(Dis)comfort and Health-induced Stress: The Need for Unravelling Their Effects

Bluyssen, P.M.

Publication date
2025

Document Version
Final published version

Citation (APA)
Bluyssen, P. M. (2025). *(Dis)comfort and Health-induced Stress: The Need for Unravelling Their Effects*. Paper presented at IEQ 2025 Conference, Montreal, Quebec, Canada.

C02

(Dis)comfort and Health-induced Stress: The Need for Unravelling their Effects

Philomena M. Bluyssen, PhD
Full Member ASHRAE

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 are mainly based on single-dose response relationships (effect modelling using dose-related indicators) for the physical stressors (odour, light, sound, and temperature) determined for an average adult person; aimed at preventing short-term discomfort, not long-term health effects, ignoring situation-related aspects, ignoring different preferences and needs of occupants. In four steps, the question "What is needed to determine other indicators that can help to prevent long-term health effects?" is answered. In step 1, a more comprehensive research model than the single dose-response model is introduced. Step 2 is concerned with the validation of that model based on a series of field studies. Step 3 addresses the need for methods (and indicators) that enable us to study interactions ocurring at human level (perceptual and physiological) induced by indoor environmental stressors resulting in both short-term and long-term (integrated) effects. Finally, in step 4, it is emphasized that to determine indicators that can be used to predict long-term health effects from 'short-term' perceptual assessments and/or physiological measurement requires understanding of how aour body copes with stressors that trigger the (dis)comfort-induced mechanisms and the health-induced mechanisms.

INTRODUCTION

Exposure to air, noise, 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 (Bluyssen 2014a; Morawska et al. 2020). Moreover, the consequences of climate change for indoor environmental quality (IEQ), the effects of the retrofitting measures we take to reduce energy consumption on health and comfort indoors, are an emerging concern (review in Ortiz et al. 2020). Additionally, 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 (Ortiz et al. 2020).To avoid health risks and discomfort, the European Energy Performance for Building Directive (EPBD) (EU 2024) 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." Research has shown, however, 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 (review in Bluyssen 2014a). Reasons for this discrepancy might be the fact that these guidelines (such as ventilation rate, lighting level, and temperature ranges) (e.g. CEN 2019) are mainly based on single-dose response relationships (effect modelling using dose-related indicators, see Figure 1) for the physical stressors (odour, light, sound, and temperature) determined for an average adult person, aimed at preventing short-term discomfort, not (long-term) health effects, ignoring situation-related aspects, ignoring different preferences and needs of occupants. Building-related indicators (such as type of building materials and furnishings, ventilation system types, and maintenance protocols) and occupant-related indicators (e.g. preferences and needs, personal factors) are rarely considered (Bluyssen 2017; Eijkelenboom and Bluyssen 2019; Zhang et al. 2022; Bluyssen 2022a; Hamida et al. 2023).

P M Bluyssen is Professor of Indoor Environment at the faculty of Architecture and the Built Environment, Delft University of Technology, Delft, the Netherlands.

Several weighting and classification schemes, rating tools, models, digital twins, and intelligent monitoring and feedback systems for the integrative evaluation of IEQs have been introduced (e.g. Wargocki et al. 2021; Heinzerling et al. 2013; Salthammer et al. 2022; Murray et al. 2020). However, all of these are still merely focussed on the separate IEQs (thermal, air, acoustic, and lighting quality) due to a lack of knowledge on the interrelationships and integration between and among environmental factors and their effects on health, comfort, and behaviour (e.g. Altomonte et al. 2024; Rohde et al. 2020; Schweiker et al. 2020). For health threatening exposures for which a clear dose-response relationship has been determined this single-dose response model tends to work well; For example, dose-related maximum allowed sound levels to prevent damage to the inner ear causing tinnitus, and/or hearing loss (e.g. CEN 2019; Hamida et al. 2023a). Unfortunately, for a lot of these indicators the mechanisms used behind the values or ranges, are not always that clear. The minimum ventilation rate is a good example is. Based on either CO_2, carbon dioxide, 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.

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 (EU 2024), it is important to go beyond the comfort-based dose-related indicators and determine other indicators that can help to prevent long-term health effects. The question is then what is needed to determine those indicators?

STEP 1 NEED FOR ANOTHER RESEARCH MODEL

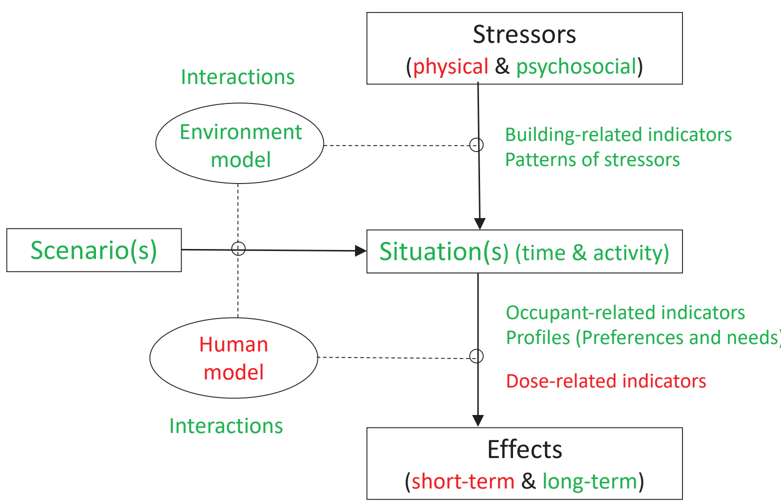

Figure 1 New model (situation modelling), including the old model (effect modelling).

The first step is to acknowledge that IEQ is more than the sum of its parts and that people differ in their preferences and needs. This requires a different research model than the the 'single dose-response models on which our guidelines are based. 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, was introduced (Bluyssen 2010; Bluyssen et al. 2011; Bluyssen 2014b; Bluyssen 2022; Altomonte et al. 2020) (Figure 1). This model includes all situation-related stressors (physical and psycho-social; positive and negative), modifiers, and confounders. 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, Figure 2a) and the individual differences in needs and preferences (expressed with profiles of people as shown in the Human model, Figure 2b), depending on their scenario (e.g. home, office, school) and situation (activity and time).

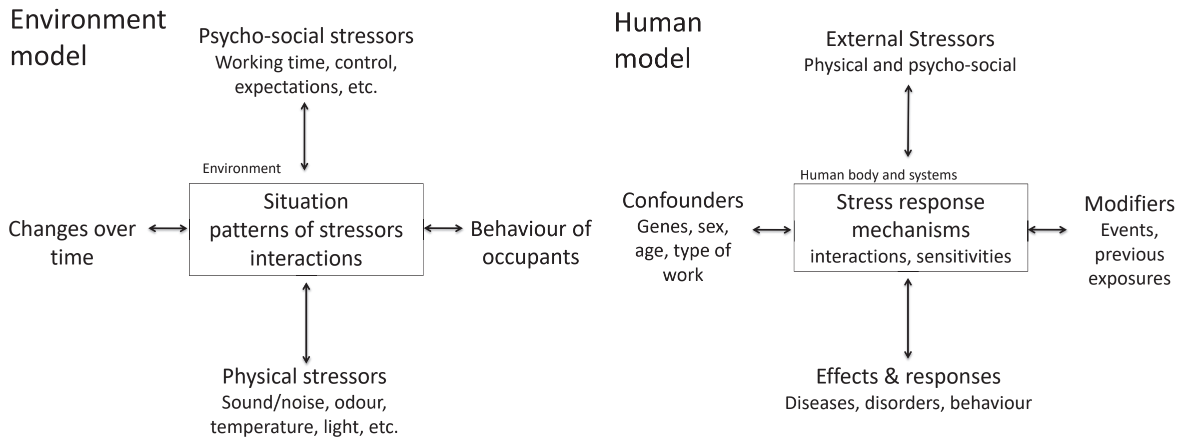

Figure 2. a) Environment model and b) Human model (Bluyssen 2020).

STEP 2 VALIDATION 'NEW' RESEARCH MODEL

The second step is the validation of the 'new' research model. The 'new' model was validated for 1) office workers and their workplace (Bluyssen et al. 2015; Kim and Bluyssen 2020; Ortiz and Bluyssen 2022); 2) students and their homes & study places (Bluyssen et al. 2016; Bluyssen et al 2021a; Bluyssen et al. 2022; Hamida et al. 2023b); 3) primary school children and their classrooms (Bluyssen et al. 2018; Zhang et al. 2019); and 4) employees of outpatient areas in hospitals (Eijkelenboom and Bluyssen 2020; Eijkelenboom et al. 2021a). For each scenario, occupant-related indicators and building-related indicators were collected through a questionnaire and checklist(s) to associate patterns of positive & negative stressors to occupant-related indicators (health: symptoms; comfort: complaints) using multi-variate analysis; and to determine clusters of occupants and their profiles (preferences and needs) using 2-steps cluster analysis. With these studies it was shown that for different scenarios (and situations) 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 (when leaving the building the severity of the symptom (e.g. stuffy nose) or disorder (e.g. rhinitis) decreases) for different profiles, resulting in better insight which risk factors play a role in such an effect (Bluyssen 2022a; Bluyssen 20022b).

For example, in the student homes study of 2015 (Bluyssen et al. 2016) first year bachelor students completed the so-called 'Home' questionnaire, comprising of questions on personal factors such as age and gender, questions on your health and comfort, questions about the building you live in, its surroundings, the occupants and their activities, possible water problems that occur or have occurred, questions about materials, furnishings and furniture that you have, and the possibilities for ventilation. The outcome showed that 33% of those 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 than once a week) and personal factors (e.g. working out) (Table 1).

The studies resulted in 'other' factors and stressors than used in guidelines confirming the importance of considering all possible stressors as well as personal and psycho-social factors, when studying a certain disease or disorder (Bluyssen 2022a and 2022b). Moreover, clustering showed the importance in better pinpointing the patterns of stressors that form a risk for getting a disease or disorder for a particular group (Bluyssen et al. 2022). The outcome showed that profiles can differ even when the occupants are exposed to the same situation at the same time (Zhang et al. 2019): 949 primary school children completed a questionnaire on their comfort and preferences for IEQ in the classroom in the school study of 2017. 2-Steps cluster analysis resulted in six profiles (Table 2). 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. It must be noted that 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.

Table 1. Multivariate Logistic Regression Model of the Relations between Rhinitis and Several Risk Factors (Bluyssen et al. 2016).

Risk factor	Odds Ratio	P
Family rhinitis vs. no	5.27	**<0.0001**
Training/exercise vs. no	0.50	**0.046**
No pets vs. pets	0.37	**0.005**
MDF furniture in bedroom (< 1 year) vs. no or yes (> 1 yes)	2.26	**0.015**
Opening windows (winter) (> 1/week) bedroom vs. less	0.55	**0.041**
Negative events	1.74	0.054
Airconditioning vs. no	0.48	0.121

Table 2. IEQ-Preferences Profiles: School Study 2017 (Zhang et al. 2019) vs. MyStudyplace 2022 (Hamida et al. 2023b).

School study 2017	MyStudyplace 2022
All concerned	IEQ concerned
Sound concerned	
Smell and sound concerned	
Thermal and draught concerned	
Light concerned	Visual concerned
Nothing concerned	IEQ unconcerned

Interestingly, in the MyStudyplace study of 2022 (Hamida et al. 2023b), all three clusters of IEQ-preferences had similar profiles as three of the six profiles identified in the primary school children study: the ‘IEQ concerned’ or ‘All concerned’, the ‘IEQ unconcerned’ or ‘Nothing concerned’ profile, and the ‘Visual concerned’ or ‘Light concerned’ profile (Table 2).

It was observed, however, in some of the field studies that environmental level changes in context (situation) may affect the preferences and needs of the occupants (profiles) (e.g. Ortiz and Bluyssen 2022; Zhang and Bluyssen 2019; Eijkelenboom et al. 2021b). How these changes in context affect the number of clusters (and their profiles) for a certain situation is unclear, and therefore, needs to be investigated further.

STEP 3 NEED FOR ‘OTHER’ RESEARCH METHODS

The third step is to acknowledge that our current guidelines do not account for integrated health effects of different exposures over time, which requires ‘other’ research methods than applied in the field studies. 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. Building-related risk factors were correlated to self-reported comfort conditions and symptoms (that get better when away from the building) of the past three months, and self-reported diseases of the past 12 months. The outcome was based on self-reported occupant-related indicators, assessed once. Unfortunately, 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 might require ‘other’ methods (study design) and/or indicators.

Moreover, other studies have shown that perceptual interactions at brain level can occur when exposed to different environmental stressors at the same time. During perception with our senses interactions of different environmental stressors (olfactory, auditory, visual and thermal stimuli) at brain level (central nervous system) might occur (reviews in Torresin et al. 2018; Schweiker et al. 2020; Wu et al. 2020; Zhao and Li 2023). In cross-modal studies in the Experience room of the SenseLab, we also observed this: first with primary school children (Bluyssen et al. 2021b) 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 (Bluyssen et al 2025). IEQ perceptual assessments and preferences for them, on which our comfort-based guidelines are largely based, can be affected by previous experiences and exposures, mood, state of health, preferences, etc. (Bluyssen 2014a). There is need for unravelling these interaction effects; it might help to explain why people have different preferences for comfort-related aspects, why they differ in different contexts.

Next to perceptual interactions, from research in different fields it is seen that interactions at human level that occur through the mechanisms that take place in the human body to cope with the different stressors, causing diseases when not coping, are complex (Bluyssen 2014a) (see Figure 3) and might explain why it is so difficult to correlate a certain dose-related indicator to a certain health effect.

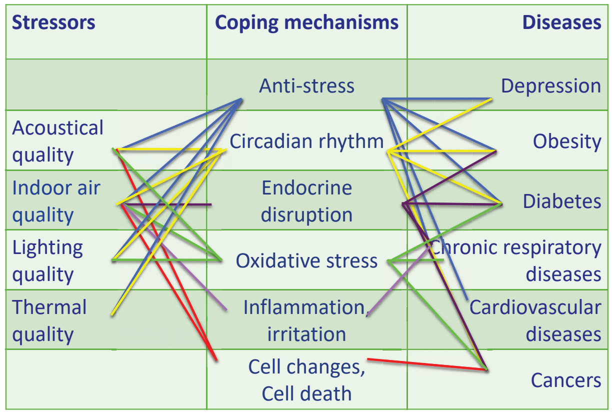

Figure 3. Possible associations between stressors, coping mechanisms and diseases (adapted from Figure 1.3 in Bluyssen 2014a).

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 at human level (Bluyssen 2014a). Both perceptual and physiological (inter)actions occur, leading to (integrated) effects, direct and/or over time (Bluyssen 2014a). Therefore, possible interactions occurring at human level (perceptual and physiological), induced by environmental stressors over time, need to be explored for different scenarios and situations (e.g. Allomonte et al.; Kim and de Dear 2012; ASHRAE 2023). It has been suggested to use physiological indicators to investigate human comfort and apply machine learning to predict human comfort (Wu et al. 2020; Zhang et al. 2024). 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 (Martins Gnecco et al. 2023). There is clearly a need for 'other' research methods, including 'oher' indicators.

STEP 4 UNRAVELLING THE HUMAN MODEL

Finally, the fourth step is to determine which indicators can be used to predict long-term health effects from 'short-term' perceptual assessments and/or physiological measurements. To get a better understanding of which indicators can be used, we need to investigate 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 grouped into stressors that trigger the so-called a) (dis)comfort-induced mechanisms (such as the anti-stress mechanism and the circadian rhythm mechanism) and b) the health-induced mechanisms (for example oxidative stress and inflammation) (see Figure 4). With '(dis)comfort' induced stress, the nervous system and the endocrine system cooperate, while the 'noxious or health' induced stress is handled by the immune system and the endocrine system (Bluyssen 2009).

The effects of not coping with the (dis)comfort-induced stress can be seen in the nervous system induced bodily responses (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 (Bluyssen 2014), all potentially occupant-related indicators. 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. 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' (Basner et al. 2023; Liu et al. 2020; Ohayon and Liesi 2016; Brown et al. 2022; Sekhar et al. 2020).

With health-induced stress our immune system responds at cell level and by production of substances to deal with the stress (e.g. cytokines). Coping fails when damage to cells prevent your immune and/or endocrine system to work properly (Bluyssen 2014). Next to indicators in blood and urine, several skin, eye, and airway symptoms have been correlated with exposure to health-induced stress. To prevent oxidative stress, in particular, exposure time limits for several dose-related indicators have been established (e.g. for sound (Bluyssen 2009), light (Heckman et al. 2022), fine particles (WHO 2021)). Additionally, several building-related indicators focussed on 'source' control can help to prevent health-induced stress. Moreover, the DALY (Disability adjusted life-years) concept has been proposed to estimate how harmful the indoor air is during a specific time frame [Murray et al. 2020; de Jong and Laverge 2022). However, to estimate the integrated effect of health-induced stress on a disease based on the DALY calculation, the exposure-function, the other risk factors, and the interactions of those risk factors, need to be known.

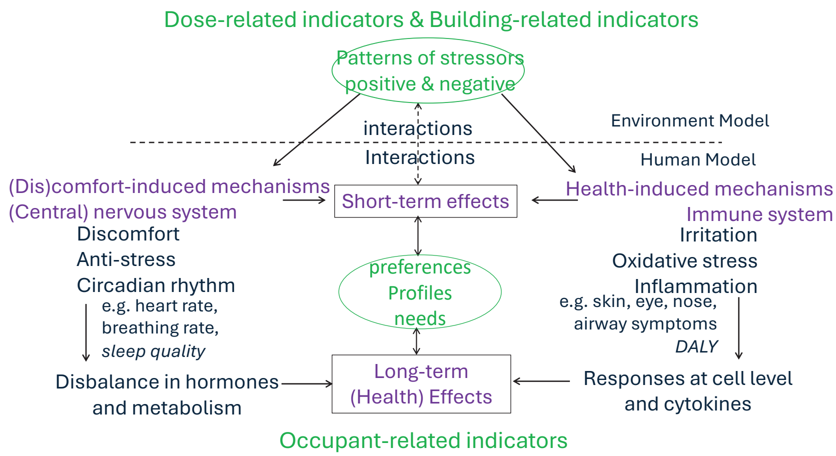

Figure 4. Human model: stress, coping mechanisms and effects.

CONCLUSION

To question "What is needed to determine other indicators that can help to prevent long-term health effects?", was answered in four steps. In steps 1 and 2, a more comprehensive research model than the single dose-response model was, respectively, introduced and partly validated. Then step 3, following from the outcome of the validation of the 'new' model, addressed the need for 'other' methods (and indicators) that enable us to study interactions ocurring at human level (perceptual and physiological) induced by indoor environmental stressors resulting in both short-term and long-term (integrated) effects. Finally, in step 4, the need for unravelling the human model to determine those 'other' indicators is emphasized. Only when the 'right' indicators and methods are identified, it will be possible to determine the 'right' algorithms that are needed to predict (prevent) health effects of each individual over time.

REFERENCES

Altomonte S, Allen J, Bluyssen PM, Brager G, Heschong L, Loder A, Schiavon S, Veitch J, Wang L, Wargocki P (2020) Ten questions concerning well-being in the indoor environment, *Building and Environment* 180:106949.

Altomonte S, Kacel S, Wegertseder Martinez P, Licina D (2024) What is NExT? A new conceptual model for comfort, satisfaction, health, and well-being in buildings, *Building and Environment* 252: 111234.

ASHRAE (2023) Guideline 10-2023, *Interactions affecting the achievement of acceptable indoor Environments*, Atlanta, USA.

Basner M, Smith MG, Jones CW, Ecker AJ, Howard K, Schneller V, Cordoza M, Kaizu-Lutu M, Park-Chavar S, Stahn AC, Dinges DF, Shou H, Mitchell JA, Bhatnagar A, Smith T, Smith AE, Stopforth CK, Yeager R, Jeith RJ (2023) Associations of bedroom $PM_{2.5}$, CO_2, temperature, humidity, and noise with sleep: an observational actigraphy study, Sleep Health: *Journal of the National Sleep Foundation* 9:253-263.

Bluyssen PM (2009) *The Indoor Environment Handbook*: *How to make buildings healthy and comfortable*, Taylor & Francis, London, UK.

Bluyssen PM (2010) Towards new methods and ways to create healthy and comfortable buildings, *Building and Environment* 45: 808-18.

Bluyssen PM (2014a) *The Healthy Indoor Environment: How to assess occupants' wellbeing in building,* Taylor & Francis, London, UK.

Bluyssen PM (2014b) What do we need to be able to (re) design healthy and comfortable indoor environments? *Intelligent Buildings International* 6(2): 69-92.

Bluyssen PM (2017) Health, comfort and performance of children in classrooms – new directions for research. *Indoor and Built Environment* 26(8): 1040-50.

Bluyssen PM (2020) Towards an integrated analysis of the indoor environmental factors and its effects on occupants, *Intelligent Buildings International* 12(3):199-207.

Bluyssen PM (2022a) All you need to know about the indoor environment, its occupants, interactions and effects, *Comfort at the Extremes 2022*, September 5-6, Edinburgh, Scotland.

Bluyssen, P.M. (2022b) Patterns and profiles for understanding the indoor environment and its occupants. *CLIMA 2022*, REHVA 14th World congress, May 22-25, Rotterdam, the Netherlands, paper 1504.

Bluyssen PM, Janssen S, Brink L van den, Kluizenaar Y de (2011) Assessment of wellbeing in an indoor environment, *Building and Environment* 46: 2632-40.

Bluyssen PM, Roda C, Mandin C, Fossati S, Carrer P, de Kluizenaar Y, Mihucz VG, de Oliveira Fernandes E and Bartzis, J (2015) Self-reported health and comfort in 'modern' office buildings: first results from the European OFFICAIR study, *Indoor Air* 26: 298-317.

Bluyssen PM, Ortiz M, Roda C (2016) Self-reported rhinitis of students from different universities in the Netherlands and its association with their home environment, *Building and Environment* 110: 36-45.

Bluyssen PM, Zhang D, Kurvers S, Overtoom M, Ortiz M (2018) Self-reported health and comfort of school children in 54 classrooms of 21 Dutch school buildings. *Building and Environment* 138: 106-23.

Bluyssen PM, Zhang D, Ortiz-Sanchez M (2021a) Self-reported rhinitis and headaches of students from universities in Taiwan, Chile, Suriname, China and the Netherlands, and its association with their home environment, *Intelligent Buildings International* 1964424.

Bluyssen PM, Zhang D, Kim DH, Eijkelenboom A, Ortiz-Sanchez M (2021b) First SenseLab studies with primary school children: exposure to different environmental configurations in the experience room, *Intelligent Buildings International* 13(4): 275-92.

Bluyssen PM, Zhang D, Ortiz M (2022) Associations between self-reported IEQ stressors of students' homes and self-reported rhinitis, stuffy nose, migraine and headache in student profiles, *Building and Environment* 228:109903; https://doi.org/10.1016/j.buildenv.2022.109903

Bluyssen PM, Hamida A, D'Amico A (2024) How different sounds affect bodily responses and the perception of odour, light and temperature: a pilot study on interaction effects within IEQ domains, (under review).

Brown TM, Brainard GC, Cajochen C, Czeisler C, Hanifin JP, Lockley SW, Lucas RJ, Münch M, O'Hagan JB, Price LLA, Roennberg T, Schlangen LJM, Skene DJ, Spitschan M, Vetter C, Zee PC, Wright KP (2022) Recommendations for daytime, evening, and nighttime indoor light exposure to best support physiology, sleep, and wakefulness in healthy adults, *PLoS Biol.* 20(3): e3001571.

CEN (2019) EN 16798-1:2019, *Energy performance of buildings - Ventilation for buildings* - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6, CEN-CENELEC Management Centre, Brussels, Belgium.

De Jonge K and Laverge J (2022) Time-resolved dynamic disability adjusted life-years estimation, *Indoor Air* 32(11). doi:10.1111/ina.13149.

EU (2024) Directive (EU) 2024/1275 of the European Parliament and of the council of 24 April 2024 on the energy performance of buildings, Official Journal of the European Union https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401275 (assessed June 25, 2024).

Eijkelenboom A and Bluyssen PM (2019) Comfort and health of patients and staff, related to the physical environment of different departments in hospitals: a literature review, *Intelligent Buildings International*, DOI: 10.1080/17508975.2019.1613218.

Eijkelenboom A and Bluyssen PM (2020) Profiling outpatient workers based on their self-reported comfort and preferences of indoor environmental quality and social comfort in six hospitals, *Building and Environment* 184: 107220.

Eijkelenboom A, Ortiz M, Bluyssen PM (2021a) Building characteristics associated with the prevalence of dry eyes and headaches of outpatient workers in six hospital buildings in the Netherlands, *Indoor and Built Environment* 31(3): 1420326X211023125.

Eijkelenboom A, Ortiz MA, Bluyssen PM (2021b) Preferences for indoor environmental and social comfort of outpatient staff during the COVID-19 pandemic, an explanatory study, *International Journal of Environmental Research and Public Health* 18: 7353. https://doi.org/10.3390/ijerph18147353.

Hamida A, Zhang D, Ortiz MA, Bluyssen PM (2023a), Indicators and methods for assessing acoustical preferences and needs of students in educational buildings: A review, *Applied Acoustics* 202:109187. https://doi.org/10.1016/j.apacoust.2022.109187.

Hamida A, Eijkelenboom A, Bluyssen PM (2023b) Profiling students based on the overlap between IEQ and psychosocial preferences of study places, *Buildings* 13:231, https://doi.org/10.3390/buildings13010231.

Heckman CJ, Liang K, Riley M (2022) Awareness, understanding, use, and impact of the UV-index: a systemic review of over two decades of international research, *Preventive Medicine* 123:71-83.

Heinzerling D, Schiavon S, Webster T, Arens E (2013) Indoor environmental quality assessments models: A literature review and a proposed weighting and classification scheme, *Building and Environment* 70: 210-22.

Kim DH and Bluyssen PM (2020) Clustering of office workers from the OFFICAIR study in the Netherlands based on their self-reported health and comfort, *Building and Environment* 176: 106860.

Kim J and de Dear R (2012) Nonlinear relationships between IEQ factors and overall workspace, *Building and Environment* 49: 33-40.

Liu J, Wu T, Liu Q, Wu S, Chen J-C (2020) Air pollution exposure and adverse sleep health across the life course: A systematic review, *Environment Pollution* 262: 114263.

Martins Gnecco V, Vittori F, Pisello AL (2023) Digital twins for decoding human-building interaction in multi-domain test-rooms for environment comfort and energy saving via graph representation, *Energy & Buildings* 279: 112652.

Morawska L Tang J, Bahnfleth W, Bluyssen PM, Boerstra A, Buonanno G, Cao J, Dancer S, Floto A, Franchimon F, Haworth C, Hogeling J, Isaxon C, Jimenez JL, Kurnitski J, Li Y, Loomans M, Marks G, Marr LC, Mazzarella L, Melikov AK, Miller S, Milton D, Nazaroff W, Nielsen PV, Noakes C, Peccia J, Querol X, Sekhar C, Seppänen O, Tanabe S, Tellier R, Tham KW, Wargocki P, Wierzbicka A, Yao M (2020) How can airborne transmission of COVID-19 indoors be minimised? *Environment International* 142: 105832.

Murray CJL, Aravkin AY, Zheng P, and GBD Risk Factors Collaborators (2020) Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *Lancet* 396(10258): 1223-49.doi:10.1016/S0140-6736(20)30752-2.

Ohayon MM and Milesi C (2016) Artificial outdoor nighttime lights associate with altered sleep behavior in the American general population, *Sleep* 39(6): 1311-20.

Ortiz M, Itard L, Bluyssen PM (2020) Indoor Environmental Quality related risk factors with energy-efficient retrofitting of housing: a literature review*, Energy and Buildings* 221:110102.

Ortiz M and Bluyssen PM (2022) Profiling office workers based on their self-reported preferences of indoor environmental quality at their workspace during COVID-19. *Building and Environment* 211: 108742.

Rohde L, Steen-Larsen T, Lund Jensen R, Kalyanova Larcen O (2020) Framing holistic indoor environment: definitions of comfort, health and well-being, *Indoor and Built environment* 29(8): 1118-36.

Salthammer T, Zhao J, Schieweck A, Uhde E, Hussein T, Antretter F, Kunzel H, Pazold M, Radon J, Birmili WZh (2022) A holistic modelling framework for estimating the influence of climate change on indoor air quality, *Indoor Air* 32:13039.

Schweiker M, Ampatzi E, Andargie MS, Andersen RK, Azar E, Barthelmes VM, Berger C, Bourikas L, Carlucci S, Chinazzo G (2020) Review of multi-domain approaches to indoor environmental perception and behaviour, *Building and Environment* 176: 106804.

Sekhar C, Akimoto M, Fan X, Bivolarova M, Liao C, Lan L, Wargocki P (2020) Bedroom ventilation: Review of existing evidence and current standards, *Building and Environment* 184: 107229.

Torresin S, Pernigotto G, Cappelletti F, Gasparella A (2018) Combined effects of environmental factors on human perception and objective performance: A review, *Indoor Air* 28: 525-38.

Wargocki P, Wei W, Bendzalova J, Espigares-Correa C, Gerard C, Greslou O, Rivallain M, Sesana MM, Olesen BW, Zirngibl J, Mandin C (2021) TAIL, a new scheme for rating indoor environmental quality in offices and hotels undergoing deep energy renovation (EU ALDREN project), *Energy & Buildings* 244: 111029.

WHO (2021) WHO Global air quality guidelines: Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, https://www.who.int/publications/i/item/9789240034228.

Wu H, Wu Y, Sun X, Liu J (2020) Combined effects of acoustic, thermal and illumination on human perception and performance: A review, *Building and Environment* 169: 106593.

Zhang D and Bluyssen PM (2019) Actions of primary school teachers to improve the indoor environmental quality of classrooms in the Netherlands, *Intelligent Buildings International* 13(2): 103-15.

Zhang D, Ortiz M, Bluyssen PM (2019) Clustering of Dutch school children based on their preferences and needs of the IEQ in classrooms, *Building and Environment* 147: 258-66.

Zhang D, Ortiz M Bluyssen PM (2022) A review on indoor environmental quality in sports facilities: Indoor air quality and ventilation during a pandemic. *Indoor and Built Environment* DOI:10.1177/1420326X221145862.

Zhang D, Mui K-W, Masullo M, Wong L-T (2024) Application of machine learning techniques for predicting students' acoustic evaluation in a university library, *Acoustics* 6:681-97.

Zhao Y and Li D (2023) Multi-domain indoor environmental quality in buildings: A review of their interaction and combined effects on occupant satisfaction, *Building and Environment* 228: 109844.