Fundamentals of IEQ and Occupant Needs

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2 Fundamentals of IEQ and Occupant Needs

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Summary

In this chapter, we will introduce the link between occupant needs and elements of the indoor built environment, between sensory inputs and perception, and between perception and behavior. We will then review common practices in standards and guidelines. We will close the chapter with a discussion of three topics with open questions that require ongoing work.

2.1 Introduction

The first step toward occupant-centric building design and operation is a fundamental understanding of the relationship between the built environment and occupants' needs for health, well-being, and productivity. We begin this chapter with a brief overview in Section 2.2 of occupant needs and theories related to people's perception of indoor spaces and their behavior. Thereby, we introduce the four main domains of indoor environmental quality (IEQ)—namely, thermal, visual, acoustic, and indoor air quality (IAQ). This description of theoretical foundations is contrasted by Section 2.3, where we reflect on common compliance-checking methods based on codes, standards, and rating systems and the way the large body of scientific knowledge introduced in Section 2.2 is reflected in these forms of guidance. We conclude this chapter with a discussion in Section 2.4 of several critical factors that reflect the complexity of occupants' perception and behavior in indoor environments, bridging factors typically considered in research looking at occupants' needs and variables included in occupant behavioral models.

2.2 The Human Being in a Built Environment: Fundamentals and Theories

The objective of this section is to introduce the relationship between human needs and the indoor built environment, starting with human needs and reflecting on human perception and behavior.

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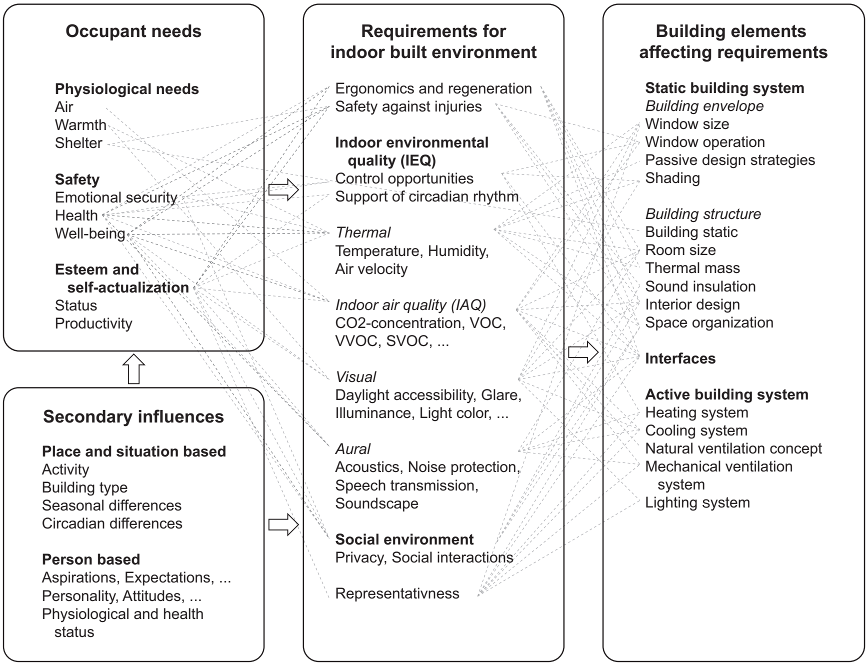

Figure 2.1 Framework reflecting the design flow from human needs in relation to requirements for the indoor built environment to related design elements affecting the performance of buildings as related to the requirements. In reality, this is an iterative process and, once built, a building's elements will affect occupants' needs. Note that elements and connections are only examples for graphical reasons.

2.2.1 Human Needs and the Indoor Built Environment

A basic understanding of human needs is fundamental in occupant-centric building design. While there are various definitions and categorizations of human needs in the literature, their presentation and discussion are beyond the scope of this book. On a very high level, human needs are referred to as the "drivers of people's actions, the motives behind behaviour" (Guillen-Royo, 2014). One of the most prominent categorizations of human needs still widely referred to these days is that by Abraham Maslow (Maslow, 1943, 1954). He distinguishes, in his early work, between deficiency needs (physiological, safety, love and belongings, esteem) and growth needs (self-actualization).[1] His framework offers a suitable structure to discuss human needs and to reflect on their relationship to design elements of the indoor built environment, aiming at occupant-centric building design. Figure 2.1 gives an overview of the mapping between human needs and design elements.

Physiological needs are related to biological requirements for human survival. These include air, warmth, and shelter against environmental hazards. While the vast majority of existing buildings meets these requirements, recent events partly related to climate change emphasize the need to assure that the building design provides conditions for survival. Floods, hurricanes, and other natural disasters have led to the destruction of buildings and corresponding fatalities. The combination of e.g., heat waves, power outages, and building designs relying on active conditioning while ignoring passive design strategies can lead to conditions beyond the limits for human survival.

Under normal circumstances, the building envelope itself—consisting of wall, roof, and floor elements, which may include opaque, transparent, insulating, ventilating, and shading elements—provides shelter and serves as a buffer against natural and man-made outdoor environmental conditions, such as low temperatures, high wind speeds, sunburn, or traffic noise. At the same time, the provision of sufficient fresh air needs to be assured. These examples all relate to the four dimensions of IEQ. The thermal dimension includes temperature, humidity, and air velocity levels.[2] The visual dimension considers illuminance levels, glare effects, color temperature, and color rendering index, among others. IAQ considers the freshness of the air, odors, particles within the air, and the concentration of CO_2 and volatile organic compounds (VOC). The acoustic dimension includes room acoustics, noise insulation, speech transmission, and others.

Depending on weather conditions, the type of envelope, and the activities within the building, the building envelope alone may not be sufficient to meet all the physiological needs required for survival. In these circumstances, the active building system needs to be designed to provide these conditions. If designers consider physiological needs and disregard the need for well-being (as described below), design requirements can remain minimal; for example, when clothing is available, the human body can survive for prolonged periods in a range of temperatures far beyond those occurring in modern buildings.

Safety needs as described by Maslow include financial security, social stability, and law and order, which have not been directly linked to the indoor built environment. Yet, safety needs can also include emotional security, health, and well-being, which have been directly mapped onto design elements of the building. **Emotional security** is linked to both privacy and interactions with others, which are either enabled or complicated by the organization of space and the interior design. The above-mentioned four dimensions of the IEQ and their respective requirements relate to health, well-being, and the concept of indoor environmental comfort (see Rohde *et al.*, 2019) for an extended discussion of the differences between the terms health, well-being, and comfort within the indoor environment). Requirements related to the IAQ domain are often aimed at a reduction of potential **health** implications, such as increased risk of cancer due to asbestos or polychlorinated biphenyls (PCBs), or reduced productivity due to reduced IAQ, such as increased CO_2 concentration levels.[3] The basis for most IEQ-related standards associated with the other three domains is often subjective level of comfort (see Section 2.3 of this chapter). Respective limits are based on a large amount of research following psycho-physical approaches to quantitatively investigating the relationship between physical stimuli and the sensations and perceptions they produce (see also Section 2.2.2 of this chapter). Thereby, the goal is to minimize IEQ conditions that lead to discomfort or dissatisfaction when the building is occupied. These conditions include, among others, temperatures that are too high or too low, glare, darkness, noise, or bad smells. Following the discussion by Rohde *et al.* (2019), **well-being** is distinct from comfort and includes: (1) positive emotional responses, including delight (Heschong, 1979), due to specific stimuli such as pleasant sounds, smells, or views; (2) varied and dynamic environments offering the potential for moments of alliesthesia, a feeling of very high satisfaction; and (3) environments that potentially reduce stress, offer a high level of controllability and contact with nature, and facilitate unrestrained activities. Related requirements for well-being would go beyond the restriction of IEQ conditions in the four domains and promote dynamic environments with conditions outside traditional comfort limits, e.g., set by ASHRAE 55 or ISO 7730.

Additional requirements for the indoor built environment related to health include those related to safety against injuries and harmful conditions. The duration of exposure to different conditions and individual constitution influence the magnitude of these effects. For example, the intent of some IEQ requirements is to limit, minimize, or avoid occupants' exposure to specific IAQ contaminants, which are harmful after short- or long-term exposures and for which effects have been directly assigned to the cause, like asbestos and cancer.

Safety needs related to comfort, well-being, and health also include the need for regeneration, growth, and repair, especially at night. Research on circadian rhythm suggests that a high sleep quality starts with the provision of sufficient daylight required for melatonin suppression during the daytime (Boubekri *et al.*, 2014). A further condition is limited exposure to lighting with reduced blue wavelengths in the evening, which is related to occupants' behavior and the lighting emission design of the lighting system and appliances such as televisions or smartphones (Wahl *et al.*, 2019). Furthermore, access to silent, dark, and well-tempered conditions during the night-time that allows for increased sleep quality (Chepesiuk, 2009) is a further requirement for building design and operation following human needs.

While not immediately apparent, there is a relationship between **esteem and self-actualization needs** and the indoor built environment. Esteem needs include aspects of respect, status, and recognition, while self-actualization is related to the realization of personal potential. All these aspects can, to some extent, and depending on their exact operationalization, be promoted or impeded by the indoor built environment. For example, reaching respect, status, or recognition is associated with success in professional life (Ormel *et al.*, 1997). In addition to health status—influenced partly by IEQ conditions as discussed before—one's ability to perform the tasks required for professional life partly depends on IEQ conditions. Success in viewing and completing tasks may depend on several aspects of the visual environment, such as luminance, illuminance, spectrum, color temperature, direction, color rendering, and contrast. Listening tasks and communication with customers, peers, or superiors, for instance, may be inhibited by excessive and unprotected background noise or poor acoustic properties of an indoor space. At the same time, IEQ conditions can also be designed to manipulate occupants and clients—for example, adjusting light settings to make fruits looking fresher and tastier than they are. The design of a space will likely need to consider the needs of different types of occupants, such as those working in a setting and those visiting, e.g., for shopping or leisure.

In this section, we have outlined a multitude of connections between human needs and the indoor built environment and could describe many more. Before moving forward, however, we should note that there are challenges involved in defining requirements for indoor spaces. For instance, human needs within the indoor built environment vary depending on the intended activities as well as the attitudes and personality of the human itself (Schweiker, Huebner *et al.*, 2018). Likewise, the requirements vary when aiming for an occupant-centric building design. There are seasonal and circadian differences; some needs are more likely at specific times of the day (e.g., sleeping) or year (e.g., the desire for cooling), but in general, most activities may occur anytime. Needs are also related to or can form the basis of occupants' aspirations, which can either be fulfilled or lead to disappointment when they are not met (Schweiker, Rissetto *et al.*, 2020). Some of these needs may be readily evident to human consciousness, such as fresh air to combat bad odors or a certain threshold luminance level, and can therefore be communicated with others. Yet, other needs may remain at the subconscious level—for example, the introduction of fresh air to reduce non-odorous but harmful components of the indoor air, which can be measured but not sensed by the human being. Occupant-centric building design should consider both perspectives to provide satisfying and healthy conditions.

2.2.2 Sensory Input and Perception

This section briefly touches upon the pathway from sensory inputs to perception/sensation and evaluation (satisfaction, comfort) of IEQ-related stimuli. The next section will describe the process from perception to human-building interaction. The whole process is schematized in Figure 2.2. A basic understanding of these pathways and related terminology is fundamental to evaluating key aspects of the literature about the relationship between IEQ

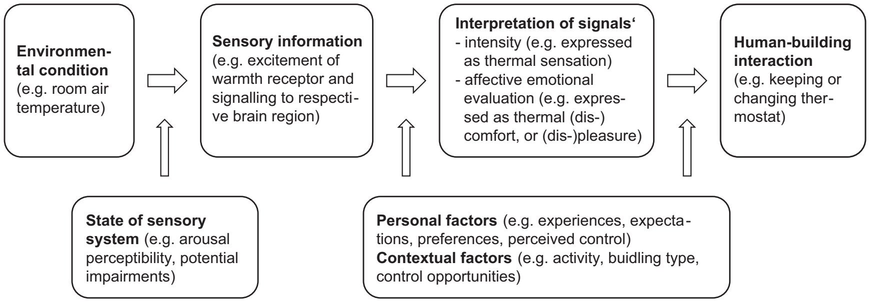

Figure 2.2 Schematic flow from environmental stimuli to human-building interaction.

and human behavior. Readers interested in the details of these processes are referred to corresponding literature (Bluyssen, 2009), as these are beyond the scope of this book.

The human body cannot directly measure parameters of IEQ in absolute terms as, for example, a thermometer might do. The human body can only detect changes to stimuli of our sensory systems. Distinctions are commonly made between the six sensory systems: vision, hearing, touch, taste, smell, and balance. Except for taste, all these factors are related to aspects of the indoor environment, and each of the four domains of the IEQ is related to at least one of them. Balance—often overlooked and taken for granted—is less required for typical plane floors, but can lead to sensory stimuli and training, e.g., as promoted by Hundertwasser in his treatise on the advantages of the uneven floor (Hundertwasser and Schmied, 1985).

Each of the sensory systems consists of sensory receptor cells, neural pathways, and dedicated parts of the brain. Examples of sensory receptor cells are the cold and warm thermoreceptors in our skin (part of the sensory system touch), which react to varying temperatures. The neural pathways carry the corresponding nerve impulses from the receptor to the brainstem and up to specific areas of the brain (Bluyssen, 2009). Except for direct reflexes, such as removing a hand immediately from a hot plate, the information regarding the stimuli is interpreted in various brain regions. Such interpretations can lead to a conscious or subconscious perception. When asking participants in a study or occupants in buildings about their perception of IEQ variables, they are forced to find a conscious representation. Depending on the type of question, they can then report their sensory-discriminative, affective-motivational, or cognitive perception (Schweiker *et al.*, 2017). As Schweiker *et al.* (2017) outlined, sensory-discriminative perceptions include perceived intensity, e.g., a statement between hot and cold in response to the question “How do you feel right now?” or an evaluation in terms of acceptability. Affective-motivational perceptions include aspects such as pleasantness or the motivation to change the conditions. Cognitive perceptions include comparisons of perceptions of previous experiences, perceived controllability of conditions, or the ability to cope (mental or behaviorally) with perceived conditions.

Three points are important to note. Firstly, the type of question influences the type of perception assessed, and a perception of intensity (e.g., the commonly used thermal sensation scale) is, in general, not suitable to assess whether a condition is perceived as comfortable, acceptable, or even stimulating emotions like pleasantness (see also Schweiker, Abdul-Zahra *et al.*, 2020). Secondly, the same physical stimuli can elicit different perceptions of pleasure or dissatisfaction for the same person depending on their internal state (e.g., level of acclimatization, preferences, expectations, experiences), the external conditions (e.g., socio-cultural aspects, relation to source of noise), or the current task or activity. Thirdly, all parts of the sensory system may vary between and within individuals. One example is when a person's visual sensory system changes with age. Age is associated with reduced transmission of light through eye media, a reduction of the width of the pupil, and further processes that, in turn, lead to the average 65-year-old receiving only half the light at the retina as a 25-year-old (Schierz, 2008). Thus, it is important to be explicit in methods that assess occupant needs, not rely on small samples, and strive for variety in the occupants being approached. At the same time, designers and researchers should be careful in following advice based on studies that do not follow these points.

2.2.3 From Perception to Human-Building Interaction

Once the sensory stimuli from the sensory nerve cells are interpreted—again, excluding reflexes—a subconscious or conscious reaction is followed. Reactions related to IEQ have been grouped in various ways. Schweiker *et al.* (2018) distinguished between (1) physiological adjustments done unconsciously, (2) individual adjustments like changing body posture or clothing, (3) environmental adjustments, including interactions with the building interfaces, and (4) spatial adjustments such as leaving a room. Taking no action and leaving everything (internal and external settings) as it is, is also considered a reaction. The type and degree of reaction are influenced by the evaluation of the stimuli together along with additional variables related to preferences, attitudes, experiences, norms, and others.

Subconscious reactions, such as the narrowing of blood vessels (called vasoconstriction) to reduce heat loss through the extremities in cold environments, happen immediately. In contrast, conscious reactions, such as opening a window to improve the IAQ, may begin with a behavioral intention but many factors will impact whether an action is pursued or not (for an overview of related theories see, e.g., Heydarian *et al.*, 2020). It is important to note that human-building interactions do not end the moment an occupant has completed the action, but rather may continue iteratively with further evaluation of subsequent sensory stimulation. The changes detected through the sensory systems impact whether the reaction or interaction will be evaluated as a successful or failed intervention. Repeated failure or the perception of lack of control can lead to dissatisfaction, learned helplessness, and acute or long-term stress reactions that can potentially affect well-being and/or health. Therefore, occupant-centric design demands careful consideration of human needs in addition to the design and selection of the interfaces that are provided to occupants to alter their respective IEQ conditions (see Chapter 4 for methods to collect occupant data, needs, and interface usability).

In any given building, there are many controls or interfaces such as windows, doors, and lights, that occupants can interact with to maintain their comfort, preferences, and so on. These interactions can impact the building's energy use and occupants' IEQ and comfort outcomes, both at the room and individual levels. Hence, due to the above-mentioned individual differences, what is beneficial for one occupant may be annoying for another sharing the same room. Building controls and interfaces lie on a spectrum ranging from fully manual control (human-driven action) to fully automated (machine or technology driven; see Chapter 9 for more details). In between this spectrum, there are also solutions such as human/occupant-in-the-loop control strategies (OCC). For example, with demand-controlled ventilation (DCV) strategies, ventilation rates are adjusted based on indoor air contaminant concentrations (e.g., CO_2) or occupant counts. Chapter 10 of this book covers a wide range of OCC solutions and case studies.

Many factors encourage (or discourage) occupant interactions with a given building, such as comfort, personal habits or preferences, health (e.g., a migraine), or privacy (Schweiker, Carlucci *et al.*, 2018). Different building interfaces offer varying forms of feedback and degrees of control to occupants. Understanding how occupants engage with interfaces—and their respective feedback mechanisms and controls—has important implications for meeting both occupant needs and energy savings design goals (see Chapters 3 and 9). If occupant interface needs are not carefully considered, designers risk not meeting energy goals and occupant comfort and IEQ needs. For instance, while keeping all occupants satisfied and comfortable at the same time is an impossibility, one solution to maximize comfort and satisfaction is to offer occupants local controls to maintain their personal comfort and satisfaction (Day and Heschong, 2016). Based on studies of occupants' heating and cooling behaviors, personal comfort models can predict individuals' thermal preference and lead to improved comfort, satisfaction, and energy use outcomes (Kim, Schiavon *et al.*, 2018; Kim, Zhou *et al.*, 2018). At the same time, we believe that the explanatory capacity of machine learning approaches is still questionable, as observed earlier elsewhere (de Dear *et al.*, 2020). As with other approaches, they may fail when applied to contexts other than those for which they were trained.

The types of controls occupants interact with in their environment vary based on building type, climate, and so on. The nature of occupant interactions with building interfaces will continue to evolve as building technologies and controls as well as occupant preferences continue to advance. Therefore, while there are many interesting hybrid and automated solutions to guide (or prevent) occupant interactions with interfaces, there are also inherent challenges to maintaining occupant comfort, IEQ, satisfaction, productivity, and so on. These challenges and possible solutions will be further outlined in Section 2.4. Additional details of building interface characteristics that influence occupants' interactions are detailed in Chapter 9.

The following section contrasts the above overview related to occupant needs with the content of common compliance checking methods based on codes, standards, and rating systems for the four main domains of IEQ.

2.3 Common Practices Regarding Specification of IEQ

Given the wide variety of human needs in the built environment discussed in the previous section, multiple quality requirements must be considered in the design, construction, and operation of buildings, including building integrity as well as safe and secure building operation. Thereby, requirements regarding IEQ must directly address occupants' needs (see Figure 2.1). A general classification of criteria concerning occupants' requirements could be listed as follows, starting from most evident (basic) to less tangible:

1 Avoid major or irreversible damage to organism due to extreme exposure situations.
2 Avoid long-term health issues due to, for instance, sustained stressful situations.
3 Provide IEQ conditions compliant with requirements pertaining to occupants' comfort and productivity.
4 Provide conditions that are subjectively perceived as pleasant.

It is commonly assumed that scientific disciplines such as biology, physiology, medicine, psychology, and ergonomics provide the evidentiary basis for criteria and mandates tied to IEQ standards. Whereas risks in category 1 above must be avoided at all costs, category 2 risks may be tolerated under certain limited term exposure situations. This means that, in most indoor settings (residential, commercial), the focus is on categories 3 and 4. Note that while the conditions that constitute a comfortable environment ultimately depend on occupants' subjective judgment, the same does not necessarily apply to physical health considerations. Adverse health implications of indoor environmental factors are not always consciously perceived. For example, there are well-known cases of dwellings with dangerously high carbon monoxide and radon concentrations, both of which are imperceptible by humans.

Codes, standards, and guidelines that specify IEQ requirements represent the main reference sources for professionals and stakeholders. Specifically, building designers and engineers are expected to abide by the provisions in these documents. Responsible parties for building construction and operation may need to provide proof of compliance with regard to applicable mandates. More recently, various building quality assessment and rating schemes have been introduced to encourage more holistic building evaluation processes. The intention is to promote better performing and more sustainable building practices. However, actual code compliance processes and adoption of rating systems do not appear to involve, as a matter of course, critical reflection concerning the source, uncertainty, and applicability of the entailed mandates and recommendations. This can lead to a perfunctory attitude of demonstrating compliance with the minimum criteria or pro forma acquisition of some quality label, rather than seeking a genuine understanding of what constitutes a high-quality indoor environment. It would be thus useful to critically examine the content of standards for explicit and implicit references to their underlying theoretical reasoning and the scientific evidence for their prescriptions.

As alluded to previously, the presumed primary purpose of IEQ-related performance mandates in standards is to define conditions that are conducive to building occupants' health, comfort, and well-being (Mahdavi *et al.*, 2020). The assumption might be that the recommendations in such documents have been issued not by edict but based on theoretically sound and empirically derived evidence pertaining to the processes by which indoor environmental conditions influence occupants' health, comfort, and well-being. Unfortunately, the validity of this assumption, as obvious as it may seem, cannot be taken on faith. Past research efforts have significantly contributed to our understanding of IEQ-related human requirements. However, they have also demonstrated that the definition and operationalization of occupants' requirements are rather non-trivial endeavors, given the imprecise and at times overlapping concepts such as health and comfort. It would be thus beneficial to query if typical instances of IEQ-related evaluation schemes and standards bolster their requirements through the explicit inclusion of their theoretical and empirical underpinnings.

To identify such instances, one can begin with frequently deployed building rating and certification systems. A previous review of such systems (Mahdavi *et al.*, 2020) clearly revealed that they do not independently set the IEQ-related criteria but refer to thematically relevant national and international standards. For instance, the certification system LEED (2021) refers to various ISO, EN, and ANSI standards (2021) regarding thermal, IAQ, and acoustic criteria. Likewise, DGNB (2021) includes references to EN, ISO, ANSI, and DIN standards. As the intention of this section is not to conduct an exhaustive review of such documents, the focus is on a number of typical and frequently referenced instances that specifically address the IEQ domains of interest to the present discussion, that is, thermal (e.g., ISO 17772-1), visual (e.g., DIN EN 12464-1), acoustic (e.g., DIN 18041), and indoor air quality (e.g., DIN ISO 16000-1). The study of such resources can reveal if they use content counting as the basis for and reasoning behind the adapted criteria and target values of relevant occupant-centric indoor environmental performance indicators.

2.3.1 Limits, Thresholds, Ranges, and Zones

From a practitioner's point of view, the main elements of interest in standards are likely to be the explicitly mandated values of IEQ-relevant variables and their specifications, usually in terms of minimum or maximum values, recommended ranges, and zones. The numeric nature of the variables' values and the fact that they are, at least in principle, measurable, implies certain practical advantages in terms of rationalizing and streamlining the quality assurance and compliance processes, and contributing to the clarification of liability issues. Mandates may be specified in various formats, including, for example, maximum permissible values (e.g., CO_2 concentration, glare level, noise level), minimum required values (e.g., illuminance level, ventilation rate), recommended or "optimal" values (e.g., comfort temperature, reverberation time), a range of acceptable values (e.g., daylight factors), and multi-variable "comfort" zones (e.g., combination of ambient air temperature and humidity level).

The conceptual graphs of Figure 2.3 illustrate for the thermal comfort domain typical instances of mandated values of recommended operative temperature and maximum permissible air flow speed. When looking for the underlying logic of these types of IEQ-related prescriptions, it helps to think of common code-based regulations in building design and construction domains. Consider, for instance, the prescribed minimum dimensions of basic architectural elements such as doors, corridors, and stairs in common universal design standards. In all these cases, features of various design elements are prescribed, the designs are expected to incorporate those

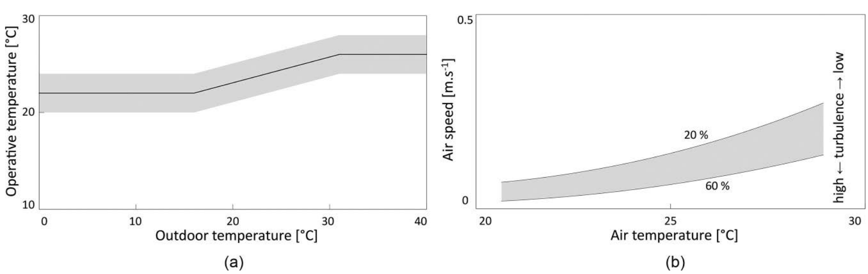

Figure 2.3 Conceptual graphs showing comfort (operative) temperature as a function of the outdoor temperature (left) as well as maximum permissible air flow speed as a function of air temperature and turbulence intensity (ranging from 20% to 60%, right; based on standards EN 16798 and ISO 7730).

features, and they can be checked during post-construction inspections. The assumption is that, as the prescribed minimum width of a door may be inferred from the dimensions of a wheelchair or the dimensions of stairs from basic anatomic features of the human body, it should be possible to infer the mandated values of IEQ-related variables from a relevant, scientifically established knowledge base. However, attempts to directly map from basic facts to specific performance requirements are not at all straightforward. Thereby, two questions are of special interest. First, given the inherent complexity of IEQ-related requirements, can the corresponding standards rely on a comparably objective scientific knowledge base? Second, do IEQ-related standards provide clear and traceable references to whatever scientific foundation they refer to? These questions are further explored in the following section.

2.3.2 Scientific Foundations versus Engineering Guidance

To start with a key observation, IEQ-related standards include much in terms of explicit and specific performance mandates and requirements (see the previous section), but relatively little in terms of direct and explicitly stated underlying science-based reasoning and evidence. The aforementioned rating system instances seldom spell out the details of the IEQ-related mandates, let alone provide explicit reasoning behind them. Rather, they refer to various international and national standards. These, in turn, frequently refer to other standards. Occasionally, references are made to technical papers that are suggested to provide some reasoning. However, such references are not always directly linked to the specific sets of requirements in the standards. Rather, they appear to be included as elements of thematically relevant bibliographies. At least three reasons for the paucity of direct explanations and evidence in common IEQ standards can be identified:

- There is a basic difference between scientific inquiry, which is mainly geared toward understanding phenomena, and engineering, which typically targets practical solutions. Standards and codes are mostly consulted by professionals looking for applicable prescriptions and constraints, not necessarily for the purpose of deep understanding.
- In contrast to "classical" engineering domains such as building construction and structural design, IEQ standards and guidelines regarding human requirements cannot only rely on natural sciences but must also consider insights from life and human sciences (e.g., physiology and psychology). The considerable role of qualitative and subjective factors in such fields can render the definition of standard requirements more challenging.
- The genesis of IEQ standards does not always occur through a completely transparent and thoroughly organized process with human health and comfort requirements as the sole focus. Rather, it can also

involve other factors, including economic considerations (e.g., return on investment) and special group interests. The processes leading to the formulation and publication of standards often require consent and comprise from a diverse set of participants from government, industry, and academic institutions. It is possible that not all content in and all aspects of standards are strictly objective and the direct result of scientific reasoning.

However, even if IEQ standards referred to frequently by professionals do not provide direct and explicit reasoning behind their recommendations, they do include features that point to implicit underlying principles and methods. These features allow for at least a partial backtracking or reverse engineering from standards to theory. A look at the syntax, terms, and formal logic of IEQ standards may thus yield some interesting and useful insights.

2.3.3 Measurements and Constructs

Recommendations in thermal and visual comfort standards are typically based on relationships referred to as comfort equations (Figure 2.4). A comfort equation maps the values of a set of independent variables meant to capture salient indoor environmental conditions to the value of a dependent variable meant to indicate the occupants' level of comfort (Mahdavi, 2020). The former comprises a number of physical parameters that can be measured. The latter is a construct, resulting from methods that make occupants' typically subjective perception (and evaluation) of the indoor environmental conditions measurable (see Table 2.1).

In regulations concerning thermal comfort, measurable independent variables of the indoor environment that are considered relevant include air and radiant temperatures, together with ambient concentration of water vapor and air movement velocity. Occupants' evaluation of thermal conditions is represented via constructs such as estimated voting tendencies, as expressed through qualitative scales common in psychological studies. The inference rules (i.e., the logic of mapping operations in the comfort equation) are often based on two sources. One source relies on physiologically

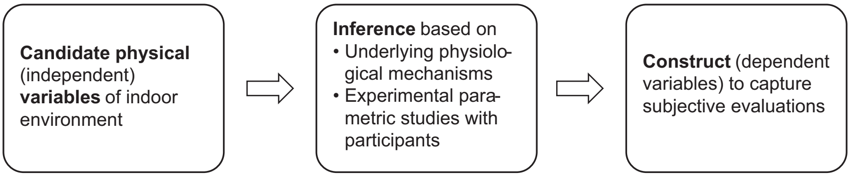

Figure 2.4 Schematic illustration of the elements of indoor environmental comfort equations.

Table 2.1 Illustrative instances of independent variables (thermal and visual indoor-environmental parameters) and dependent variables (constructs assumed to represent subjective evaluations of thermal comfort and visual discomfort) in respective comfort equations

	Thermal comfort	*Visual discomfort*
Independent variables: assumed relevant indoor environmental parameters	Air and mean radiant temperature, air humidity, air speed	Luminance of the glare source, luminance of the background
Dependent variables: comfort constructs representing occupants' subjective assessment of comfort conditions	PMV (predicted mean vote), PPD (predicted percentage of dissatisfied)	UGR (unified glare rating), VCP (visual comfort probability)

based insights. In case of thermal comfort, this is mainly the heat balance of the human body and its significant role in the thermo-regulatory process that maintains, among other things, the human body's core temperature (Mahdavi, 2017). The other source includes experimental studies with human participants who evaluate parametrically varied ambient conditions using the aforementioned subjective scales. The relative contribution of these two sources on the derivation of the comfort equations' mapping rules may be very different. The knowledge of humans' thermoregulatory system plays a significant role in the initial formulations of thermal comfort models. However, experiments with human participants provide key data relating physiologically relevant variables to subjective evaluation processes (see also Section 2.2.2). In the visual performance domain, the physiological basis of the so-called disability glare and the main responsible physiological mechanism (light scatter in the eye) are well understood. Visual discomfort, however, is mainly assessed based on people's subjective complaints.

2.3.4 About the Limits of Limits

Standards and codes typically include very specific requirements (including numeric limits for and ranges of various variables deemed relevant), but they rarely disclose directly and explicitly the corresponding reasoning. Some of the reasons for this circumstance have been alluded to previously, including: (1) the challenges of operationalizing the occupant-centric concepts of health, comfort, and well-being; (2) the identification and measurement of appropriate IEQ proxies; (3) the multi-aspect nature of indoor environmental exposure situations; (4) the diversity and dynamic nature of occupants' dispositions and needs; and (5) the real-life complexities of practical standardization procedures.

The intention of this chapter is not to identify and lay bare IEQ standardization's implicit logic based on unreasonable expectations. Obviously, it is unlikely that the underlying theoretical and evidentiary basis of the multitude of relevant indoor environmental regulatory systems and documents could be reduced to a single scheme or formula. Nonetheless, there is a recurrent pattern, familiar from fields such as physiology, medicine, and psychology. This pattern can be characterized as follows. The values of selected variables thought to represent salient features of the indoor environment are mapped to the values of selected indicators of occupants' health and comfort. The mapping operation is typically based on a mix of two complementary ingredients, namely (a) some physiologically or psychologically grounded theory and (b) available experimental data from research involving human participants. Whereas in cases involving explicit comfort equations (e.g., thermal comfort, visual discomfort), the codes include concrete constructs representing occupant health and comfort (together with their mandated value ranges), in other cases such constructs may not be explicitly present. The de facto assumption in such cases appears to be that by virtue of keeping the relevant indoor environmental variables (e.g., carbon dioxide concentration in the ambient air) within certain ranges, the terms relevant to occupants' health and comfort are met.

There are three notable implications of the preceding discussion about standards and their future development. First, notwithstanding the need for a differentiated stance, the path from standards to their underlying evidentiary basis should be recognized as at times intractable. This bears the risk of reducing standards and their mandates to inscrutable instructions that are followed unreflectively, rather than viewing them as sources of deep guidance for enlightened practitioners. This is not to suggest that standards must reproduce the entire theoretical foundation and scientific data they rely on. As regulatory instruments, they justifiably need to focus on operational matters and concrete instructions. Still, it would not be unreasonable to expect that standards could ideally represent a link between objective, scientifically based sources, and practical instructions. For example, within the German medical field, guidelines clearly acknowledge the procedure to summarize available knowledge, the resulting consequences, and the level of confidence or agreement regarding these points (e.g., Sammito *et al.*, 2014).

Second, in tracing back the standards to their explicitly specified or implicitly indicated sources in theories and data, various limitations stand out. Looking at the state-of-the-art in research on human health, comfort, and well-being issues reveals a continuously evolving field confronted with various challenges and uncertainties. Whereas respectable scientists in this area habitually abstain from doctrinal standpoints and absolute truth claims, regulatory bodies are obliged to boil down what is known to what is mandatory. In other words, to avoid a chaotic situation in the building design, construction, and operation processes, IEQ standards tend to adopt concrete thresholds and specific limits, even if the underlying science is not entirely conclusive. The concern appears to be that the compliance verification processes would become difficult otherwise, if not unfeasible.

Third, the diagnosed challenges of the IEQ-related regulatory frameworks, particularly the paucity of explicit theoretical reasoning, reflect also, at least to a certain degree, the gaps in scientific understanding in this area. There are uncertainties about what physical features of the indoor environment are the "right" variables for health and comfort evaluation processes. There are even more challenges concerning the definition and robustness of the constructs for health and comfort, which insufficiently address the interdependence of physiological, psychological, and even social dimensions of occupants' perception and evaluation of indoor environments. Datasets used for testing and validating perceptual and behavioral theories are limited. The pragmatic dissection of IEQ into distinct domains may fall short of capturing the realistic and inherently multi-domain nature of indoor environmental exposure situations. The current understanding of the extent of occupants' diversity and the dynamics of their requirements has been improving, but perhaps not enough to consider their reflections in the current IEQ standards as sufficient.

The implication of these observations may come across as a truism, but it is a critical one: the study of IEQ-related regulatory frameworks not only reveals their limitations, but also points to gaps in the current state of scientific understanding regarding occupants' needs and preferences in indoor environments. There is a need for a more transparent, traceable, and objective process when translating the current state of scientific knowledge, limited as it may be, into IEQ codes and standards. At the same time, there is also a need to advance and enrich understanding of how human health, comfort, and well-being are influenced by conditions in indoor environments. A number of knowledge gaps in the theoretical understanding of occupants' perceptions of IEQ, as well as related behaviors and interactions with indoor environments are further addressed in the following section.

2.4 Ongoing Work and Open Questions

There is a complex relationship between occupants and the buildings they inhabit, as outlined in Section 2.2. As previously mentioned, IEQ factors such as glare and thermal comfort may impact or drive behaviors, and these building interactions, whether misguided or not fully considered, may impact IEQ factors for other occupants (e.g., comfort) or building outcomes (e.g., energy performance). This section discusses select challenges related to the above topics, as well as viable solutions. Many of the presented concepts are less studied or understood and/or less firmly established or agreed upon when compared to many of the scientific theories presented earlier in the chapter; still, they are all extremely important factors in the design and operation of buildings and are not intended to be downplayed.

2.4.1 Adaptive Thermal Comfort, Perceived Control, and Personalized Control

One challenge in the domain of IEQ and occupant needs relates to occupant control (real or perceived) of building interfaces. A problem may occur when designers perceive building automation as an all-or-nothing situation, or a 0/1 decision where “1” is fully automated (no occupant control) and “0” is no automation (full occupant control). As a solution to this dilemma, there may be a blend of automation and manual control that is most beneficial for IEQ and energy outcomes. These types of solutions are addressed through, for example, hybrid ventilation (Parkinson *et al.*, 2020) and OCC, which are further discussed in Chapter 10. The best solutions may seek a balance of control to best accommodate occupant health, IEQ needs, and energy goals. For example, adaptive thermal comfort, perceived control, and personalized control may all be solutions, in no particular order. Another problem occurs when the level of automation is set in direct relation with the level of energy efficiency (as done in, e.g., EN 15232) in a way that higher automation is unconditionally related to higher energy efficiency.

There have been many models and theories of perceived control, and ultimately, most research has found that occupant satisfaction and perceptions of IEQ are higher when occupants perceive that they have control over their environment (real or perceived). There is agreement that perceived control may lead to positive outcomes (Hellwig, 2015; O’Brien and Gunay, 2014; Yun, 2018) and that designers should be encouraged to consider and implement perceived control strategies. However, perceived control may only be a short-term solution. An even better solution is to encourage designers to give occupants actual control of building interfaces that are not hidden, easily accessible, and intuitive to understand (see Chapter 9). For example, in one study (Brager *et al.*, 2004), occupants were provided with differing degrees of personal control over their windows (with four stages ranging from direct control to no control). Participants showed significant differences in thermal responses, where those with a higher level of control also had higher ratings of personal comfort, even under the same conditions (thermal environment, clothing, and activity levels). Findings from this study illustrate clear support for the adaptive model of thermal comfort (Brager *et al.*, 2004). While most engineers can agree for instance, that personalized controls are beneficial to occupant outcomes, there is still more work to do in terms of how access to controls really impacts people’s decisions, perceptions, and behaviors and how all these factors may be impacted by multi-domain aspects and drivers. Some research has begun to address these (e.g., Mahdavi *et al.*, 2020), but more work is needed to identify clear parameters and solutions, especially in real-world scenarios and conditions. In addition, this topic appears to be close to absent in existing standards and guidelines.

2.4.2 Energy, IEQ, and the Human-Building Interactions

While some designers choose to remove control, as addressed above, in most cases, occupants are typically expected to adjust their interior environment to maintain personal thermal and/or visual comfort, environmental satisfaction, and so on. However, issues may emerge when occupants control or manipulate the building in ways that designers did not intend and/or foresee. For example, if controls are not well thought out, or if occupants do not understand how to use their building effectively to achieve or maintain comfort, occupants may disable or override building interfaces-related IEQ factors such as windows and lighting. For instance, an occupant may duct tape over or cover an air vent, block a sensor, and more (see Day and O'Brien, 2017). At the same time, occupants may have needs not anticipated by the designer. Uninformed occupant behaviors can compromise energy-saving goals, building operation costs, worker productivity, and occupant health, especially when occupants do not always understand how to operate building interfaces (Day and Heschong, 2016; Day and O'Brien, 2017). See Chapter 9 for interface characteristics that better facilitate adaptive opportunities.

To maximize occupant comfort and minimize costs associated with productivity and energy use, at times, occupants may need education on building control interfaces and expected behaviors. Many current occupant behavior change programs implement feedback, motivation, and gamification (Jain *et al.*, 2012; Papaioannou *et al.*, 2018; Vassileva and Campillo, 2014), but studies have found that occupants may still not fully understand how their actions may impact others or the conditions within their space. A better scenario is to design the building interfaces in a way that is thoughtful and intuitive and enables occupants to fulfill their needs so that occupants do not require "training."

Although many "human-in-the-loop" approaches do indeed consider humans and behaviors, these methods are often about machines learning from humans and their behavioral patterns as opposed to humans learning the "right" behaviors—an important distinction. Behaviors and preferences may and should vary; however, there are ways in which designers can strive to design to enhance occupant outcomes and minimize unintended occupant interactions (e.g., occupants taping over sensors, tricking thermostats with popsicles [Day and O'Brien, 2017]).

Therefore, there is a critical research need to better understand: (1) how occupant interactions with building controls affect associated building energy use in a real test bed building scenario; and (2) how to best design buildings and interfaces to create and foster informed interactions, while also educating and engaging occupants as needed. The fundamental role of building interfaces and their associated characteristics on occupant interactions have not yet been thoroughly addressed in building or social science research. More importantly, existing occupant behavior models do not consider multiple layers of comfort (e.g., thermal, visual, acoustic, and IAQ) or other drivers/triggers of behavior (e.g., privacy, lack of understanding) that may affect occupant interactions with human-building interfaces. Chapter 9 further discusses specific characteristics, design recommendations, and solutions related to some of these issues related to building interfaces that might further encourage beneficial actions or deter counterproductive interactions.

2.4.3 Interaction among IEQ Domains and Other Factors

Many technical and design solutions rely heavily on solving one primary IEQ solution, and these are often founded on strong scientific foundations. However, some existing technical solutions do not necessarily translate into practice, or perhaps they were founded in a laboratory or experimental settings and are not fully applicable to real-life scenarios where other uncontrolled variables are present. This interaction among other IEQ domains, or lack of testing in field settings, may create unintended consequences or lack of understanding during design. For example, theories in the visual comfort domain often cite glare as a determining factor for blind use patterns (e.g., Day *et al.*, 2019; Reinhart and Voss, 2003). Glare is indeed one key indicator of blind use; however, additional factors may also come into play that are difficult to predict and/or model, such as privacy, job type or needs, inaccessible controls (Day *et al.*, 2012), as well as other IEQ or comfort-related driving factors, such as thermal comfort (Frontini and Kuhn, 2012). In these cases, there are certain factors and relationships among IEQ variables (multi-domain) that have not yet translated into practice—primarily because research is not conclusive regarding how IEQ factors impact one another or the occupant's experience or behaviors.

The challenge is thus the complex relationship between multi-domain aspects of IEQ. For instance, as cited in the example above, opening the blinds to allow for increased illuminance or visual comfort might also lead to a great deal of thermal discomfort. Other features that may improve daylighting, such as low partitions, open spaces, reflective and hard surfaces, and narrow floor plates may also increase instances of acoustic discomfort for occupants. There is much to learn, research, and further understand in terms of how these IEQ factors interact with one another, and how these interactions impact occupant behaviors. More research is needed to address an ever-growing list of questions, such as: How should occupant needs be related to one another? In design (and operation), which form of IEQ should get priority? How is a designer to navigate the various IEQ calculations and standards for a given design decision?

Some of these questions have been swirling around in the minds of researchers for years, and there have been a few efforts to better understand these multi-domain interactions (Bourikas *et al.*, 2021; Mahdavi *et al.*, 2020; Schweiker, Ampatzi *et al.*, 2020), yet there is still more to do.

2.5 Conclusions and Outlook

In this chapter, we first explored the relationship between human needs and the elements of the indoor built environment. Using Maslow's characterization of needs, we explored examples of their interaction with IEQ and other design elements to set the basis for occupant-centric design. We followed the examples with a brief introduction of the pathway from sensory stimuli to human-building interaction via human perception. Next, we explored the status of standardization with respect to available scientific evidence and discussed the role of standardization for occupant-centric design. This discussion was important because standards and guidelines give guidance to designers and engineers, and yet their scientific evidence is often hard to grasp and their formulation a result of interactions between evidence-based recommendations and additional considerations. The challenges and solutions we presented in the third and final part of this chapter included aspects related to perceived and personalized control, levels of automation, energy use, and interactions between the individual sensory domains. These ongoing works and open questions we proposed are certainly not exhaustive, and understanding the right balance of manual vs. automated building interfaces, perceived vs. actual control, occupant expectations, multi-IEQ-domain influences, and other factors that contribute to occupant-building interactions is key to designing for both IEQ and energy outcomes within the context of occupant-centric design.

2.6 Closing Remarks

The first step toward occupant-centric building design and operation is a fundamental understanding of the relationship between the built environment, IEQ, and occupant needs. This chapter started with an overview of occupant needs from physiological needs to self-esteem. Individual needs were linked to the indoor built environment, including the four main domains of IEQ parameters: thermal, visual, acoustic, and indoor air quality. Next was a brief summary of mechanisms, from sensory input to human perception, and from human perception to occupant behavior. The second part of this chapter looked at existing standards and how they incorporate the large body of scientific evidence presented in the first part of this chapter. The third part addressed three topics still being discussed that need further work before conclusions can be drawn. The topics were: perceived control, the relationship between IEQ and energy, and the interaction between individual sensory domains. As such, this chapter laid the foundation for the following Chapter 3, which reflects on how to incorporate the occupant perspective into the building design process, and Chapter 4, which identifies ways to obtain the occupant perspective and needs to inform design. The topic of control and interfaces is further detailed in Chapter 9.

Notes

1 Despite many scholars presenting these needs in the form of a pyramid, the order of needs is not fixed; the order depends on external circumstances and individual preferences. Still, it is reasonable to consider them as different levels, and we will discuss them in order, starting from the most basic level. In addition, it is not required that the needs in one level are completely fulfilled before another one is activated or met (Maslow, 1954).
2 Note that air movement is typically referred to as wind speed outdoors and as air velocity indoors.
3 While CO_2 concentration is often used as an indicator for ventilation performance and overall IAQ, other direct effects of increased CO_2 concentration include decreased performance, e.g., decision-making (Satish *et al.*, 2012).

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