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Bluyssen, Philomena M.

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The need to go beyond the comfort-based dose-related indicators in our IEQ-guidelines

Philomena M. Bluyssen

Faculty of Architecture and the Built environment, Delft University of Technology, Delft, the Netherlands

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ABSTRACT

Research has shown that even though the indoor environmental conditions seem to comply with current standards and guidelines and those conditions seem 'comfortable' enough, staying indoors is not good for our health. Reasons for this discrepancy might be the fact that these guidelines (such as ventilation rate, lighting level, and temperature ranges) are mainly based on single-dose response relationships (effect modelling using dose-related indicators) for the physical stressors (e.g. odour, light, sound, and temperature) determined for an average adult person. They are aimed at preventing short-term discomfort rather than long-term negative health effects, ignoring situation-related aspects and different preferences and needs of occupants. A more comprehensive model, accounting for integrated effects of all stressors, and different preferences and needs of occupants in different scenarios and situations, based on situation modelling making use of building and occupant-related indicators, is introduced and partly validated in a series of field studies in different scenarios. Based on the outcome of these field studies and insights from other studies, the methods, indicators and in particular the human model are discussed. Research directions to go beyond the mainly comfort-based dose-related indicators in our IEQ (indoor environmental quality)-guidelines are proposed.

1. Introduction

1.1. Problems

While outdoor air, heat, noise, and light pollution are accepted as environmental risk factors [1–4], diseases and disorders caused by exposure indoors, in which we spend 80–90 % of our time, are less common knowledge. Exposure to increasingly prolonged periods of light pollution (indoors and/or outdoors), characterized by excessive or inappropriate use of artificial light (e.g. increasingly use of computers, mobile phones etc.), and chronic exposure to relatively low environmental sound levels (e.g. noise from air conditioning, heat pumps, traffic), causes disruptions in sleep patterns, disturbances in circadian rhythms, and fluctuations in melatonin and cortisol levels, and can lead to a whole range of diseases and disorders [4–6]. Bad quality of sleep has been correlated with light, air, noise, and heat pollution exposure indoors and outdoors [7–11]. Exposure to air, sound, light and thermal stressors indoors, contribute to diseases such as mental illnesses, diabetes, obesity, cardiovascular and chronic respiratory diseases, cancer, and very recently, COVID-19 [12,13].

Additional to the above mentioned disease burden, studies have shown that indoor environmental conditions, comprising of thermal factors (e.g. draught, temperature), lighting aspects (e.g. reflection, view, luminance ratios), air quality (e.g. odours, mould, chemical compounds, particulates, and ventilation rate) and acoustical aspects (e.g. noise and vibration), 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 [review in 12]. Moreover, the consequences of climate change [14] for indoor environmental quality (IEQ) and the effects of the retrofitting measures we take to reduce energy consumption on health and comfort indoors, are emerging concerns [review in 15]. Additionally, from studies it is concluded that such measures do not always result in the wished for energy savings, partly caused by the occupants and their behaviour related to their preferences and needs [15].

1.2. IEQ assessment

From all these findings, it seems that staying indoors is not good for our health, even when the indoor environmental conditions seem to comply with the current standards and guidelines for IEQ (thermal,

E-mail address: p.m.bluyssen@tudelft.nl.

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lighting, acoustical and air quality) and those conditions seem 'comfortable' enough [12,16]. Reasons for this discrepancy might be the fact that these guidelines (for example maximum concentrations of certain pollutants, ventilation rate, and temperature ranges used in guidelines and building certification schemes *are mainly based on single-dose response linear relationships (using dose-related indicators) to prevent negative effects for an average adult person*: for each parameter or indicator of the four physical stressors (odour, light, sound, and temperature) its effect is determined separately (effect modelling) [12, 17–21]. This tends to work well for health threatening exposures for which a clear dose-response relationship has been determined; For example, dose-related maximum allowed sound levels to prevent damage to the inner ear causing tinnitus, and/or hearing loss (e.g. [17,22]). Unfortunately, for a lot of these indicators the mechanisms used behind the values or ranges, are not always that clear. A good example is the minimum ventilation rate (see Fig. 1). Based on either CO_2, carbon dioxide, as an indicator for bioeffluents, or certain emissions of building materials, minimum ventilation rates have been discussed and are still being discussed for almost two hundred years now. Apparently, we have no clue which rate to take! Even more so during the pandemic we were in.

Most of the dose-related indicators applied, are focussed on preventing 'discomfort', not on preventing negative health effects or enhance a positive health effect. Take for example, guidelines for thermal comfort, that are based on models focused on creating thermally neutral conditions (e.g. Fanger model, adaptive comfort model) [17,19]. Thermally neutral conditions, however, 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 ([30]). It means that when your body doesn't have to work to be in a thermally neutral condition, more fat is stored, which could on the long term have negative health implications [12].

Another example is lighting quality. 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, and some also on the minimalization of blinding caused by daylight and/or artificial light [17,19]. Non-visual aspects of light, however, need to be considered when it comes to health. 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 antioxidant melatonin is immediately stopped, alertness and core body temperature is increased, and sleep is distorted (affects circadian rhythm) [31]. 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 [32]. The 'right' dosing of preferable natural light during the day is therefore important [12]. Unfortunately, this required dosing can differ per person, as their circadian rhythm can also differ [12,33].

Relationships between indoor environmental conditions and those effects (diseases and disorders) are complex and not for everyone the same and can differ in different scenarios (e.g. homes: [34]; offices: [21]; schools: [35]; hospitals: [36]). Indoor environmental stressors can cause their effects additively or through complex interactions (synergistic or antagonistic) [37,38]. It is known that those effects are influenced by psychological (e.g. mood, traits), physiological (e.g. health state, allergies), personal (e.g. age, sex), social (e.g. privacy, events) and/or environmental aspects (e.g. location, climate region) [39], that those aspects go beyond the environmental parameters used in guidelines, and that we must acknowledge the fact that IEQ is more than the sum of its parts, interactions occur between stressors at human as well as environmental level [12,37,38], which requires an integrative approach [12, 19,40,41]. From research in different fields, it is seen that interactions at human level occurring through diverse mechanisms in the human body meant to cope with the different stressors, cause diseases when not coping, are complex [12] (see Fig. 2). This might explain why it is so difficult to associate a certain dose-related indicator with a certain health effect.

1.3. Health and comfort indicators

The health and comfort indicators that are available to assess the effect of those stressors are: the dose-related indicators, the occupant-related indicators, and the building-related indicators [42]. Most current standards and guidelines for IEQ are focused on dose-related indicators (such as temperature level and ventilation rate). The latter two categories of indicators, the occupant-related indicators (focused on the occupant such as sick leave, productivity, and number of symptoms or complaints) and 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, the use of a particular ventilation system, and/or a cleaning schedule)), are rarely considered [35,36,40,43,44].

Although several weighting and classification schemes, rating tools, models, digital twins, and intelligent monitoring and feedback systems for the integrative evaluation of indoor environmental qualities have been introduced in the past decades (e.g. [45–49]), most of these are still merely focussed on the separate qualities (thermal, air, acoustical, and

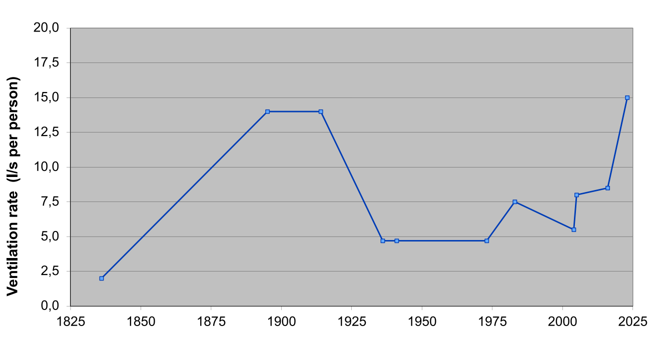

Fig. 1. The recommended minimum ventilation rate for offices changed over the years [23–29]: from 2 l/s person by Tredgold in 1836 to 14 l/s per person by Billings in 1895, down to 4.7 l/s person in 1936 by Yaglou, up again to 7.5 l/s person in 1983, down to 5.5 l/s per person by ASHRAE in 2004 and up to 8 l/s per person by CEN in 2005 (both for a single person office), then 8,5 l/s per person in 2016 by ASHRAE (for a single person office) and 15 l/s person by ASHRAE in 2023 for infectious control (adapted from Figure 5.2 in [19]).

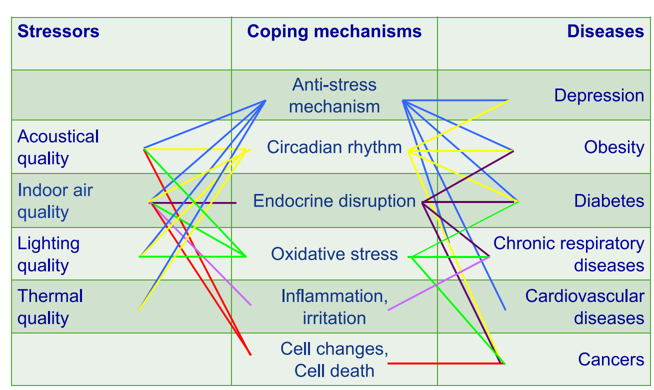

Fig. 2. Possible associations found in previous studies described in Chapter 3 of [12] between stressors, coping mechanisms and diseases that occur when not coping (this figure is adapted from Figure 1.3 in [12]). The colours of the lines represent associations for the coping mechanisms: blue for the anti-stress mechanism (see description in Section 4.2), yellow for circadian rhythm (see description in Section 1.2), purple for endocrine disruption, green for oxidative stress (see description in Section 4.1), pink for inflammation, irritation, and red for cell changes and cell death.

lighting quality). 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. [21]), and certain building materials and furnishings have been linked to certain health effects (review in [12]). Moreover, these comfort and health effects are related to preferences and needs of the occupants (occupant-related indicators) and therefore can differ [42]. 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.

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. During the COVID-19 pandemic, to decrease the risk of far-range airborne transmission of SARS-CoV-2, the use of 'proper' ventilation measures was recommended (e.g. [13,50,51]). '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 preferably without recirculation of air. In spaces in which the main pollution sources are people, the standards and guidelines are mainly aimed at controlling bioeffluents of the occupants and base this control on maximum values for CO_2 concentration. Also, during the COVID-19 pandemic, several organisations made recommendations to use CO_2 as an indicator of the risk of airborne infection transmission (e.g. [51]). 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 [52]. The outcome of these CO_2 measurements gives us information on how much should be ventilated at room level when occupied, 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 [53]. To be able to say something about the how and when, thus, to provide 'proper' ventilation, both building-related and occupant-related indicators are required. Moreover, interactions with the other environmental factors need to be included in the action plan.

To increase ventilation in classrooms during the pandemic, it was observed that windows and doors were open almost all the time, even in the presence of mechanical ventilation [54]. Consequently, many school children were sitting with their coats on in the classroom, fighting the cold air from outdoors. Next to the cold, opening windows can also introduce noise from outdoors. In situations with a mechanical ventilation system or mobile air cleaners, problems with noise from the increased airflow can increase, when systems are put on their max possible airflow for as much ventilation or cleaning as possible [55]. Not to speak about the drafts these systems and devices can cause. So, actions to solve one problem might create other problems.

To avoid health risks and discomfort, the European Energy Performance for building directive (EPBD) [56] mandates that "Member states should support energy performance upgrades of existing buildings that contribute to an adequate level of indoor environmental quality achieving a healthy indoor environment." It defines indoor environmental quality as "the result of an assessment of the conditions inside a building that influence the health and wellbeing of its occupants." (p.19 note 66). However, how this integrated assessment should be executed, is not included. It only states (p.30 article 13): "Member states shall set requirements for the implementation of adequate indoor environmental quality standards in buildings to maintain a healthy indoor climate". To set those requirements as mandated by the EPDB [56], it is therefore important to go beyond the comfort-based dose-related indicators and determine other indicators that can help to prevent long-term negative health effects and turn the negative effect around into a positive one.

1.4. 'New' model

To assess IEQ and determine these additional indicators, there is a need for a more comprehensive research model than the single dose-response model (effect modelling) we have used so far. A more comprehensive model, accounting for integrated effects of all stressors, interactions at environment level and human level, and different preferences and needs of occupants in different scenarios (e.g. homes, offices, schools) and situations (e.g. sleeping/eating; meeting/concentrated work; getting lessons), based on situation modelling making use additionally of building-related and occupant-related indicators, was introduced [16,18,39,42,57] (Fig. 3).

The model is focussed on situations instead of single components, including all situation-related stressors (physical and psycho-social). The 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, Fig. 4a) over time and the individual differences in preferences and needs (expressed with profiles of people as shown in the Human model, Fig. 4b), depending on their situation (activity and time).

To validate and elaborate this 'new' model and determine which indicators and assessment methods to apply, several field studies have been executed [58–70] to determine profiles of people (based on occupant-related indicators) and patterns of stressors (based on building-related and occupant-related indicators) for different scenarios and situations. In this paper, the methods applied in the field studies and their outcomes are presented. Based on the outcome of these field studies and insights from other studies, the methods, indicators and in particular the human model is discussed. Research directions to go beyond the mainly comfort-based dose-related indicators in our guidelines are proposed.

2. Field studies

2.1. Study design

Patterns and profiles were determined for different scenarios: 1) office workers and their workplace; 2) university students and their homes & study places; 3) primary school children and their classrooms; and 4) employees of outpatient areas in hospitals. For each scenario, occupant-related indicators and building-related indicators were collected through a questionnaire and checklist(s) to associate patterns of stressors to occupant-related indicators (health: symptoms; comfort: complaints); and to determine clusters of occupants and their profiles (preferences and needs) [58–70]. For each scenario, except for the university students' studies, a survey was conducted comprising of a

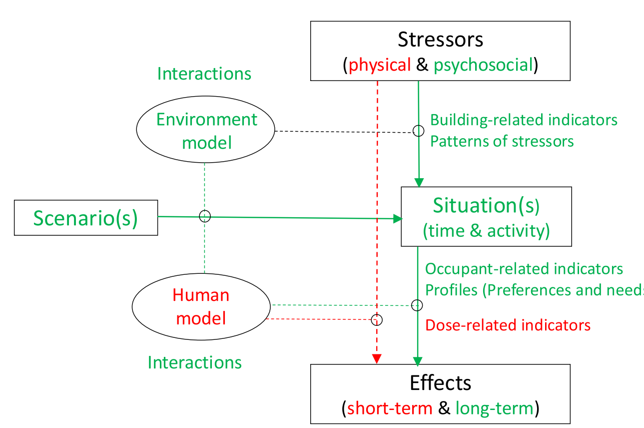

Fig. 3. New model (situation modelling), including the old model (effect modelling) (Adapted from [18]). Note: red colour refers to the old model, and green to the parts that have been added in the new model.

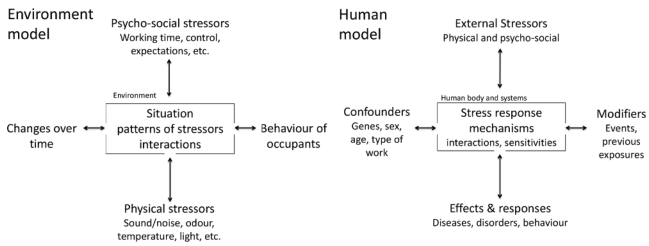

Fig. 4. a) Environment model and b) Human model [18].

questionnaire and a building inspection with the use of checklists (at building and room level). For the university students' studies, only a questionnaire was developed, including also questions on building-related indicators, because visiting the homes was not feasible. For each scenario, except for the 'primary school children and their classrooms' scenario, the questionnaire was digitally distributed. The questionnaire for the children was handed out and collected during the visit to the schools. The checklists (building and room) focused on the indoor and built environment through characteristics of building, systems and rooms (e.g., windows operable or not, type of HVAC system, lighting system, solar screens, reflection on desks, surfaces of ceiling, floor and walls, sources of noise, dampness, mould growth, condensation, pollution sources, and control system), characteristics of the built environment (e.g., busy road and rural/ surroundings), and processes to maintain and operate the building and its activities (e.g., cleaning activities/schedule, renovation and retrofitting activities, and maintenance of HVAC system). The questionnaire included questions about personal data, psychosocial environment, psychological characteristics, positive or negative events (e.g. marriage or funeral), physical effects, and preferences and needs for IEQ and in some cases also preferences and needs for psychosocial comfort.

2.2. Patterns of stressors

To determine patterns of stressors, multivariate analysis was performed on data of 7441 office workers and 167 office buildings in eight European countries [64], 396 students and their homes in The Netherlands (2015) [58], 682 students and their homes in different countries (2019) [65], 949 primary school children and 45 classrooms [66], 556 employees of outpatient areas in six Dutch Hospitals (2019) [67], and 1575 students and their homes in The Netherlands (years 2016–2020) [68]. To examine the relations between an indicator for health or comfort and building-related aspects, multivariate linear regressions were fitted considering potential confounders and/or risk factors. The building-related patterns of stressors followed from the multivariate regression analysis for each of the field studies performed are presented in Table 1.

From the field studies presented it can be concluded that it is possible to determine patterns of stressors for different scenarios (and situations) based on multivariate regression analysis of a survey of the occupants and the buildings they are occupying. After full adjustment, the regression models in all the studies for health effects confirmed their multifactorial character. Moreover, the studies resulted in 'other' factors and stressors than used in guidelines, confirming the importance of considering all possible stressors when studying a certain disease or disorder. Several building-related stressors, personal factors and psychosocial factors, showed to be related to a disease or disorder. For example, in the student homes study of 2015 [58] the outcome of the 'home' questionnaire showed that 33 % of the 396 students reported to have suffered from rhinitis in the past 12 months. Multivariate analysis showed that multiple stressors were associated (positive or negative) with having rhinitis in students: biological pollutants (caused by pets), chemical pollutants (caused by MDF from less than one-year old furniture in the bedroom), ventilation (opening windows in bedroom more

Table 1
Patterns of building-related stressors and other risk factors for different health and/or comfort indicators in different scenarios.

Scenarios	Building-related stressors + other risk factors (OR; p-value)
OFFICAIR 20,12[1]: 167 office buildings in 8 EU countries with 7441 office workers [64]	**Overall satisfaction:** acoustical solutions (1.25; **0.042**), mould growth (0.54; **0.014**), complaints procedure (0.70; **0.002**), cleaning activities in the evening after work (0.76; **0.003**); number of occupants (>100) (0.96; 0.067). **Health (BSI-5):** number of occupants (>100) (1.05; **0.002**), lack of operable windows (1.45; **0.001**), presence of carpet (1.2; **0.014**); cleaning activities in the evening after work (1.26; **0.003**); cooling system present (1.28; 0.054); printer on corridor (0.85; 0.058), office furniture made of particleboard < 1 year old (1.03; 0.059).
Student homes 20,15[2]: 396 students and homes in The Netherlands [58]	**Rhinitis:** family with rhinitis (5.27; **<0.0001**), training exercise (0.50; 0.046), having no pets (0.37; **0.005**), MDF furniture < 1 year old in bedroom (2.26; **0.015**), opening windows in bedroom (winter) > 1/week (0.55; **0.041**), negative events (1.74; 0.054)
Students international 20,19[3]: 682 students and their homes in 5 cities [65]	**Rhinitis:** no family with rhinitis (0.24; <**0.0001**), age (17–25 vs 26–39 years) (3.69; **0.006**), having no pets (0.28; **0.001**), open bookshelves (2.43; **0.005**), sweeping floors less than 1/week (1.99; **0.035**), location (urban vs. rural) (0.39; **0.016**), washer location other than in living space (0.48; 0.078). **Headache:** negative events (1.60; **0.049**), PANAS negative (0.40; **0.006**), having pets (1.92; **0.014**), location (urban vs. rural) (0.58; **0.035**), no open fireplace (0.54; 0.066), spray deodorant > 1/week (1.60; 0.090).
Schools 20,17[4]: 949 children of 45 classrooms (17 primary schools) [66]	**Health (PSI-9):** location (suburbs vs. rural) (0.89; **0.003**), heating system (radiator below window vs. floor heating or air heating) (1.13; **0.029** or 1.14; **0.014**), solar devices hampering opening windows (1.07; 0.053). **Comfort (PCI-7):** mechanical assisted ventilation vs natural ventilation (1.08; **0.021**), dark vs. light coloured window frame (1.11; **0.003**), laminated vs. synthetic smooth flooring material (1.08; **0.031**), and vacuum cleaning < 1/week (1.09; **0.009**).
Hospitals 20,19[5]: 556 outpatient workers of 6 hospitals [67]	**Dry eyes:** rotating heat exchanger (1.65; **0.018**), having no windows (3.42; **<0.001**), type of workplace (office vs consultation room) (1.96; **0.008**), 2–4 persons in room (0.46; **0.031**), > 4 persons in room (0.42; **0.016**). **Headache:** having no windows (2.80; **0.001**), type of workplace (office vs consultation room) (2.03; **0.005**), ERI (2.18; **0.018**), over commitment (1.07; **0.031**), daily coffee consumption 5 or more cups (0.55; 0.075).

notes: OR = odds ratio; p-values in bold refer to significant relationship at 5 % level; BSI-5 = Building Symptom Index based on five symptoms: dry eyes, blocked or stuffy nose, dry/irritated throat, headache, and lethargy [71]; ERI = the Effort Reward Imbalance ratio [72]; PANAS = Positive Affect Negative Affect Scale [73]; PSI-9 is defined based on 9 symptoms: dry eyes, itching or watery eyes, blocked or stuffy nose, running nose, sneezing, dry throat, difficulty breathing, dry, irritated or itching skin, and headache; PCI-7, is defined based on 7 classroom conditions: thermal discomfort, temperature changes, wind/-draught, smells, noise, sunlight and artificial light.
Adjusted for: 1) gender, age mean, current smoker percentage, ERI,

overcommitment and negative affect means; 2) gender, family rhinitis, smoking status, alcohol consumption, work out, and PANAS negative and positive; 3) rhinitis: gender, age, family rhinitis, smoking status, negative event; headache: gender and age, negative events, PANAS negative; 4) mood during completion of questionnaire; 5) dry eyes: gender, age, smoking status, alcohol consumption, ERI and over commitment; headache: gender, age, suffering from migraine.

than once a week) and personal factors (e.g. working out) (Table 1) [58]. Additionally, the students international study showed the independency of season or climate region of the identified risk factors, while some identified factors were typical for the city studied (e.g. open fireplace) [65].

2.3. Profiles

To determine clusters and their profiles, 2-steps cluster analysis was performed on comfort, health, preferences and/or needs of 1014 office workers in 20 office buildings in the Netherlands (OFFICAIR NL) [59], 949 primary school children of 45 classrooms [61]; 556 employees of outpatient areas in six Dutch hospitals [62], 502 employees of 10 office buildings in the Netherlands [63], 1575 students and their homes in 2016–2020 [68], and 474 students and their study places [70].

Before performing the TwoStep cluster analysis, correlation analysis and Principal Component Analysis (PCA) was performed for all studies except for the OFFICAIR study [59]. Correlation analysis, the strength between perceived comfort and preferences, were performed to decide if both perceived comfort and preferences should be included in the cluster analysis. This is done because multicollinearity may affect the weight of constructs in cluster analysis, so that should be prevented. Then, PCA was conducted to reduce the number of original variables into fewer independent components. As recommended by Tabachnick and Fidell [74], the number of components was determined by an Eigenvalue greater than 1; sample adequacy with Kayser-Meyer-Olkin was greater than 0.6; for the rotation method a Varimax orthogonal rotation was selected; and strength was determined by loadings within components $>$ 0.4, loadings between components $<$ 0.4 [75].

For the TwoStep analysis, the final sets of components resulting from the PCA were used to conduct the analysis. This clustering technique was used as opposed to other clustering methods, as it allows for the handling of both continuous and categorical data, the optimal number of clusters are automatically selected by the method; and the method is suitable for large data sets [76–77]. Final model validation was carried out with the fulfilment of four conditions [77]: a silhouette of above 0.2; variables predictor importance greater than 0.02; ensuring statistical significance ($p < 0.05$) between variables by conducting Chi^2 tests; applying the model to two random halves of the sample and ensuring that the results are similar. The clusters and their profiles for each of the studies are presented in Table 2.

For example, in the primary school study of 2017, 2-steps cluster analysis of self-reported comfort and preferences for IEQ in the classroom of 949 children (average age: 10) resulted in six profiles [61]. Among them, four clusters of children had specific concerns related to the IEQ factors, while the other two clusters of children did not show a specific concern. These profiles were observed in most groups of the different participating schools, indicating that the preferences of children can differ, even when they are exposed to the same situation.

Because other aspects than IEQ factors affect occupants' health and comfort, especially at work, several studies were performed including also psychosocial aspects, resulting in profiles for both preferences for IEQ and preferences for psychosocial comfort. For example, the 'Home' questionnaire for students was slightly adapted to include questions on perception and preferences for IEQ and psycho-social aspects, focussed on their study place [70]. Two step cluster analysis was performed twice: first to cluster the students (average age: 20 years) based on their IEQ preferences, and second to cluster them on their psychosocial comfort preferences. Both clustering resulted in three clusters. Then the

Table 2
Studies performed with 2-steps cluster analysis and their profiles.

Name study	Profiles
OFFICAIR 2012 NL: 1014 office workers in 20 office buildings [59]	3 profiles clustered on self-reported IEQ-related complaints (comfort): • Healthy and satisfied workers • Moderate healthy and noise-bothered workers • Unhealthy and air and temperature-bothered workers
Schools 2017: 949 children of 45 classrooms (17 primary schools) [61]	6 profiles clustered on self-reported IEQ-comfort and IEQ-preferences: Sound concerned, Smell and sound concerned, Thermal and draught concerned, Light concerned, All concerned, and Nothing concerned
Hospitals 2019: 556 outpatient workers of 6 hospitals [62]	6 profiles clustered on self-reported IEQ-comfort and IEQ-preferences 3 profiles clustered on self-reported psychosocial comfort and preferences for psychosocial aspects
MyWorkplace 2020: 502 employees of 10 office buildings [63]	4 profiles clustered on self-reported preferences for IEQ and 6 profiles clustered on self-reported preferences for psychosocial comfort
Students 2016–2020: 1575 students and their homes [68]	3 profiles: 'most symptoms, and the least diseases'; 'average symptoms and diseases'; 'the least symptoms and the most diseases'
MyStudyplace 2022: 474 students [70]	3 profiles clustered on self-reported preferences for IEQ (IEQ concerned, visual concerned, and IEQ unconcerned) 3 profiles clustered on self-reported preferences for psychosocial comfort (preference for most of psychosocial aspects, for presence and company of others, only for amenities and cleanliness) 9 overlap profiles: (1) the concerned perfectionist, (2) the concerned extrovert, (3) the concerned non-perfectionist, (4) the visual concerned perfectionist, (5) the visual concerned extrovert, (6) visual concerned non-perfectionist, (7) the unconcerned introvert, (8) the unconcerned extrovert, and (9) the unconcerned non-perfectionist

overlap of these two models was determined, which resulted in nine unique profiles (see Table 2). In particular interesting is that for the IEQ preferences profiles, two profiles were similar to two of the six profiles identified in the primary school children study: the 'IEQ concerned' or 'All concerned', and the 'IEQ unconcerned' or 'Nothing concerned' profile, while only one of the four remaining profiles was similar: the 'Visual concerned' or 'Light concerned' profile (Table 2). This finding could relate to the fact that all students were from the faculty of Architecture, which is a group that might be more concerned with lighting aspects than students of other faculties.

Based on data collected with the 'home' questionnaire of 1575 students and their home in 2016–2020, cluster analysis resulted in three clusters: a cluster with the most symptoms, and the least diseases; a cluster with average symptoms and diseases; and a cluster with the least symptoms and the most diseases [68]. Multivariate analysis per cluster for the self-reported diseases rhinitis and migraine, and the self-reported building-related symptoms stuffy nose and headache, showed that the patterns of stressors and risk factors can differ per cluster. Moreover, in case of an overlap in response (correlation of the same stressor with a reported disease or symptom), the associated stressor for one cluster can have a positive effect, while for another cluster a negative effect. The outcome showed that clustering is important to better pinpoint the patterns of stressors that form a risk for getting a disease or disorder for a particular group [68].

3. Discussion

3.1. Preferences, behaviour and health

The field studies confirmed that people differ in their preferences and needs, and it seems possible to distribute them into clusters based on Twosteps cluster analysis of preferences and needs, and profile them based on occupant-related indicators (incl. preferences and needs) acquired through a questionnaire.

The good news is that seemingly each cluster of occupants, has similar preferences and needs (profiles) for certain situations. That means, that in theory, for each cluster the 'ideal' indoor environment (patterns of positive and negative stressors) can be determined. For example, based on the preferences, satisfaction, personal, work and building-related aspects of the survey among outpatient workers in 2017, cubes were created of the IEQ and psychosocial comfort profiles of hospital workers in outpatient areas [78]. Each colour on the cube represents a cluster (group of outpatient workers with similar preferences and satisfaction). A cube shows the profiles (& colours), preferences, satisfaction, personal, work and building-related aspects, respectively on the six sides of the cube (see Fig. 5). With these cubes, new design strategies can be developed as well as strategies to match or fit different users with available indoor environments in an existing building.

The bad news is that the field studies showed that in a classroom or office space all these different profiles coincide. A certain action (such as turning on/off lights; lift/lower shades; close/open windows; etc.) can, therefore, improve the conditions for one child with a certain profile, while for another child with another profile the same action can cause a problem, because of their different preferences and needs [79]. Personalized environmental control systems (PECS), which emphasize individual control of IAQ, but also sound, thermal, and lighting quality, might be a solution but still require development (e.g. [80–82]). There are few studies linking perception and actions (behaviour) at individual level, accounting for differences in perception and preferences for IEQ [83]. Moreover, the link between occupant behaviours and their health effects tends to be overlooked [84] but are important to include [85–89]. For example, studies show that when occupants perceive stuffy air they tend to open windows rather than increase the ventilation [90]. Knowing that when you are indoors for some time you do not notice if the air is stuffy, this could lead to health problems.

Comparison of the self-reported health and comfort of the workers in the MyWorkplace study [63] with the hospital study [62] and the OFFICAIR NL study [59], proposed that the prevalence of anxiety, depression, migraine, and rhinitis, increased for this population during the work-from-home period of the COVID-19 pandemic. As the students' studies showed, having rhinitis and/or migraine is linked with both

Fig. 5. Image of the cubes of the IEQ and psychosocial comfort profiles of hospital workers in outpatient areas [78].

negative events and pollution sources indoors [58,65,68]. While at the office, most likely, mechanical ventilation was increased, most of the office workers that worked at home did not have that possibility, and had to rely on opening windows. Moreover, they spend much more time at home and were therefore a lot more exposed to indoor air pollution sources.

Behaviours are difficult to study since they are influenced by multiple factors (environment, personal, psychosocial, physiological). Researchers have studied them by profiling occupants into behavioural types. These profiles can be based on quantitative factors (i.e. room usage, heating times, income, dwelling type, cleaning schedules, window opening, heating schedules, etc.) [91–94] or qualitative factors (needs, preferences, or emotions) (e.g. [60,95–98]). Studies on occupant behaviours, comfort preferences, and energy use in homes resulted in five clusters [60], showing clearly differences among home occupants with regards to preferences for IEQ comfort and behaviours related to energy use. Behavioural profiling is valuable for creating resilient buildings as retrofits can be customized to the occupant profile, a strategy that can reduce energy consumption and increase comfort and health [84]. Nevertheless, in a review on the use of AI (Artificial intelligence) for energy efficiency and IEQ in buildings it was concluded that most studies applied machine learning on thermal comfort and indoor air quality to predict energy consumption, based on the same few dose-related indicators that our IEQ-guidelines prescribe [17,99].

3.2. Changes in context

In some of the studies it was observed that environmental level changes in context (situation) may affect the preferences and needs of the occupants (profiles) (e.g. [63,79,100]). This was for example seen in the comparison of preferences and needs of hospital workers before and during the COVID-19 pandemic. A qualitative study, comprising of semi-structured interviews and photo-elicitation of seventeen outpatient workers who had been part of a previous study on clustering outpatient workers in hospitals before the outbreak of the coronavirus disease 2019 (COVID-19) [62], was performed to explain the outpatient workers' main preferences for comfort during the COVID-19 pandemic, and compare these with the interviewees' preferences that were identified before the COVID-19 pandemic started [100]. The answers to the questions in the interviews, including contextual changes due to the COVID-19 pandemic and based on the profiles of the clusters, were analysed with content analysis. Main differences in perceptions of comfort as compared to the situation before the pandemic were concerns with the indoor air quality, decreased speech intelligibility with patients, impoverished interaction with patients, increased problems with patient privacy, and threatening behaviour of patients. Comparing preferences and needs before and during the COVID-19 pandemic, showed that occupant's preferences changed over time and were situation-related [100].

In the MyWorkplace study [63], performed during the COVID-19 pandemic, in which cluster analysis revealed four IEQ clusters (e.g. sound and smells, presence of windows, localized temperature, and building systems) and six psychosocial comfort clusters (differences on variables about the personalization of the place, the ergonomics and hygiene, and the size of the space) (see Table 2), this was also observed. Comparison of the results with other clustering studies ((e.g. the hospital study [62] and the OFFICAIR NL study [59]) suggested that both IEQ and psychosocial comfort preferences are situation-related, therefore, can change from situation to situation. How these changes in context affect the number of clusters for a certain situation is unclear, and therefore, needs to be investigated.

3.3. Short-term versus long-term effects

The field studies performed showed that multivariate regression analysis based on data of a survey of the occupants and the buildings they are occupying, leads to other factors and stressors (patterns of stressors) than the conventional comfort-based dose-related indicators used in guidelines. These patterns of stressors include both building-related and occupant-related indicators that form a risk for getting a certain disease, symptom (or number of symptoms), or complaint (or number of comfort complaints). Building-related risk factors were correlated to comfort conditions of the past three months, symptoms occurring the past three months that get better when away from the building, and diseases present in the past 12 months. The field studies showed that preferences and comfort of IEQ seem to be related to health (that is 'short-term' health effects).

The good news is that additional risk factors were identified for some of these 'short-term' effects, which may help to define additional guidelines for indoor environments. Based on the field studies, mainly in The Netherlands, Table 3 lists several building-related indicators that would be worthy to include, whether related to improve comfort or to prevent health effects [101]. More studies in different countries and cultures could lead to more additional risk factors.

The 'bad' news is that diseases that usually take longer to manifest (longer than 12 months), such as chronic respiratory diseases, cancer, and obesity, cannot be studied in this way, and therefore require other ways of investigating and perhaps also other indicators. We are exposed to a mix of stressors in different situations, resulting in both short-term and long-term effects. In the field studies, the focus was on short-term effects and on one situation at the time. Moreover, the outcome was based on self-reported occupant-related indicators, assessed once. A long-term follow-up of populations who have been exposed and who are at risk (cohort), with an exposed (case) and non-exposed (control) group, might have been a better choice than the cross-sectional study design that was applied.

Moreover, perceptual assessments can be affected by previous experiences and exposures, mood, state of health, habits, preferences, etc. [19]. Interactions of different environmental stressors (olfactory, auditory, visual and thermal stimuli) at brain level (central nervous system) might occur, demonstrated in previous studies (reviews in [38,83,102,103]). This was also observed in cross-modal studies in the Experience room of the SenseLab, first with primary school children [104] who assessed the air more odorous when exposed to talking children, and later with bachelor students, who assessed the air more odorous when exposed to traffic sounds [105]. Both observations are most likely related to previous exposures and experiences of the subjects. It has, therefore, been suggested to use physiological indicators to investigate human comfort and apply machine learning to predict human comfort [102,106]. Additionally, digital twins of indoor spaces have been used to simulate sensory experiences based on sound, smell, visual and/or thermal comfort inputs and graph neural networks [49]. How to translate these experiences and physiological measurements into long-term health effects is, however, the question.

Table 3
Suggested building-related indicators to be included in standards and guidelines for IEQ (adapted from [101]).

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

4. Unravelling the human model

To answer this question, let us go into how our body copes with the different stressors. Our body has three systems available to cope with the external stressors: the nervous system, the immune system and the endocrine system. Stressors can be divided into stressors that trigger the (dis)comfort-induced mechanisms and stressors that trigger the health-induced mechanism. With (dis)comfort-induced stress, the nervous system and the endocrine system cooperate (through for example the anti-stress mechanism and the circadian rhythm mechanism), influenced by the status of the immune system, while 'noxious or health' induced stress (initiating for example oxidative stress and inflammation) is handled by the immune system and the endocrine system, and the handling can be influenced by the nervous system [19] (Fig. 6).

4.1. Health-induced stress

An example of a health-induced stress mechanism is oxidative stress [12]. Oxidative stress occurs when there is an excess of free radicals (they steal electrons) over antioxidant defences. Oxidative stress can damage cells, lead to systemic inflammation and may induce cell death. Oxidative stress is responsible for burning your skin by the sun, or when too loud noise ruptures the eardrum in your ears. But air pollution is the main cause of oxidative stress, in particular ultra-fine particles that we breath in and can reach all our organs via the gas exchange in the alveoli, the lung cells.

With health-induced stress our immune system responds at cell level and by production of substances to deal with the stressors (e.g. cytokines). Coping fails when damage to cells prevent your immune and/or endocrine system to work properly [12]. Next to indicators in blood and urine, several skin, eye, and airway symptoms have been correlated with exposure to health-induced stressors (Table 4). Exposure time limits for several dose-related indicators have been established to prevent oxidative stress, such as for sound to prevent damage to the hearing (oxidative stress) [19]; UV-index for direct UV exposure (sun) to decrease the risk on skin cancer (cell damage) [107]; and for fine particles ($PM_{2.5}$) to decrease the risk on several diseases [108]. Whether those limits can be/are kept indoors depends largely on the design, maintenance and use of the buildings and the occupants (behaviour). Moreover, indoor air pollution, originating from sources indoors (including humans and their activities, building materials and furnishing) and outdoors and from chemical reactions between pollutants in indoor air, comprises a lot more pollutants than fine particles (e.g. VOCs). The pollutants recommended to monitor - CO, $PM_{2.5}$, and CO_2 (as an indicator of pollutants emitted by people including infectious airborne particles) - are just a start [109]. Additionally, several building-related indicators focussed on

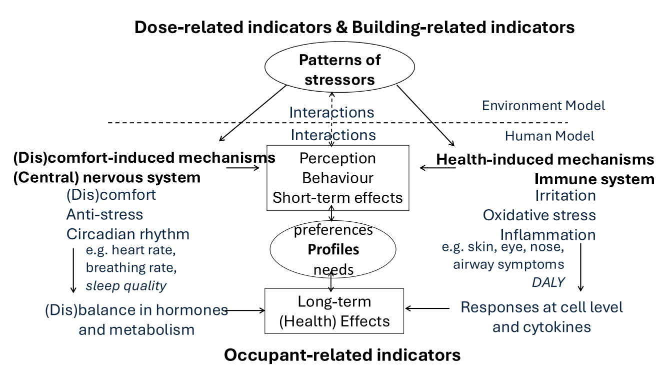

Fig. 6. Human model: stress, coping mechanisms and effects.

Table 4
Examples of indicators for health-induced and comfort-induced stress.

Indicators	Health-induced stress	(Dis)comfort-induced stress
Dose-related	Exposure limit values • Sound: 85 dB(A) averaged over 8 h [19] • Light (natural light): UV-index [107] • Air: $PM_{2.5}$, 24-h average < 15 μg/m^3 [108]	For 'short-term' comfort: • Sound: sound pressure level in dB (A), reverberation time, • Light: light level (lux), luminance ratio, • Air: CO_2 concentration (indicator), ventilation rate • Thermal: temperature range, relative humidity range
Occupant-related	• Skin, eye and airway symptoms • Indicators in blood and urine (e.g. cytokines) • Cell changes • Diseases	• Nervous system: heart rate, breathing rate, etc. • Hormones (e.g. cortisol) in blood, saliva, hair • Preferences, acceptability, behaviour
Building-related	• Proper ventilation: e.g. cooking hood and air cleaning/filtering • Low-emitting materials and products • Protection from sources (sun, noise, heat/cold, air pollutants)	Focused on preventing discomfort • Ventilation, heating and/or cooling systems, solar screens, personal control systems, etc.
Integrated effects	• DALY	• Sleep quality

'source' control are available to address the health induced stressors and their effects [101] (see Table 4).

The DALY (Disability adjusted life-years) concept has been proposed to estimate how harmful the indoor air is during a specific time frame [48,110]. However, to estimate the integrated effect of the health-induced stressors on a disease based on the DALY calculation, we need to know the exposure-function, the other risk factors, and the interactions of those risk factors.

4.2. (Dis)comfort-induced stress

An example of a (dis)comfort-induced mechanism is the anti-stress mechanism: in response to various stresses, such as noise, reflection, too warm/too cold, an increase of secretion of anti-stress hormones can occur. In 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 [12]. It has been proven, although other hormones and reactions are involved, that *cortisol* plays an important role in the health effects of this chronic imbalance: 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 [6].

With (dis)comfort-induced stress our nervous system responds first, followed by our endocrine system and when our body fails or can no longer cope with (dis)comfort-induced stress, a disbalance in hormones can occur. The effects of not coping with (dis)comfort-induced stress can be seen in the bodily responses induced by the nervous system (e.g. heart rate, breathing rate, blood pressure, local responses), metabolism (e.g. fat tissue, cholesterol), and disbalance in hormones (e.g. cortisol, melatonin) that is created with chronic stress [5,6,111–113], all potentially occupant-related indicators (see Table 4). An interesting occupant-related indicator that has been correlated to light, air, noise, and heat pollution through (dis)comfort-induced stress, is 'quality of sleep' [7–11]. Bad quality of sleep has been associated with several diseases and disorders. However, several (dis)comfort induced stressors can also lead to short-term positive effects that can have a positive effect on health over time. For example, the right dosing of light during the day will lead to a better sleep quality, music can help to unstress you, plants can improve people's mood, some odours can increase the balance of people's behaviour [12]. It is therefore important to consider both the positive and negative effects of stressors in our studies. Moreover, as was seen in [68], one stressor can have a negative effect on a person, while the same stressor can have a positive on another person.

Our current IEQ-guidelines, to keep people 'comfortable' and performing well, are based on short-term assessment of dissatisfaction or annoyance (perception) of the individual IEQs, expressed with dose-related indicators in combination with building-related indicators focussed on preventing discomfort (see Table 4). In a recent study on which indicators can be used to identify differences in bodily responses and perceptual assessments of each individual when exposed to different sounds, both heart rate and breathing rate were recommended to be used in future sound experiments [114]. Moreover, hearing acuity and type of sound (sound frequencies) were key indicators for identifying differences in bodily responses (such as heart rate and respiration rate) as well as perceptual assessments [114]. Also, other physiological/physical testing have been used: such as the finger pulse wave amplitude [115]; wearable electroencephalography (EEG) devices to record and analyse emotional experience [116]; saliva sampling to monitor changes in salivary alpha-amylase and cortisol with changes in thermal comfort [117]; and eye-tracking has been used to record pupil diameter as an indicator of emotional arousal [118]. So clearly, the use of physiological indicators needs to be explored.

5. Conclusions and recommendations

To "set requirements for the implementation of adequate indoor environmental quality standards in buildings in order to maintain a healthy indoor climate", as mandated by the EPDB, it is important to go beyond the mainly comfort-based dose-related indicators used in our guidelines and determine indicators (building-related, occupant-related, and/or dose-related indicators) that can help to prevent negative health effects and enhance positive health effects. The question is then what is needed to determine those indicators.

First of all, we need to acknowledge that IEQ is more than the sum of its parts and that people differ in their preferences and needs, which requires an integrative approach and a different research model than the single dose-response model on which our guidelines are based: a more comprehensive model, accounting for integrated effects of all stressors and modifiers, and different preferences and needs of occupants in different scenarios and situations. Field studies that were performed to validate this 'new' model showed that: 1) occupants can be clustered into clusters with different profiles (preferences, needs, and behaviours) and 2) patterns of stressors can be associated with different effects (for different clusters), resulting in better insight which indicators (stressors) play a role in such an effect. The 'new' model makes it possible to match profiles of people with patterns of stressors for a certain situation. How the number of clusters vary, how the profiles of these clusters change over time, and how dependent these profiles and patterns are on the scenario and situation (context), will need to be studied.

The outcome of the validation of the 'new' model addressed the need for 'other' methods (and indicators) that enable to study interactions occurring at human level (perceptual and physiological) induced by indoor environmental stressors resulting in both short-term and long-term (integrated) effects. The methodology applied in the field studies was focused on relatively 'short-term' self-reported effects and on one situation at the time, which makes it difficult to study stressors in relation to (integrated) long-term health effects. Additional studies showed that both the perceptual and physiological interactions at human level can affect our responses and can differ per person, leading to an integrated effect, direct and/or over time. Thus, possible interactions occurring at human level (perceptual and physiological) induced by changes at environmental level need to be explored. It might help to explain why people have different preferences for comfort-related aspects, why they differ in different contexts, and how this might relate to certain behaviours and health.

Our IEQ-guidelines do not account for integrated health effects of different exposures over time. Indicators (occupant-related, building-related, and/or dose-related indicators) and algorithms or models that can be used to predict long-term health effects from 'short-term' perceptual assessments and/or physiological measurements are needed. To determine those indicators, it is recommended to unravel the effects of (dis)comfort and health-induced stress on preferences, behaviour, needs, and health, by studying interactions at human level in different scenarios and situations that:

1. a) affect IEQ preferences of occupants; b) evoke short-term (dis) comfort induced behaviour at environment level (e.g. use of air conditioning system, windows, curtains, artificial lighting, thermostat); and c) activate (dis)comfort-induced stress-mechanisms (e.g. (dis)comfort, anti-stress mechanism, circadian rhythm) that can lead to long-term negative health effects (e.g. depression, obesity, diabetes), when not coping.
2. a) affect IEQ needs of occupants; b) evoke short-term health-induced effects at environment level (e.g. skin, eye and airway symptoms); and c) activate health-induced stress-mechanisms (e.g. irritation, oxidative stress, inflammation) that can lead to long-term negative health effects (e.g. chronic respiratory diseases, cancer), when not coping.

Long-term IEQ-monitoring of different indicators (occupant, building, and dose-related) in different scenarios and situations (living labs) in combination with lab studies and machine learning are recommended.

Only when the 'right' indicators and methods are identified, it will be possible to determine the 'right' algorithms that are needed to prevent negative and enhance positive health effects of each individual over time.

CRediT authorship contribution statement

Philomena M. Bluyssen: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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