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All you need to know about the indoor environment, its occupants, interactions and effects

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Abstract: Research has shown that, even though the conditions seem to comply with current standards for indoor environmental quality (IEQ), staying indoors is not good for our health. We are confronted with diseases and disorders related to IEQ such as mental illnesses, obesity and illnesses that take longer to manifest, among which cardiovascular and chronic respiratory diseases and cancer, and very recently, COVID-19, caused by mainly airborne transmission of SARS-CoV-2 indoors. Except for these health effects, the consequences for indoor environment of climate change, the effects of the retrofitting measures we take to reduce energy consumption on health and comfort indoors, is also an emerging concern. IEQ is still described with quantitative dose-related indicators, expressed in number and/or ranges of numbers for each of the factors (indoor air, lighting, acoustics and thermal aspects). Building and occupant-related indicators are overlooked. Interactions of stressors and effects at and between human and environment level are ignored. Individual differences in needs and preferences of occupants (over time) are not accounted for. Resilient new ways of creating and maintaining healthy and comfortable indoor spaces for different occupants in different situations, require better understanding of the indoor environment, its occupants, interactions, and effects.

keywords: indoor environmental quality, diseases and disorders, interactions, preferences and needs, stressors

1. Introduction

Most people are aware of the importance of the outdoor environment, especially in relation to climate change issues but also related more directly to our health. The effects of indoor environment quality are, however, not that common knowledge. We know that air pollution such as fine dust and noise pollution caused by airplanes, or too much sunlight can be very unhealthy. We, however, don't realize that people in the Western world in general spend 80-90% of their time indoors, of which more than 60% of their time at home (Bonnefoy, et al. 2004) and the rest of their time at their work, at school and/or commuting. Exposure 'indoors' is therefore much longer than outdoors. What most people also don't realize is that there are many diseases and disorders related to that indoor environment, such as mental illnesses, obesity, cardio-vascular and chronic respiratory diseases (think of asthma with children and Chronic Obstructive Pulmonary Disease (COPD) with adults), cancer (Bonnefoy et al., 2004; Fisk et al., 2007; Lewtas, 2007; Houtman et al., 2008), and more recent COVID-19 (Marowska, et al. 2020).

Worldwide, studies have shown that the relationships between indoor building conditions (thermal aspects, air quality, lighting, and noise) and wellbeing (health and comfort) of occupants of different buildings are complex and not easy to unravel (e.g. homes: Bonnefoy et al., 2004; offices: Kim and de Dear, 2012; schools: Bluyssen, 2017). Indoor building conditions may be associated with discomfort (annoyance), building-related symptoms (e.g. headaches, nose, eyes, and skin problems, fatigue etc.), building-related illnesses (e.g. legionnaires disease), productivity loss and decrease in learning ability

(Bluyssen, 20014a).There are many indoor environmental stressors: thermal factors (e.g. draught, temperature), lighting aspects (e.g. reflection, view, luminance ratios), air quality (e.g. odours, mould, chemical compounds, particulates) and acoustical aspects (e.g. noise and vibration). These stressors can cause their effects additively or through complex interactions (ASHRAE, 2016; Torresin et al., 2018), and depend/are influenced by psychological, physiological, personal, social and other environmental factors (Bluyssen, 2014a) (Figure 1).

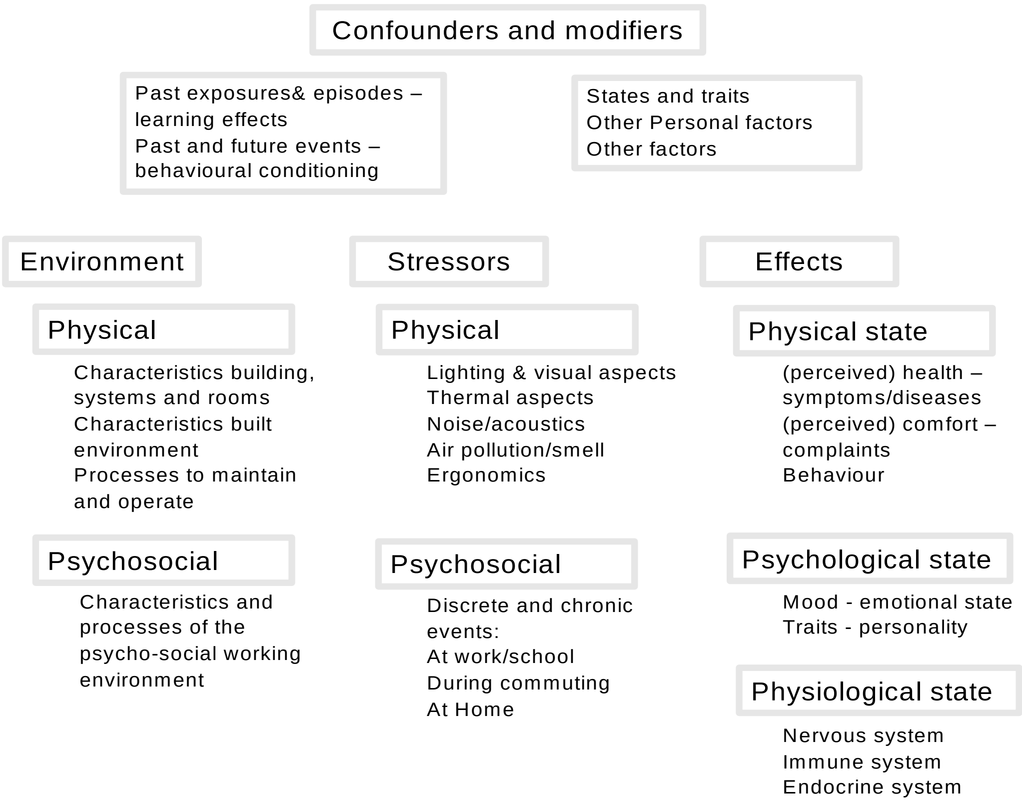


Figure 1. Stressors, factors, causes and effects (adapted from Bluyssen, 2014a).

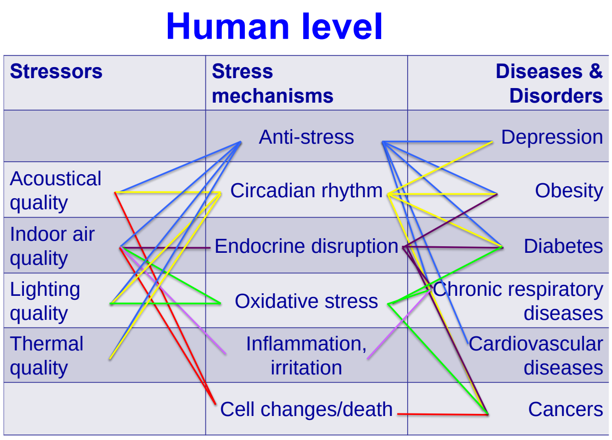


Figure 2. Possible interactions between stressors, mechanisms and diseases and disorders at human level (from Bluyssen, 2014a).

If you look at the scientific outcomes it seems that staying indoors is not good for our health, even though the conditions seem comfortable enough. Even when the conditions seem to comply with the current guidelines for indoor environmental quality (thermal, lighting, acoustical and air quality), people feel uncomfortable and get sick. This can partly be explained by the way our human bodies cope with the different stressors we are exposed to.

We have several stress mechanisms available for that and from research in different fields, it is clear that the relations between the stressors, those mechanisms that take place in the human body causing the diseases and disorders, are very complex (Bluyssen, 2014a) (Figure 2).

2. What is indoor environmental quality?

Indoor environment quality is determined by the quality of four factors: indoor air quality, thermal quality, acoustical quality and visual or lighting quality.

2.1 Thermal quality

Thermal quality or thermal comfort, the parameter we are probably the most familiar with., includes aspects such as feeling warm, cold, draught etc. In our daily conversations, in the Netherlands, we often use these to describe the weather, of yesterday, today or tomorrow. The big name most people know in this area is Prof. Fanger, who tested his thermo-physiological model in climate chambers in the 1970s using several subjects. His model has been and is still the basis for guidelines on thermal comfort. In the Netherlands, those guidelines comprise of ranges for the operative temperature (the average of the air and the radiant temperature), air velocity, draught risk (calculation based on air velocity, air temperature and turbulence), vertical temperature gradient and radiant asymmetry (CEN, 2019).

When people are dissatisfied with their thermal environment, thermal stress can occur. For example, when one is not able to regulate its thermal balance, or when one believes or perceives it isn't possible. The psychological effect of expectations and the perceived individual level of control seem important in this process. To deal with that, another model than the model of Fanger, begins to win ground: the adaptive comfort model, in which the context and preferences of the occupant are considered to be important (de Dear and Brager, 2002). Both of these models are focused on creating thermally neutral conditions. Recently it was found, however, that thermally neutral conditions do not have to be necessarily healthy. Studies indicate that increased exposure to thermally neutral conditions might be related to increased adiposity, an increase of fat tissue. This was first observed in experiments with rats and later with adult men (Marken Lichtenbelt et al., 2009). Actually, it means that when your body doesn't have to work to feel thermally comfortable, more fat is stored!

2.2 Lighting quality

The parameter visual or lighting quality comprises of aspects such as illuminance, luminance ratios and colours, but also aspects you would rather like to prevent, such as reflection on a floor or desk. Visual comfort is more that providing enough light to perform a task. View is also an important aspect to consider. The lighting quality of a space is determined by the interplay between the sources of light (indoors and outdoors), the distribution of light in that space, and the way light is received and interpreted by the receiver. Current guidelines for lighting quality are focussed on the provision of enough light to perform a task well, such as the horizontal illuminance on a desk, colour temperature of artificial light, and daylight factor, but also the minimalization of blinding caused by daylight and/or artificial light (CEN, 2019).

For visual perception, we have the light sensitive cells, located in the inner layer of the eye (the retina): the rods and the cones, of which the cones (three types) are sensitive to colours (the different wavelengths of light). Additionally, not so long ago, a third type of light-sensitive cell was found (Brainard et al., 2001). These cells are distributed between the rods and the cones, and play a role in the control of the size of the pupil opening and the biological clock (via the production of the hormone melatonin). Under influence of light during the day, the hypothalamus signals to the pineal body to produce melatonin, a hormone that makes us want to sleep. If exposed to light during night, however, for example during a night shift, the production of the anti-oxidant melatonin is immediately stopped, alertness and core body temperature is increased and sleep is distorted (Hinson, Raven & Chew, 2010). Moreover, the Dutch health council reported that people who are working night shifts are exposed to an increased risk for cardio-vascular disease and diabetes type 2 (Gezondheidsraad, 2017). This shows that also non-visual aspects of light are important to consider.

2.3 Acoustical quality

Acoustical quality of a space is determined by its sources of noise or sound indoors (for example quarrelling neighbours and flushing a toilet) and outdoors (such as traffic), the distribution of the sound in the space and the way the sound is received and interpreted. A sound enters the external auditory canal, setting the eardrum and the ossicles in motion. Then, these vibrations are transmitted to the fluid of the inner ear, where nerve impulses are transmitted via the eight cranial nerve to the brain. The inner ear also contains the equilibrium organ that acts independently of hearing. While the equilibrium sense is sensitive to low frequencies (vibrations), the auditory sense is more sensitive to higher frequencies (hearing). Current guidelines for sound comprise mainly of maximum allowed sound levels (e.g. CEN, 2019). Additionally, reverberation time and intelligibility are applied (Bluyssen, 2009).

Exposure to sound or noise has been associated with direct stress reactions, such as temporary or even permanent hearing loss. It is known that noise effects do not only occur at high sound levels, but also at relatively low environmental sound levels, when certain activities such as concentration, relaxation or sleep are disturbed (Babisch, 2008). Annoyance seems to play an important role in this mechanism. If we look into that anti-stress mechanism, we can see that in response to various stressors, the secretion of anti-stress hormones can increase. On the short-term adrenaline is produced and the body is prepared for action by producing noradrenaline. If the stressor is limited in time and perceived intensity, in due time the balance is restored. However, with prolonged stress (chronic stress), production of anti-stress hormones such as cortisol is increased and a chronic imbalance in the hormones released during stress can occur. It has been proven, although simplified because there are other hormones and reactions involved, that cortisol plays an important role in the health effects of this chronic imbalance (McClellan and Hamilton, 2010). High cortisol levels contribute to changes in carbohydrate and fat metabolism and can lead to anxiety, depression and heart disease. While a low cortisol production can lead to fatigue, allergies, asthma and increased weight.

2.4 Air quality

Indoor air quality is determined by its sources, the distribution of their pollutants in the space and how the receiver is exposed to these pollutants over time (Bluyssen, 2009). The pollutants that can be found in that indoor air comprise of gaseous pollutants, of which some of them you can smell, and others do not smell, plus several other components that influence the air quality such as water and particles.

We perceive air with our nose, which contains the senses with which you can perceive air quality yourself: one for smell - the olfactory sense in the olfactory epithelium, and one for irritation - the trigeminal nerve, which endings are located all over the nasal respiratory lining, forming the common chemical sense. On being stimulated by pollutants, the olfactory and trigeminal nerve endings send signals to the brain where the signals are integrated and interpreted. The result of this process is called perceived air quality (Bluyssen, 2014a).

When you breath in air through the nose or mouth, the air enters the trachea, a long tube, which branches into two bronchial tubes, or primary bronchi, that go to the lungs. In the lungs, the primary bronchi branch off into bronchioles, which end in the alveoli. In those alveolar sacs the gas exchange with blood takes place. Oxygen of the inhaled air passes through the walls of the alveoli and blood vessels and enters the blood stream. At the same time, carbon dioxide (CO_2) produced passes into the lungs and is exhaled. While larger particles are too heavy to stay suspended and will not be inhaled, of the sizes that can be inhaled and reach the lung cells, the ultra fine or nano particles can together with oxygen pass the membrane of the alveoli and in this way reach our organs via our blood, where they can cause so-called oxidative stress. Oxidative stress occurs when there is an excess of free radicals over antioxidants (Kelly, 2003). Oxidative stress can damage cells and can lead to systemic inflammation, and even cell death.

Air pollution is probably the most important cause for oxidative stress indoors, but air pollution is responsible for more mechanisms. Fine dust can cause inflammation, radon and asbestos fibres can cause lung cancer, SARS-CoV-2 can cause COVID-19, several VOCs can cause annoyance to toxic reactions, and several phthalates of certain plastics - these are the so-called endocrine disruptors, which can have an effect on hormone production and hormone balance - can cause a whole range of effects that are still hard to grasp. Specific chronic respiratory diseases and disorders caused by air pollution are for example COPD, asthma, allergic rhinitis and hay fever. Besides all those diseases and disorders, there are several building-related symptoms that have been related to exposure of air pollutants, such as symptoms of eyes and nose, the upper airway-related symptoms, tiredness and headaches (Bluyssen, 2009).

Guidelines for air quality comprise of: a) minimum ventilation rates in l/s/person or $l/s/m^2$ floor area to ventilate/dilute the emissions of persons and emissions of building- and furnishing materials; b) a limit value of the CO_2 concentration above the outdoor air concentration as indicator for emissions of persons, applied to determine the required amount of fresh (outdoor) air; c) limit values for maximum exposure to pollutants in indoor air, such as formaldehyde, carbon monoxide and radon (e.g. CEN, 2019).

3. Assessing the indoor environmental quality

3.1 Single dose response relationships

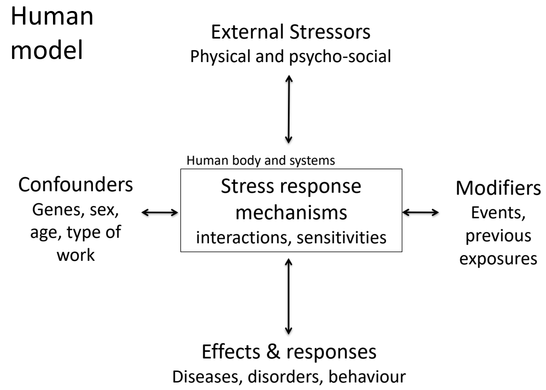
From section 2 follows, that although the built environment is a complex system, IEQ is still most of the time assessed with indicators using the dose or indoor environmental parameter, such as concentrations of certain pollutants, temperature, lighting level or ventilation rate (e.g. CEN, 2019). We assess IEQ on effect modelling: for each parameter or indicator its effect is determined separately. These dose-related indicators are based on linear single dose-response relationships for negative stressors, developed for the average occupant; ignoring that we are dealing with individuals in different scenarios and situations; neglecting other stressors and their integrated effects over time; and ignoring interactions between stressors at environmental level, and interactions between various body responses to exposure(s) at human level; forgetting that there are two other categories of indicators available (Bluyssen 2010; 2014b):

- The occupant-related indicators: focused on the occupant such as sick leave, productivity, and number of symptoms or complaints;

- The building-related indicators concerned with buildings and its components, such as certain measures or characteristics of a building and its components (for example the possibility of mould growth), or even labelling of buildings and its components.

Thus, according to the standards, a healthy building is a building that complies with the existing standards and guidelines for mainly the environmental or dose-related indicators. However, from the previous it is clear that in order to assess whether a building is healthy, more is needed. A good example is the minimum ventilation rate. Based on either CO_2, as an indicator for bioeffluents, or on certain emissions of building materials, minimum ventilation rates have been discussed and are still being discussed for almost two hundred years now. We still have no clue what to take. Even more now, as a result of the corona crisis.

A 'healthy' building is a building that has the means to support the physical, psychological, and physiological health and comfort of its occupants over time. A healthy building has the means to influence health and comfort of its occupants through the thermal, lighting, acoustical and indoor air quality of the indoor environment. It is clear that next to the dose-related indicators we need to also make use of the occupant-related indicators providing information on the effects of stress, and preferences and needs, preferable at individual level because people differ and situations change over time (Figure 3 The Human Model); and we need to make use of building-related indicators, providing information on the stressors, and the interactions that occur in the indoor environment over time (Figure 4 The Environment model) (Bluyssen, 2020).



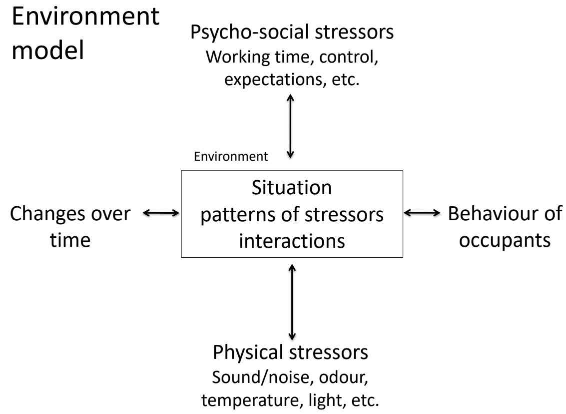


Figure 3. The Human model (Bluyssen, 2020). Figure 4. The Environment model (Bluyssen, 2020).

3.2 Human Model

The human body has a number of stress mechanisms available to cope with all the physical and chemical external stressors such as noise, indoor air pollutants, bad lighting or thermal discomfort, that is (Figure 2): the anti-stress mechanism, the mechanism to keep to our bio-rhythm, endocrine disruption, oxidative stress, infections, cell changes, and cell death. When the coping fails, or when the mechanisms make us overreact, diseases and disorders will occur. The relations between the stressors, the mechanisms that take place in the human body, and the effects that can occur (the diseases and disorders), are very complex. Each of the mechanisms has a relation with one or more diseases and disorders (see Figure 2). This can partly explain the difficulties we are having with identifying clear cause-effect relations for diseases or disorders reported by/diagnosed with occupants. Moreover, during perception with our senses interactions of different environmental stressors (smell, sight and hearing) at brain level (central nervous system) might occur (Bluyssen et al., 2019).

People differ in their preferences and needs, influenced by psychological, physiological, personal, social and environmental factors and stressors (Figure 3). We are exposed to a mix of stressors, that can change over time, and our responses (the coping and the effects) are influenced by genetics, previous exposures and interactions between those stressors (e.g. Bluyssen, 2014b).

3.3 Environment Model

Besides interactions at human level, we also have to deal with the interactions that occur in the indoor environment over time, which makes it even more complex (ASHRAE, 2016; Bluyssen, 2014b; Torresin et al., 2018). Interactions, such as chemical interactions between pollutants in the air and microbiological growth at indoor surfaces, and interactions between different indoor environmental factors:

- Light and thermal aspects, when sunlight heats up the interior surfaces.
- Thermal conditions and indoor air. Emission rates of most volatile organic compounds increase with increasing temperature.
- Acoustics and indoor air, via the introduction of ventilation air by mechanical ventilation systems, which can produce equipment as well airflow noise, or via natural ventilation through open windows, bringing the noise produced outdoors indoors.

Also, interactions occur as a result of human behaviour (actions). When certain actions are taken to improve one factor, other factors might be affected negatively (Table 1), improving the situations for one person, but creating problems for another (Zhang and Bluyssen, 2021).

Table 1. Actions and possible interactions in the indoor environment (Bluyssen, 2015).

Factor	Action	Factor	Interaction-effect
Thermal quality	Increase temperature Use of solar screens to prevent overheating	Indoor air quality Visual quality	Emissions of most volatile compounds increase Possible reduction of daylight entrance
Visual quality	Use of internal walls made out of glass Increase of glass surface area in facade	Acoustical quality Thermal quality	Possible reflections of sound Possible overheating
Acoustical quality	Sound adsorption material in air supply ducts Closing of windows	Indoor air quality Indoor air quality	Possible reduction in air quality Possible reduction of ventilation
Indoor air quality	Increase of ventilation rate Opening of windows Increased relative humidity Removal of fleecy surfaces (such as curtains, carpet)	Thermal quality Acoustical quality Thermal quality Acoustical quality	Possibly draught Possibly noise from outdoors Influence on mould growth Possible reduction of sound adsorption

3.4 A 'new' model

It is clear, therefore, that we are in need of a more complex model to assess IEQ. A model that accounts for all stressors, both positive and negative, interactions, and preferences and needs of the individual for different scenarios and situations (Bluyssen, 2014a). A first concept of a 'new' model was introduced in Bluyssen (2014b); an improved version in Bluyssen (2020) (Figure 5). The model takes account of the combined effects of stress factors in buildings on people (patterns) as well as the individual preferences and needs of the occupants (profiles) for different scenario's (such as homes, offices, schools), and different situations (for example sleeping/eating; meeting/concentrated work; getting lessons); and interactions at human and environmental level. This model features the stress factors caused by the (indoor) environment that a person is exposed to (represented by patterns of stressors and the

Environment model, Figure 4), and the individual differences in needs and preferences (profiles of people as shown in the Human model, Figure 3), depending on their situation (activity and time).

Together with this 'new' model, a methodology to determine profiles of occupants and patterns of stressors for different scenarios (office workers and their workplace; students and their homes; primary children and their classrooms; employees of outpatient areas in hospitals) was introduced and validated in several field studies (Bluyssen et al., 2015; Bluyssen et al., 2016; Kluizenaar et al., 2016; Bluyssen et al., 2018; Zhang, Ortiz and Bluyssen, 2019; Kim and Bluyssen, 2020; Eijkelenboom and Bluyssen, 2020; Bluyssen, Eijkelenboom, Ortiz and Bluyssen, 2021; Zhang and Ortiz, 2021; Ortiz and Bluyssen, 2022). For each scenario, occupant-related indicators and building-related indicators were collected through a questionnaire and checklist(s) to associate patterns of building-related stressors to occupant-related indicators (health: symptoms; comfort: complaints) based on multivariate regression analysis; and to determine clusters of occupants and their profiles based on TwoSteps cluster analysis (Bluyssen, 2022a).

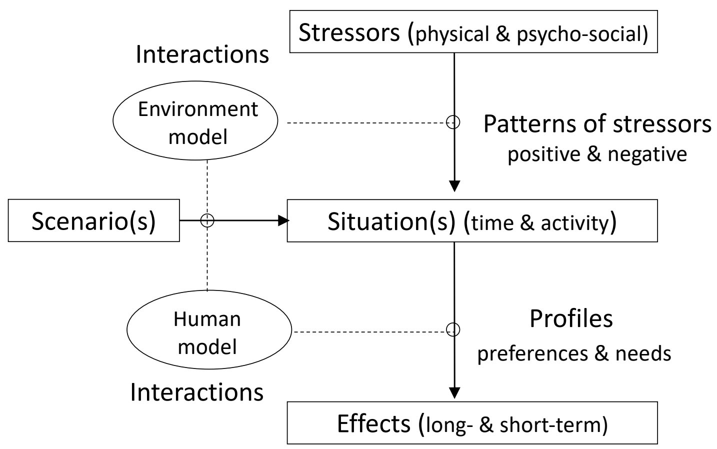


Figure 5. New model (Bluyssen, 2020).

4. Future directions

4.1 Risk-based guidelines

Most current standards and guidelines for IEQ are focused on dose-related indicators (such as temperature level and ventilation rate), while building-related indicators and occupant-related indicators have been rarely considered. Previous studies show, however, that building-related indicators such as building layout and the amount of space can influence occupants' overall satisfaction with IEQ (e.g. Kim and de Dear, 2012), building materials and furnishings can affect health (e.g. Bluyssen et al., 2016). Moreover, these comfort and health effects are related to preferences and needs of the occupants (occupant-related indicators), and therefore can differ (Bluyssen, 2010). Therefore, there seems to be a need to include both building-related and occupant-related indicators, additionally to the dose-related indicators listed in most standards and guidelines. Moreover, it is necessary to adopt risk-based, rather than absolute guidelines and standards.

A good example is the discussion on how to provide good IAQ. An important control strategy for IAQ is to reduce emissions of pollutions as much as possible, also named source control. If this is not possible, for example when you are cooking or the outdoor air is polluted, then you can choose to ventilate and/or clean/filter the air. How to ventilate 'properly' and how much ventilation is required depends on the pollutants and the situation. Nevertheless, our current standards and guidelines for IAQ are based on dose-response relationships only.

To decrease the risk of far-range airborne transmission of SARS-CoV-2, the use of 'proper' ventilation measures has been recommended (Morawska et al., 2020; ASHRAE, 2020; REHVA, 2021). 'Proper' ventilation means the supply of 'clean' air and exhaust of polluted ('infected') air from the breathing zones of each individual person, without passing through the breathing zones of other persons, and preferable without recirculation of air. In spaces in which the main pollution sources are people, the standards and guidelines are aimed at controlling odour and CO_2 exhaled by occupants, and base this control on limit values for CO_2. Also, during the COVID-19 pandemic, a number of organisations made recommendations to use CO_2 as an indicator of the risk of airborne infection transmission (e.g. REHVA, 2021). While CO_2 can be useful as an indicator of ventilation of a space under certain circumstances, indoor CO_2 concentrations do not necessarily correlate with other important indoor air pollutants (ASHRAE, 2022). Moreover, the outcome of these CO_2 measurements gives us information on how much should be ventilated at room level, and not on how and when to 'properly' ventilate: how is this fresh air ventilated and distributed through the space, in relation to the activities taking place and the occupancy over time (Bluyssen, 2022b). To be able to say something about the how and the when, thus to provide 'proper' ventilation, it is clear that both building-related and occupant-related indicators are required.

In Tables 2 and 3, respectively, a list of building-related and occupant-related indicators is presented that would be worthy to include and have been suggested in previous studies (overview in Bluyssen, 2022a). More research is required to better define the criteria/requirements for these indicators for different scenarios, occupants, activities and spaces.

Table 2. Suggested building-related indicators to be included in standards and guidelines for IEQ.

Component/topic	**Building-related indicators**
Ventilation regime	ventilation type; (local) ventilation efficiency; airflow pattern
Natural ventilation	windows location and dimensions; passive grills
Mechanical ventilation	location of air supply and exhausts; grilles direction flow; maintenance schedule
Air cleaning	type of air filter; air cleaning devices
Floor	type of wall material; emission label; hard/fleecy material
Walls	type of ceiling material; emission label
Ceiling	type of ceiling material; emission label; height
Cleaning	cleaning schedule; cleaning products
Windows	window frame colour vs. wall colour; single/double/triple glazing
Lighting	type of lighting; natural or artificial; reflection on the surface
Sound absorption material	presence and location of sound absorption material
Heating and cooling system	type of heating system; location of radiators (if present); type of cooling system

Table 3. Suggested occupant-related indicators to be included in standards and guidelines for IEQ.

Component/topic	**occupant-related indicator**
Personal characteristics	number of occupants; age range; sex; duration of stay; activity level
IEQ and health	needs to deal with diseases and disorders, such as: allergies, asthma, diabetes, etc.
IEQ and comfort	preferences for IEQ to perform well, such as preferences for light (brighter/darker), background noise (non/a lot), temperature (warm/cold), draft/still air, etc.

4.2 Climate change

Except for the health effects that we see today, the possible consequences for indoor environment of climate change, is also a topic to be mentioned (Aries and Bluyssen, 2009; Salthammer et al., 2022). The average outdoor air temperature is rising; variation in weather conditions is increasing: we experience more heatwaves, more heavy rainfalls, sudden wind speeds and storms (IPCC, 2021). We observe an increase in smog frequency in urban areas caused by temperature rise, resulting in an even more polluted outdoor air. As a consequence, we will stay even more indoors, due to the air quality (smog events) but also because of these sudden heavy rainfalls and wind speeds. The air outdoors will be hotter, more humid, and more polluted. Changes in heat and mass transfer between the inside and outside of buildings will have an increasing impact on indoor air quality and thermal quality (Salthammer et al., 2022). Consequently, the outdoor air will need to be cleaned before it can be used to ventilate indoors, depending on regional climate and concentrations of ambient air pollutants.

To combat climate change, a transition to less carbon emissions in the buildings and construction sector is needed (EU, 2018). This transition implies retrofitting the existing building stock as such that no (or less) fossil fuels (e.g. gas and coal) are used to heat and/or cool our buildings. Unfortunately, homes that already have been retrofitted to use less 'energy' (fossil fuels), seem to not use less energy in real life. Behaviour of people towards energy use and comfort has an important role in this discrepancy (Ortiz and Bluyssen, 2019). Moreover, more health problems seem to occur as a by-coming result of these retrofits. Energy-efficient retrofitting measures have shown to lead to complaints about mould growth, built-up of pollutants (including radon), lack of control, thermal comfort stress (people feel too cold, or too warm, draught), noise annoyance from heating and ventilation installations, and a whole range of health problems (Ortiz, Itard and Bluyssen, 2020). Clearly, resilient new ways of creating and maintaining healthy and comfortable indoor spaces for different occupants in different situations, require better understanding of the indoor environment, its occupants, interactions, and effects.

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