.

Humphreys, M.A., J.F. Nicol, and K.J. McCartney. 2002. "An Analysis of Some Subjective Assessments of Indoor Air Quality in Five European Countries." *Indoor Air 2002: Proceedings of the Ninth International Conference on Indoor Air Quality and Climate* 5:86–91.

Humphreys, M.A., J.F. Nicol, and I.A. Raja. 2007. "Field Studies of Thermal Comfort and the Progress of the Adaptive Model." *Advances in Building Energy Research* 1:55–88.

Innominato, P., V.P. Rocke, O.G. Palesh, A. Ulusakarya, D. Spiegel, and F.A. Levi. 2014. The circadian timing system in clinical oncology. *Ann. Med.* 46(4):191–207.

Institute of Medicine. 2000. "Dose Concepts." In *Clearing the Air: Asthma and Indoor Exposures*, p. 55. Washington, DC: Institute of Medicine, National Academy Press.

Jaakkola, J.J.K., O.P. Heinonen, and O. Seppanen. 1991a. "Mechanical Ventilation in Office Buildings and the Sick Building Syndrome: an Experimental and Epidemiological Study." *Indoor Air* 1:111–22.

Jaakkola, J.K.K., L.M. Reinikainen, O.P. Heinonen, A. Majanen, and O. Seppänen. 1991b. "Indoor Air Requirements for Healthy Office Buildings: Recommendations Based on an Epidemiologic Study." *Environment International* 17:371–78.

Jenkins, P., T. Phillips, and J. Waldman. 2004. "Environmental Health Conditions in California's Portable Classrooms." California Air Resources Board, Report to the California Legislature.

Kanikar, K., A.N. Carlson, and R. Yee. 2005. "Ocular Problems Associated With Computer Use." *Review of Ophthamology* 12(4):47–52.

Kiliccote, S., MA Piette, D. Watson, and G. Hughes, 2006. Dynamic controls for energy efficiency and demand response: Framework concepts and a new construction study case in New York. *Proceedings of ACEEE*, August, Lawrence Berkeley National Laboratory, Berkeley, CA.

Kudo et al. 2019 Low ambient humidity impairs barrier function and innate resistance against influenza infection doi: https://doi.org/10.1073/pnas.19028401;

Kunkel, D.A., E.T. Gall, J.A. Siegel, A. Novoselac, G.C. Morrison, and R.G. Corsi. 2010. Passive Reduction of Human Exposure to Indoor Ozone." *Building and Environment* 45:445–52.

Levin, H. 1995. "Physical Factors in the Indoor Environment." In *Effects of the Indoor Environment on Health*, *Occupational Medicine: State of the Art Reviews* 10(1), ed. J. Seltzer. Philadelphia: Hanley & Belfus, Inc.

Levin, H. 1996. "Design for Multiple Indoor Environmental Factors." *Indoor Air '96: Proceedings of the Seventh International Conference on Indoor Air Quality and Climate* 2:741–46.

Levin, H. 2008. "The Big Indoor Air Emissions Threat—Secondary Emissions." *Proceedings of SB08— World Sustainable Building Conference*, pp. 445–54.

Levin, H., and L. Duhl. 1984. "Indoor Pollution: Lighting, Energy and Health." In *Architectural Research*, ed. J. Snyder. New York: Van Nostrand Reinhold.

Lewy, A.J. 2015. Circadian rhythms and mood disorders: A guide for the perplexed. *J. Clin. Psychiatry* 76(5):e662–4.

Lewy, A.J., R.L. Sack, and C.M. Singer. 1985. "Immediate and Delayed Effects of Bright Light on Human Melatonin Production: Shifting 'Dawn and Dusk' Shifts the Dim Light Melatonin Onset (DLMO)." *Annals of the New York Academy of Sciences*, 453:253–59.

Long, C.M., H.H. Suh, and P. Koutrakis. 2000. "Characterization of Indoor Particle Sources Using Continuous Mass and Size Monitors." *Journal of the Air & Waste Management Association* 50:1236–50.

Lucas, R.J., S.N. Peirson, D.M. Berson, T.M. Brown, H.M. Cooper, C.A. Czeisler, M.G. Figueiro, P.D. Gamlin, S.W. Lockley, J.B. O'Hagan, L.L. Price, I. Provencio, D.J. Skene, G.C. Brainard. 2014. Measuring and using light in the melanopsin age. *Trends Neurosci.* 37(1):1–9.

Matthews, T.G., K.W. Fung, B.J. Tromberg, and A.R. Hawthorne. 1986. "Surface Emission Monitoring of Pressed-Wood Products Containing Urea-Formaldehyde Resins." *Environment International* 12:301–309.

Menzies, D., J. Popa, J.A. Hanley, T. Rand, and D.K. Milton. 2003. Effect of ultraviolet germicidal lights installed in office ventilation systems on workers' health and wellbeing: Double-blind multiple cross-over trial. *The Lancet* 362:1785–91.

Morrison, G.C. 2007. "Workshop on Interfacial Chemistry in Indoor Environments." University of California, Berkeley, CA, July 17–18. www.arb.ca.gov/research/apr/past/sa07-3002.pdf.

Morrison, G.C. 2008. "Interfacial Chemistry in Indoor Environments." *Environmental Science & Technology* May 15, pp. 3495–99.

Mølhave, L. 1982. "Indoor Air Pollution due to Organic Gases and Vapours of Solvents in Building Materials." *Environment International* 8:117–27.

Mølhave, L. 1987. "The Sick Buildings—A Sub-Population among the Problem Buildings?" *Indoor Air '87: Proceedings of the Fourth International Conference on Indoor Air Quality and Climate* 2:469–73.

Mølhave, L., Z. Liu, A.H. Jørgensen, O.F. Pedersen, and S.K. Kjærgaard. 1993. "Sensory and Physiological Effects on Humans of Combined Exposures to Air Temperatures and Volatile Organic Compounds." *Indoor Air* 3:155–69.

Mudarri, D., and W.J. Fisk. 2007. "Public Health and Economic Impact of Dampness and Mold." *Indoor Air* 17:226–35.

Nagata, Y. 2003. "Odor Intensity and Odor Threshold Value." *Journal of Japan Air Cleaning Association* 41:17–25.

National Research Council. 1975. *Principles for Evaluating Chemicals in the Environment*. Washington, DC: National Academy of Sciences.

Pandrangi, L.S., and G.C. Morrison. 2008. "Ozone Interactions with Human Hair: Ozone Uptake Rates and Product Formation." *Atmospheric Environment* 42:5079–89.

Prezant, B., D.M. Weekes, and J.D. Miller. 2008. *Recognition, Evaluation, and Control of Indoor Mold.* Fairfax, VA: American Industrial Hygiene Association.

Rim, D., A. Novoselec, and G. Morrison. 2009. "The Influence of Chemical Interactions at the Human Surface on Breathing Zone Levels of Reactants and Products." *Indoor Air* 19:324–34.

Rohles, F. 2007. "Temperature and Temperament: A Psychologist Looks at Comfort." *ASHRAE Journal* 49(2).

Rohles, F., J. Woods, and P. Morey. 1989. "Indoor Environment Acceptability: The Development of a Rating Scale." *ASHRAE Transactions* 95(1):23–27.

Ryherd, E.E., and L.M. Wang. 2010. "The Effects of Noise from Building Mechanical Systems with Tonal Components on Human Performance and Perception (RP-1322)." *ASHRAE Transactions* 116(2):541–52.

Schneider, T., M. Bohgard, and A. Gudmundson. 1993. "Deposition of Particles onto Facial Skin and Eyes, Role of Air-Currents and Electric Fields." *Indoor Air '93: Proceedings of the Sixth International Conference on Indoor Air Quality and Climate* 4:61–66.

Selye, H. 1974. *Stress Without Distress.* New York: Lippincott and Crowell.

Sensharma, N.P., P.K. Edwards, J.E. Woods,. and J. Seelen. 1993. "Characterizing Human Response in Indoor Environmental Evaluations." *Proceedings of IAQ '93: Operating and Maintaining Buildings for Health, Comfort, and Productivity*, pp. 173–80.

Sexton, K., M.X. Petreas, and K.S. Liu. 1989. "Formaldehyde Exposures inside Mobile Homes." *Environmental Science and Technology* 23:985–88.

Skov, P., O. Valbjørn, and DISG. 1987. "The 'Sick' Building Syndrome in the Office Environment: The Danish Town Hall Study." *Environment International* 13:339–49.

Strand, F.L. 1983. *Physiology: A Regulatory Systems Approach*. New York: Macmillan Publishing Co., Inc.

Sundell, J. 1994. "On the Association Between Building Ventilation Characteristics, Some Indoor Environmental Exposures, Some Allergic Manifestations and Subjective Symptom Reports." *Indoor Air* Supplement No. 2/94.

Tichenor, B.A, ed. 1996. *Characterizing Sources of Indoor Air Pollution and Related Sink Effects* (Special Technical Publication 1287). Philadelphia: American Society for Testing and Materials.

Tiller, D.K.L., M. Wang, A. Musser, and M.J. Radik. 2010. "Combined Effects of Noise and Temperature on Human Comfort and Performance (RP-1128)." *ASHRAE Transactions* 116(2):522–40.

Wang, L.M., and C.C. Novak. 2010. "Human Performance and Perception-Based Evaluations of Indoor Noise Criteria for Rating Mechanical System Noise with Time-Varying Fluctuations (RP-1322)." *ASHRAE Transactions* 116(2):553–68.

Weschler, C.J. 2000. "Ozone in Indoor Environments: Concentration and Chemistry." *Indoor Air* 10:269–88.

Weschler, C.J. 2004. "New Directions: Ozone-Initiated Reaction Products Indoors May Be More Harmful Than Ozone Itself." *Atmospheric Environment* 38:5715–16.

Weschler, C. 2006. "Ozone's Impact on Public Health: Contributions from Indoor Exposures to Ozone and

Products of Ozone-Initiated Chemistry." *Environmental Health Perspectives*, October. www.ncbi.nlm.nih.gov/pmc/articles/PMC1626413.

WHO. 2009. *WHO Guidelines for Indoor Air Quality: Dampness and Mould.* Geneva: World Health Organization. www.euro.who.int/document/E92645.pdf.

Wisthaler, A., and C.J. Weschler. 2009. "Reactions of Ozone with Human Skin Lipids: Sources of Carbonyls, Dicarbonyls, and Hydroxycarbonyls in Indoor Air." *Proceedings of National Academy of Sciences*. www.pnas.org/content/early/2009/08/14/0904498106.full.pdf+html.

Wyon, D. 1991. "Healthy Buildings and Their Impact on Productivity." *Postconference Proceedings of ASHRAE IAQ '91: Healthy Buildings*, pp. 43–46.

Xu, P., P. Jordan, P. Fabian, J.W. Martyny, K.P. Fennelly, M. Hernandez, and S.L. Miller. 2003. "Efficacy of Ultraviolet Germicidal Irradiation of Upper-Room Air in Inactivating Airborne Bacterial Spores and Mycobacteria in Full-Scale Studies." *Atmospheric Environment* 37:405–19.

=======END==