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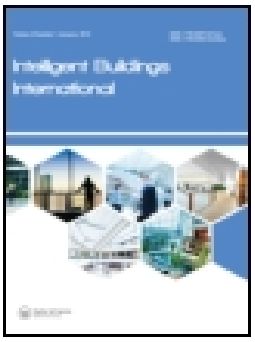

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Philomena M. Bluyssen

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Towards an integrated analysis of the indoor environmental factors and its effects on occupants

Philomena M. Bluyssen

Chair Indoor Environment, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, Netherlands

ABSTRACT
Research has shown that staying indoors is not good for our health, even though the conditions seem to comply with current guidelines for indoor environmental quality (IEQ). The growing field of indoor health and comfort studies in schools, offices and homes, shows a discrepancy of current standards with end-users needs. In a previous review it was concluded that a more complex research model than the conventional 'dose-response' model is required to explain symptoms and complaints, preferences and needs, in order to prevent negative effects and to stimulate positive experiences. In this position paper, recent research on the further development of the previous introduced approach is presented along the identified needs, i.e. a model that is suitable for determining patterns of stressors and interactions, and takes account of dynamic behaviour over time per scenario; assessment methods that can identify other factors and stressors than the environmental parameters used in guidelines and analysis methods that can determine relations and interactions. The outcome is used to improve and detail the previous introduced approach.

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Integrated analysis; indoor environment; health and comfort; occupants; interactions

Introduction

People, in general, spend more than 60% of their time at home (Bonnefoy et al. 2004) and the rest of their time at their work, at school and/or commuting, resulting roughly in 90% of their time, or more, indoors. In most buildings, the indoor environmental quality (IEQ) to which people are exposed is subjected to increased health effects, consequences of energy efficiency improvements and most likely climate change effects (Aries and Bluyssen 2009). Improved insulation and increased air tightness of the building envelope can reduce energy consumption, but also lead to severe health problems caused by problems with dampness (Adan and Samson 2011) and unwanted emissions of the insulation products applied (CDC-NIOSH 2012). Research has shown that staying indoors is not good for our health, even though the conditions seem to comply with current guidelines for IEQ, that are based on single-dose response relationships, and on preventing diseases and disorders rather than focusing on positive effects (Bluyssen 2014a).

Previous studies have shown that the relationships between indoor building conditions (thermal aspects, ventilation, lighting, moisture, mould and noise) and wellbeing (health and comfort) of occupants of office buildings, schools and homes are complex and not easy to unravel (e.g. Daisey and Apte 2003; Bonnefoy et al. 2004; Frontczak and Wargocki 2011; Kim and de Dear 2012; Bluyssen

CONTACT Philomena M. Bluyssen p.m.bluyssen@tudelft.nl Julianastraat 134, 2628 BL Delft, The Netherlands

2017a). There are many indoor environmental stressors that can cause their effects additively or through complex interactions (synergistic or antagonistic): thermal factors (e.g. draught, temperature), lighting aspects (e.g. reflection, view, luminance ratios), air quality (e.g. odours, moisture, mould, radiation, chemical compounds, particulates) and acoustical aspects (e.g. noise and vibration) (Bluyssen 2008, 2010; ASHRAE 2010; Torresin et al. 2018). External stress factors seem to be able to result in both mental and physical effects (Bonnefoy et al. 2004; Fisk, Lei-Gomez, and Mendell 2007; Lewtas 2007; Babisch 2008; Houtman, Douwes, and de Jong 2008).

Studies have indicated that indoor building conditions may be associated with discomfort (annoyance), building-related symptoms (e.g. headache, stuffy/runny/irritated nose, dry/irritated eyes, irritated skin, fatigue etc.), building related illnesses (e.g. legionnaires disease), productivity loss and decrease in learning ability (Bluyssen 2009). Mental health effects (Houtman, Douwes, and de Jong 2008), illnesses that take longer to manifest (e.g. cardiovascular diseases Lewtas 2007; a variety of asthma-related health outcomes Fisk, Lei-Gomez, and Mendell 2007) and obesity (Bonnefoy et al. 2004) have been associated with exposure indoors. Studies have shown that: high noise levels are not the only levels that can cause effects (Babisch 2008; Kang et al. 2016); 'lighting quality' is not only about the 'right' level to perform a certain task, since we know the third receptor in the eye has an important role in the control of day-night rhythm (Brainard et al. 2001; Figueiro et al. 2018); exposure to constant thermal neutral conditions might not be that healthy, even though we think we feel comfortable (van Marken Lichtenbelt et al. 2009); and that odours, even though we are adapted to it after a while, should not be ignored (Köster 2002), and might be used, as with sound, to create positive effects (von Kempski 2003; Saadatmand et al. 2013). It is known that these effects can be influenced by other factors and stressors than the environmental parameters used in guidelines, whether of psychological, physiological, personal, social or environmental nature (Figure 1). And that this cocktail of stressors people are exposed to changes over time and that the exposure is influenced by past exposures and interactions that occur between those stressors (e.g. Berglund and Gunnarsson 2000; Runeson et al. 2006; Chow et al. 2009; Mendell and Mirer 2009; Frontczak and Wargocki 2011; Bluyssen 2014a).

The built environment and its indoor environment with occupants is clearly a complex system characterised by feedbacks, interrelations among agents and discontinuous non-linear relations (Bluyssen 2017b). Nevertheless, IEQ is still assessed mainly on dose-related indicators, based on single dose-response relationships, developed for the average occupant (whoever that is), ignoring most of the time the fact that we are dealing with *individuals in different scenarios* (e.g. homes, offices and schools) and situations (sitting behind a desk, in a meeting room listening, on the phone, washing, cooking, sleeping, etc.). Not taking into account that *interactions* may occur between stressors in complex, real-life exposure situations as well as between various body responses to exposure(s), that *exposure and response may be time dependent* (e.g. daily, weekly and seasonal patterns) and that a truly *holistic approach* is required, in which the different aspects (physical, physiological, personal, psychological and social) are all taken into account, not per aspect, but integrated.

In a previous review (Bluyssen 2014a), it was concluded that there is a need for an integrated analysis approach, which takes account of the combined effects of stress factors in building on people. An approach that is suitable for determining patterns of stressors and interactions, and takes account of dynamic behaviour over time per scenario (e.g. children at school, office worker at office, sleeping at home). A model to describe this approach was introduced (Figure 2). For the development of this approach it was recommended to improve assessment as well as analysis methods applied.

In this position paper, recent research on the further development as well as validation of the introduced approach is presented along a number of the identified needs. The outcome is used to improve and detail the introduced approach (Bluyssen 2014a).

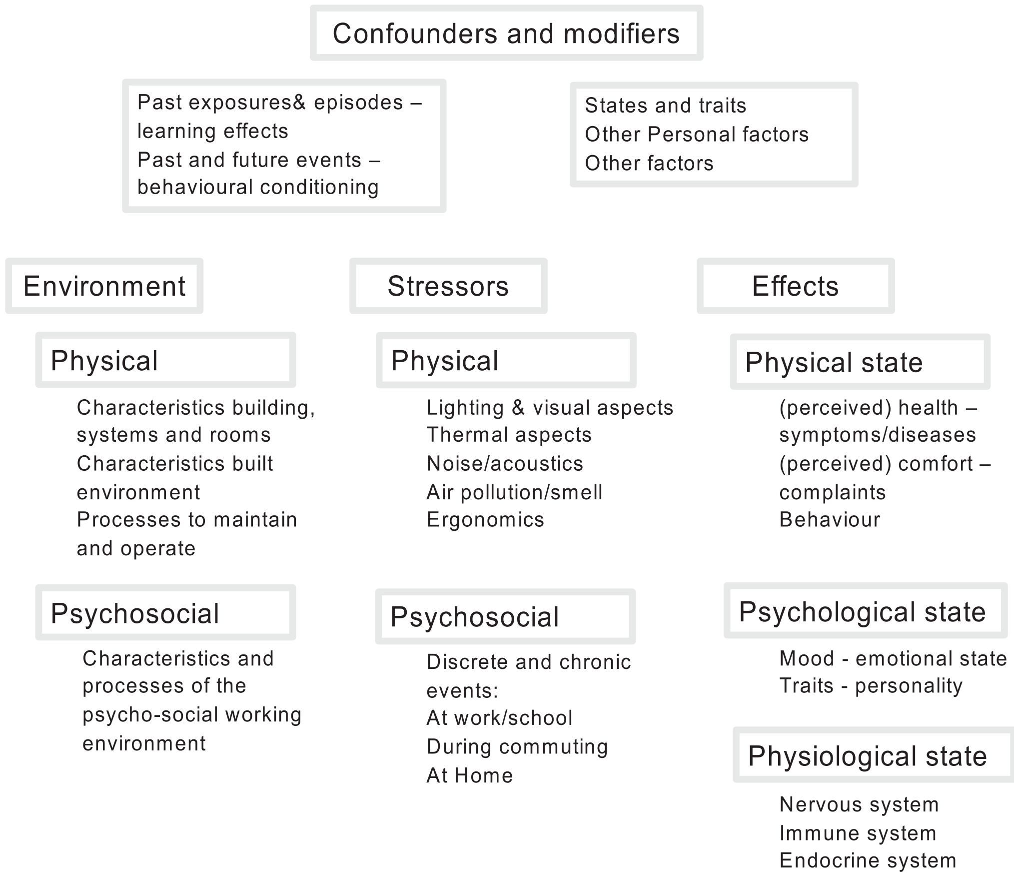

Figure 1. Stressors, factors, causes and effects (adapted from Bluyssen 2014b).

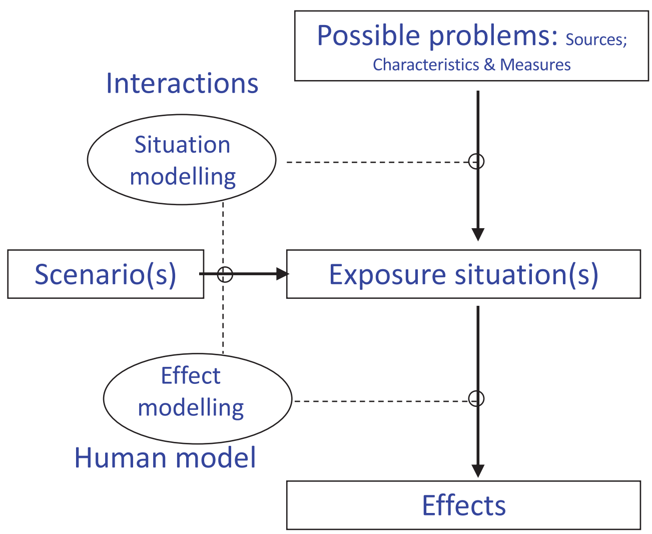

Figure 2. Original model for the integrated analysis approach.

Recent studies versus some of the identified needs

NEED 1: To identify other factors and stressors than the environmental parameters used in guidelines, whether of psychological, physiological, personal, social or environmental nature (e.g. Berglund and Gunnarsson 2000; Brauer et al. 2006; Runeson et al. 2006; Chow et al. 2009; Mendell and Mirer 2009; Bluyssen, Aries, and van Dommelen 2011; Frontczak and Wargocki 2011; Bluyssen 2014a), different assessment procedures are required.

*A procedure to determine associations between characteristics of European offices and health and comfort of office workers, through a checklist and a self-administered questionnaire including environmental, physiological, psychological and social aspects was developed (*Bluyssen et al. 2016*). A similar procedure was used to investigate primary school children at Dutch schools (*Bluyssen et al. 2018a*) and students of Dutch universities and their homes (*Bluyssen, Ortiz, and Roda 2016*). The assessment procedures applied made it possible to identify other factors and stressors than the environmental parameters used in guidelines.*

NEED 2: Usually, linear regression-based methods are applied, while many IEQ factors show non-linear relations with both satisfaction and health effects that can differ per situation and individual (Clements-Croome 2011). Interactions, feedback loops and confounding and mediating factors have hardly been considered (ASHRAE 2010). Moreover, it seems that factors influencing satisfaction can be divided into basic factors, so-called minimum requirements, and other factors that can either have a linear or a non-linear relation with satisfaction (Kim and de Dear 2012). Other analysis methods than the usual linear based methods are needed to determine these relations.

*Recent field studies in three scenarios, schools and children (*Bluyssen et al. 2018a*), office buildings and office workers (*Roda et al. 2015; Bluyssen et al. 2016; de Kluizenaar et al. 2016*) and homes and (young) adults (*Bluyssen, Ortiz, and Roda 2016*), have shown that with the use of multivariate analysis it is possible to determine patterns of factors that are associated with certain effects. For example for the study with 396 students, the findings showed that besides genetics, rhinitis was associated with biological pollutants (presence of pets) and chemical pollutants (presence of MDF from less than one-year old furniture), ventilation (opening windows in bedroom more than once a week), and with personal factors, working out (physical activity)., The study confirmed that rhinitis is a multifactorial disease; as both personal and environmental factors were linked to this disease in young adults.*

NEED 3: It is clear that we are dealing with individuals in different scenarios (e.g. homes, offices and schools) and situations (sitting behind a desk, in a meeting room listening, on the phone, washing, cooking, sleeping, etc.). Profiling of people for different scenarios and situations is required in order to understand the individual reactions to indoor environments better.

*Using two-step cluster analysis, the study in the schools identified six clusters (profiles) of children based on their comfort perceptions and the importance of environmental factors (*Zhang, Ortiz, and Bluyssen 2019*). Among them, four clusters of children had specific concerns related to the IEQ factors: sound, air & sound, thermal & draught, and light. The other two clusters of children did not show a specific annoyance, one cluster was concerned about all IEQ factors in the classroom, while the other cluster (being also the cluster with the healthiest and most comfortable children) did not show any concern.*

In another study on the relationships between behaviours, energy use, and comfort and health of 223 students and their homes, 6 clusters (profiles) were identified by Ortiz and Bluyssen (2018), *based on their behavioural characteristics, using two-step cluster analysis.*

These studies showed that indeed people can differ in their preferences and needs, and that it seems possible to distribute them into clusters (profiling).

NEED 4: Most studies have focused on negative stress factors, that is: to assess why people get sick or complain in order to define requirements/threshold levels. Few studies have considered *positive experiences* (needs and preferences), performed mainly in offices (e.g. Santos and Gunnarsen 1999; Clausen and Wyon 2008). A holistic analysis is needed, including preferences and needs to identify the positive as well as the negative effects for different scenarios.

*In a first attempt to perform a holistic analysis at 21 Dutch schools in 54 classrooms in The Netherlands, differences in preferences and needs were found for different scenarios (between non-traditional and traditional schools) and at individual level (*Bluyssen et al. 2018a*). A non-traditional school is a school in which the way of educating children is different from the traditional way of education (e.g. Dalton, Montessori and Jena).*

NEED 5: Although the determination of guidelines has been mostly focussed on lab studies performed more than 50 years ago, field studies have outnumbered the lab studies to assess health and comfort of people in buildings. Some lab studies focused on the combined effect of different environmental factors on people have been performed for mainly office settings (e.g. Nelson, Nilsson, and Johnson 1984; Veitch 1990; Hygge and Knez 2001; Fang et al. 2004; Witterseh, Wyon, and Clausen 2004; Chen et al. 2007; Lieble et al. 2012; Torresin et al. 2018). Although some trends have clearly been shown (for example the relationship between temperature, humidity and perceived air quality) (Toftum 2002), the overall non-homogeneous results make it difficult to make strong conclusions.

*First lab studies on the combined effect of different environmental factors with school children have been performed (*Bluyssen et al. 2019*). 250 children from seven primary schools were exposed to 36 different environmental configurations in the Experience room of the SenseLab (*Bluyssen et al. 2018b*): 'all' and 'fewer' acoustical panels; 'displacement' and 'mixing' ventilation; sound type: 'children talk', 'traffic', and 'none'; and 'direct', 'indirect' and 'soft' lighting. In a four-way factorial design, they assessed with 18 groups on eight different days temperature, noise, light and smell. The finding that cross-modal integration between olfactory, visual and auditory stressors probably occurs at the level of the central nervous system, not only calls for an integrated approach, considering the combined effect, towards managing the indoor school environment, but it also confirms the suspicion that interactions between these stressors occur at human level.*

NEED 6: Assessment of health and comfort is mostly based on quantitative methods for assessing the effects of air, thermal, acoustics and light, that make it possible to perform linear based analysis resulting in a mean effect/response of a certain group to one aspect. Combined field and lab studies using a mixed study design (qualitative methods, such as focus groups used in product design, or interviews used in psychology, together with quantitative methods) seem worth considering.

*In the spring of 2018, 335 children (average age 10.5 years) from seven different primary schools visited the SenseLab to perform a series of tests. In the Experience room of the SenseLab a workshop (qualitative method) was held to identify problems in their own classroom (session 1) and to design solutions to control these problems (session 2). Before, between and after the workshop sessions, the children were exposed to different environmental configurations and asked to assess the IEQ using a questionnaire resulting in quantitative data (*Bluyssen et al. 2019*). The children visited the SenseLab during 10 days divided into 24 groups of 11 to 16 children, with 2 or 3 groups per day. This study showed that it is worthwhile to apply a mixed study design.*

Improved integrated analysis approach

From the review presented above, it is clear that it seems possible to determine a more complex research model than the conventional 'dose-response' model, to explain symptoms and complaints in certain (exposure) situations by identifying patterns of stressors and profiles of people. From the studies described above in which attempts were made to assess IEQ in an integrated way, several findings and observations were used to improve the original introduced model (Figure 3) by:

(1) The introduction of the environment model (Figure 4), leading to patterns of stressors (positive and negative) that should be taken account of in the assessment, and the human model (Figure 5), leading to preferences and needs (profiles) of the occupant for which the assessment is performed. Recent studies, in particular, have given preliminary proof for the determination of patterns and profiles ('offices and workers': Bluyssen et al. 2016; 'schools and children':

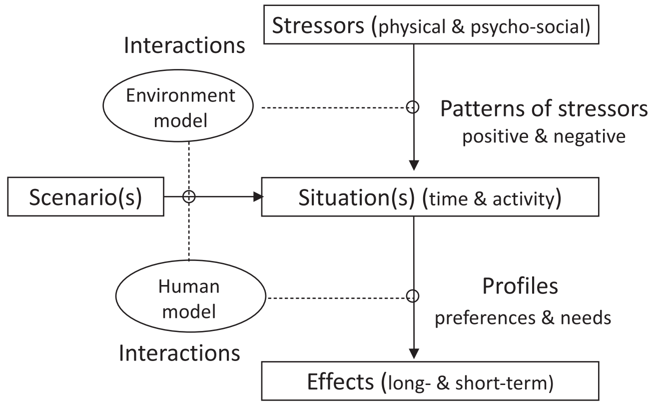

Figure 3. Improved model for the integrated analysis approach.

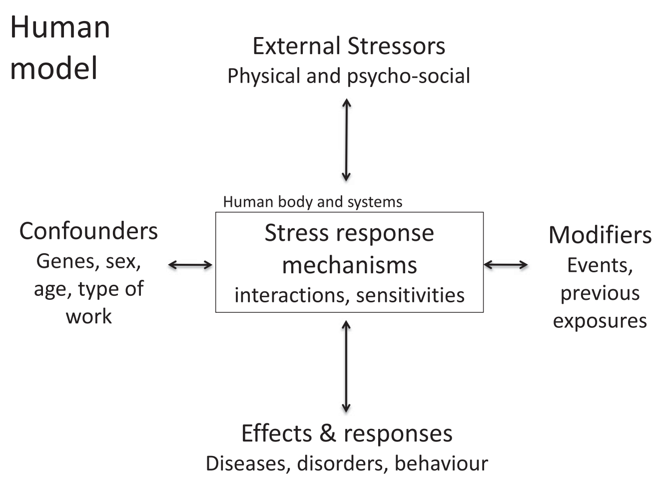

Figure 4. The Human model.

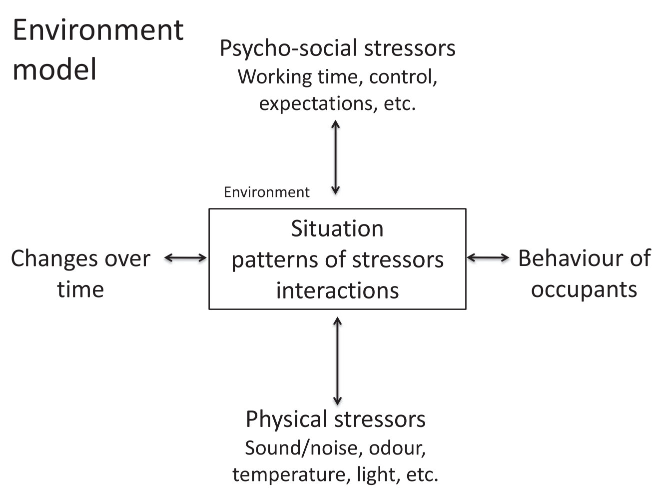

Figure 5. The Environment model.

Bluyssen et al. 2018b; Zhang, Ortiz, and Bluyssen 2019; 'homes and students': Bluyssen, Ortiz, and Roda 2016; Ortiz and Bluyssen 2018).

(2) It has also been noticed that interactions occur both at environment and human level, so also these should be included more prominent in the model. At environmental level: for example, *chemical interactions* between pollutants in the air and on surfaces; interactions between *thermal, light and air conditions,* when sunlight heats indoor surfaces, and emission rates in general increase; *acoustics* and *air*, via the introduction of (air flow and equipment) noise caused by mechanical systems, or via natural ventilation through open windows, bringing in the noise produced outdoors indoors. Indoor air, thermal environment, acoustics and illumination are all interconnected in the indoor environment. Also, at occupant level interactions occur via the mechanisms the human body has to cope with the different environmental stressors, influenced by confounders, modifiers and individual differences (e.g. Boyce and Wilkins 2018; Wang et al. 2018). This was clearly seen in the lab study with children while being exposed to different environmental configurations (Bluyssen et al. 2019).

(3) Then changes in preferences and needs over time, but also activities performed (behaviour of occupants) were introduced as important factors to be included in the model. Several studies pointed out that these aspects do matter.

To reach the goal of an integrated analysis approach for assessing indoor environmental quality, interactions at and between different levels (human and environment) over time need to be explored for different scenarios and situations. Ultimately this will result in a model that includes all interactions for both the environment (the situation) and the occupant: the stress factors caused by the (indoor) environment a person is exposed to (patterns of stressors) as well as the individual differences in needs and preferences (profiles of people), depending on their behaviour (activities). Thus, to make it possible to match profiles of people with patterns of positive and negative stressors for a certain situation.

With the outcome it will be possible to better understand the interactions between people and the indoor environment and therefore it will form the basis for improving our current standards and guidelines. With an integrated analysis approach, it will be possible:

(a) To assess for an occupant for example of an office or classroom, which profile he/she belongs to and which preferences and needs of the environment match with that profile and

(b) To identify the negative and positive stressors of concern to improve the environment people are exposed to. This is bound to lead to healthier and more comfortable occupants and buildings.

Disclosure statement

No potential conflict of interest was reported by the author.

Notes on contributor

Prof. dr. Philomena M. Bluyssen, initiator and creator of the SenseLab, was appointed full Professor Indoor Environment in 2012 at the Faculty of Architecture and the Built Environment, after working for more than 21 years for TNO, a research institute in the Netherlands. She holds a master degree (building engineer) from the Technical university of Eindhoven (1987) and a PhD from the Technical University of Denmark (1990). She has written more than 200 publications in (inter)national journals and conferences. For the Indoor Environment Handbook: How to make buildings healthy and comfortable, she was awarded the Choice Outstanding Academic Titles of 2010 Award. Her book titled 'The Healthy Indoor Environment – How to assess occupants' wellbeing in buildings', published by Taylor & Francis in 2014, was awarded the Interior Design Educators Council 2016 book award.

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