



Introduction

The 11th International conference on indoor air quality, ventilation & energy conservation in buildings (IAQVEC 2023), was held in Tokyo, May 20-23, 2023. IAQVEC is well-established conference series, and the first IAQVEC conference was held in Montreal in 1992. The conferences cover a wide range of key research areas with the goal of simultaneously improving indoor environmental quality (IEQ) and energy efficiency enhancing well-being and sustainability. With 512 abstract submissions and 374 accepted papers from 49 countries, IAQVEC2023 is one of the largest Japanese conferences related to the built-environment during this decade and the first full-fledged international conference in person in Japan since COVID-19 started. The conference theme is “FOR FUTURE SUSTAINABLE SOCIETY.” There are two plenary speeches related to Carbon Neutral policy and Climate Change, and four keynote speeches on the latest topics about the built-environment. We have organized 83 oral sessions, 2 poster sessions, and 6 seminars/workshops.



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Title, date and place of the conference

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Transformative Service Research and impact of indoor environmental quality on workers' productivity: potentialities of neuroscience in its assessment.

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Abstract. Previous research demonstrated that there is a link between workers' productivity and their overall comfort in the workspaces. Nowadays, the energy crisis is highlighting the need for energy saving measures also in workplaces to reduce expenses, thus posing threats to the overall comfort of workers: how to deal with this trade-off? In such a frame, this paper is a traditional literature review of the research, conducted so far, useful to understand the optimal point of energy needed to secure human wellbeing in workspaces (and thus, acceptable productivity). Moving from an overview of the most common adopted methodologies and related findings, this work focuses on applications and opportunities associated with merging methods from neuroscience. Neuroeconomics, in fact, uses some indexes (cognitive interests, mental fatigue) and techniques (EEG, heart rate) that allow to understand whether a person is focused on his/her work or not: this can represent a double-check of the optimal level of environmental comfort in offices. Environmental comfort studies concerning the adoption of physiological monitoring are compared here to business management studies lying on physiological indexes to assess employees' interest and cognitive effort, which influence their productivity. This comparison showed up new perspectives in the investigation of occupants' productivity and environmental comfort, which can be pursued in the coming years to understand how to achieve the optimum between energy consumption and workers' productivity.

Keywords. Thermal comfort, workers' productivity, neuroeconomics, transformative service research, occupants' wellbeing, energy saving.

1 Introduction

The role of environmental quality for humans' health and well-being is commonly recognized. People spent most of their time in the indoors, especially in Western countries where, among home, workplaces, and leisure activities, it reaches up to 90% of people lifespan [1]. Therefore, Indoor Environmental Quality (IEQ) is critical for promoting people well-being, since it impacts the occupants' overall comfort, health status, and even productivity in the case of working environment [2]. Indeed, studies in the field of building engineering [3, 4] showed that physical wellbeing can be a booster of activity. This has also a homologous in a well-known theory of the management studies: Transformative Service Research (TSR), which is a research stream aimed at creating uplifting changes and improvements in the wellbeing of individuals (consumers and employees), communities and stakeholders of a company [5].

Therefore, wellbeing is a trend topic for business and society, which gained rising importance in the last two decades, after the globalisation and the stress coming from working in hectic environments like the multi-

national offices. No wonder that, in the TSR field, there has been research conducted on the potential drivers of stress experienced by service employees [6].

Therefore, it can be asserted that employees' wellbeing and the reduction of stress is crucial for companies, since it affects workers' productivity: this contributes to their overall comfort, which depends also on the workplace environmental quality. However, with the energy crisis [7], societies and companies need to reduce energy consumptions in order to comply with the national requirements. By looking at the Google Trends of the last years, the searches "energy crisis" and "energy saving" have become increasingly popular, especially after the Ukraine/Russia war [8].

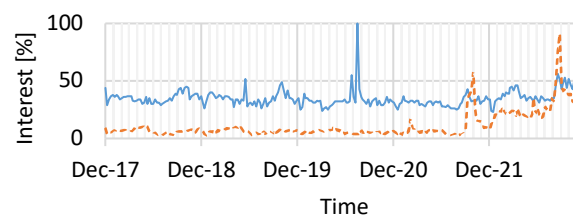


Fig. 1. Google Trends for « energy saving » (blue) and energy crisis (red) all over the world in the last 5 years.

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This means that energy saving is a priority for companies and people to save moneys by reducing energy-related expenses. As happened in previous similar crisis [9], such economic constrains could result in wider temperature ranges for indoor conditioning, causing occupants' thermal discomfort and, possibly, a drop in their productivity.

However, also the one of wellbeing is a hot topic in the business and management field, [10] which gained importance in the last years due also to the pandemic of Covid-19 (as Figure 2 shows).

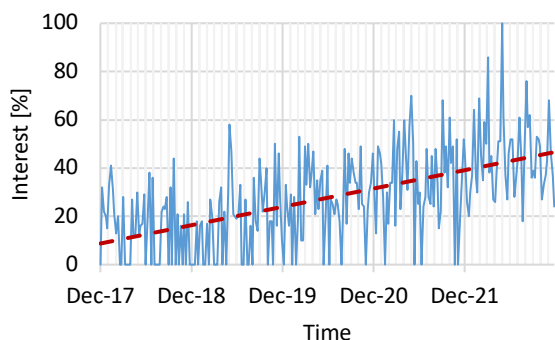


Fig. 2. Google Trends for « employees' wellbeing » all over the world in the last 5 years (continuous blue), and related linear trend (dashed red).

So, both energy saving and employees' wellbeing are top priorities for companies, which are posed the challenge to choose between less money due to a loss in workers' productivity or more expenses to secure employees' overall comfort.

A solution in this sense can be suggested by multi-domain and interdisciplinary studies on human comfort [11], aimed at understanding which environmental parameters could be more beneficial to the workers' productivity and at the same time less impacting in terms of energy consumptions. However, relying only upon the measure and control of environmental parameters for the IEQ assessment, could not be enough. The introduction of the human dimension, as well as also individuals' characteristics, is necessary to enhance occupants' comfort, while minimizing energy consumption. New parameters should accompany the traditional research of engineering, picking also from other scientific domains [12].

The present work is a literature review of the research, conducted so far, useful to understand the optimal point of energy needs to secure human wellbeing (and thus, acceptable productivity). Moving from an overview of the most common adopted methodologies and related findings, this work focuses on applications and opportunities associated with merging methods from neuroscience, in particular in the field of neuroeconomics.

Multi-domain theories and neuroeconomics, then, could be integrated in order to find an optimal solution for addressing human wellbeing and comfort (especially in the workspaces): hereby, environmental comfort studies concerning the adoption of physiological monitoring are compared to business management

studies lying on physiological indexes to assess employees' interest and cognitive effort, which influence their productivity.

2 Background

The European Council Regulation (EU) 2022/1369 on coordinated demand-reduction measures for gas suggests voluntary demand reductions as a strategic action to enhance energy security of EU Member States in light of the crisis due to Russia invasion of Ukraine [13]. Among demand-reduction strategies, the same Regulation mentions the option of defining targeted obligations to reduce heating and cooling. As a matter of facts, some governments like the Italian one put in place such strategies by reducing the heating period of 15 days, limiting daily operational schedule of 1 hour, and lowering the temperature setpoint of 1 °C (DM n. 383, 06 October 2022). This overview of EU reaction to the gas crisis is an example of the delicate relation among energy supply, economic crisis, and practical consequences on people well-being. Indeed, thermal comfort is reduced in favour of resources and economic savings. Despite the expected cost reductions directly imputable to the reduced operations of the conditioning system, what are the indirect costs that could come from the presented restrictions?

Indirect costs could be imputed to two main fields directly impacted by IEQ: healthcare and productivity. Since 2000, Fisk [14] analysed costs and benefits associated to IEQ and reported the estimated potential annual savings and productivity gains for the United States in the following: reduced respiratory disease (\$6-14 billions), reduced allergies and asthma (\$1-4 billions), reduced Sick Building Syndrome (SBS) (\$1-30 billions), direct improvements in worker performance not related to health (\$20-160 billions). In the last decade, the amount of scientific contributions that embrace the topic of IEQ and productivity increased significantly. This could be easily verified by searching in Scopus (the largest database of peer-reviewed studies available for consultation) review papers including both "IEQ" and "productivity" in their abstract. Looking for reviews instead of every type of documents provides a quick overview of the main trends in the general topic. This search results in 17 documents that were published since 2004 to date (December, 2022).

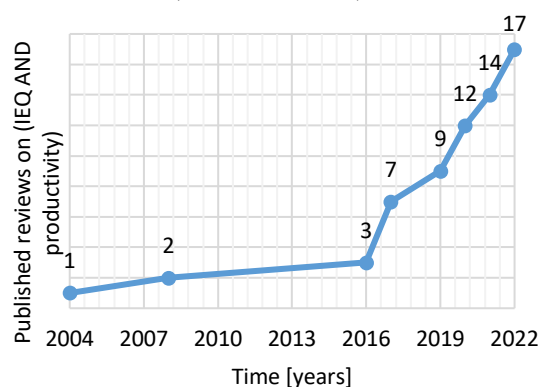


Fig. 3. Total amount of published review paper on IEQ and productivity throughout years (source: Scopus).

Only 2 reviews were dated before 2016: a first one focusing on IEQ in schools to promote best practices in educational buildings design that could be beneficial for both students' productivity and health status [15], and a second one addressing the main topic of building performance as function of IEQ, energy efficiency and cost efficiency including in the latter the impact of workspace IEQ on occupants' productivity [16]. The scarcity of reviews published in the first decade of the 21st century does not mean that those years were not characterized by intense research activities on the topic. Indeed, Al Horr et al. [17] in their review published in 2016 analyzed more the 300 papers focused on the impact of IEQ on productivity in office environments. In this work of review, the authors highlighted eight physical factors affecting IEQ and productivity adding to the four physical comfort domains (thermal, visual, acoustic, and air quality), office layout, biophilia and views, amenities, and location. This outcome implies that indoor environmental comfort is not just a matter of physical boundaries, but there are other aspects that must be considered while investigating human perception of the built environment.

More recent reviews investigate specific aspects affecting IEQ and occupants' productivity. Among others, Moya et al. [18] focused on the role of vegetation systems as elements capable of directly affect physical boundaries related to multiple comfort domains (thermal through evapotranspiration, acoustic as passive insulation system, and air quality by actively removing pollutants) further increasing occupants' comfort and wellbeing thanks to biophilia. Effects of green building features on workers satisfaction and individual productivity are the focus of both the reviews by Esfandiari et al. [19] and Nurick and Thatcher [20]. More specifically, Nurick and Thatcher look for the definition of a model linking green building features to increased individuals' productivity and organizational performance so to justify the initial capital expenditure that is needed for achieving such high-efficiency standards.

The definition of prediction models is also the focus of Asadi et al. [21] who reviewed, in 2017, the concept of occupants' behavior with respect to IEQ acceptance and building energy consumptions. As main outcomes of the review, the authors recognize:

- (i) a lack in addressing occupants' psychological responses and
- (ii) the need to effectively combine multiple comfort domains, both resulting in inaccurate predictions of occupants' interaction with buildings' systems.

How to properly address such challenges is partially covered by methodological review studies.

Rasheed and Byrd H. [22] specifically focused on the effectiveness of self-evaluation methods for the assessment of workers productivity. According to their findings, questionnaires submission or direct interviews are not reliable since subjects' responses are potentially affected by personal bias. In this view, subjective measures must be at least coupled to objective measures to provide references for effective predictive models.

A detailed review of the interrelations existing among IEQ factors and different cognitive functions is provided by Wang et al. [23]. The authors identified five main IEQ factors (indoor air quality, thermal environment, noise, lighting, and non-light visual factors) and five cognition categories (attention, perception, memory, language function, higher order cognitive skills). Through a detailed manual review of 66 studies combined to a keywords co-occurrence analysis of 8133 additional studies, they concluded that there is still room for investigation, since inconsistent or opposite results may emerge from the literature. These outcomes may be related to inter-individual differences that result in different level of acceptance and satisfaction with the IEQ thus generating different responses for each worker also in terms of productivity. In this view, Aryal et al. [24] review advances in Internet of Things (IoT) and Machine Learning (ML) to propose a vision to enhance personalized control of the close surroundings thus providing the optimal conditions for everyone.

This brief overview of existing studies on IEQ and productivity highlights that it is fundamental to further investigate the relationship between these two aspects, looking for quantitative and comprehensive assessment methods.

2.1 Multi-domain theories addressing human responses to IEQ

An emerging theory aimed at addressing human responses to environmental stimuli is the multi-domain comfort theory. As specified in the review by Schweiker et al. [11], this approach has the ambition of addressing human responses to the IEQ considering the simultaneous exposure of subjects to multiple physical stimuli and inter-individual differences. In this view, personal and contextual aspects are fundamental domains to be included in the investigation in addition to the four main physical ones (thermal, visual, acoustic, and air quality). Many researchers looked at disclosing the depicted complexity underneath human responses (including productivity) through different approaches. Three main categories could be recognized moving from a more controlled up to a more realistic environment of investigation: laboratory test in test rooms [25], living-laboratories [26], or in-field studies [3]. Fundamentals are generally investigated in test rooms where volunteers are exposed to pre-defined and controlled conditions while being monitored in terms of both subjective and objective responses via questionnaires or physiological monitoring, respectively. The latter could be the key to overcome personal bias in IEQ judgment [27] despite the collection of physiological features in real environment could be a challenge. In this view, the diffusion of low-cost, semi-invasive, wearable devices is promising, as presented by Mansi et al. [28] in a review specifically focused on thermal comfort assessment. Among others, electroencephalography (EEG) is under-investigated, due to criticalities in signals collection that require the minimization of movement artifacts. Nevertheless, Nayak et al. [29]

verified that brain power spectral densities (PSD) from EEG could predict office workers' productivity in different temperature conditions with higher precision compared to skin temperature or heart rate.

A relevant aspect in using physiological features to predict human responses to environmental stimuli is that these measures are objective and human centred. Moving the object of the analysis from the environment to the occupant allows to address both inter-individual differences and intangible IEQ factors. The latter are aspects of the living environment that are hard to be quantified and include office furnishings and layout, outside views from windows, greenspace, or personal control, among others. Despite the difficulties in quantifying and controlling such intangible factors, their impact on human responses (productivity, in particular) emerged in literature, as specified in [30]. A viable approach to verify the impact of these factors, not related to any building active system, could be the assessment of their impact on physiological features (EEG, in particular) since the building design stage via Virtual Reality (VR).

Therefore, the multi-domain theory and the proposed human-centred approach to verify IEQ impact on workers productivity could effectively support companies or institutions that need to find the optimum between occupants' well-being and building energy needs by looking at solutions that enhance productivity that do not require energy expenditure. At the same time, it could be integrated with other methods, like the one of neuroscience, that also use EEG.

2.2 Neuroscientific indexes

While engineering studies focus on the multi-domain theories described so far, on the other side of science, there is neuroscience.

The latter has merged lately with many disciplines in the social field (aesthetics, marketing etc.), among which economics, thus giving birth to the so-called Neuroeconomics. This is usually defined as "the application of neuroscientific methodologies for the analysis and the knowledge of interesting human behaviours in the economic field" [31].

In neuroeconomics, experiments are conducted with different techniques and devices (the most popular brain imaging method adopted in the neuroeconomics and neuromarketing fields, is the functional Magnetic Resonance Image - fMRI).

However, in most of the cases, lighter versions for brain imaging are preferred, like the portable EEG [32]. In the majority of the cases, neuroeconomics experiments are conducted:

- through the heart rate measurement via Electrocardiogram (HR via ECG),
- to the measurement of the skin galvanic response (GSR)
- and finally, to the electroencephalogram (EEG).

The combination of the first two signals allows the construction of an index able to measure the emotional response of the subject: in particular, the skin galvanic response (GSR) indicates the 'activation' capacity of a stimulus, while the associated heart rate (HR) indicates the value (positive or negative) attributed to it [33]. The

use of the EEG, instead, indicates the cognitive activity of the subject, and therefore his/her degree of interest in the marketing stimulus.

In this frame and in view of the assessment of comfort in employees, what is important to underline about neuroeconomics is that the experiments in this field return some indexes that, can give us a hint of the personal comfort/discomfort of an individual: among the most important ones there is the (Visual) Attention, the Memory, the Mental Workload, the Approach/Withdrawal Motivation [34], assessed with the data coming from the EEG, the GSR and the eye-tracking (as shown in Figures 4,5 and 6).

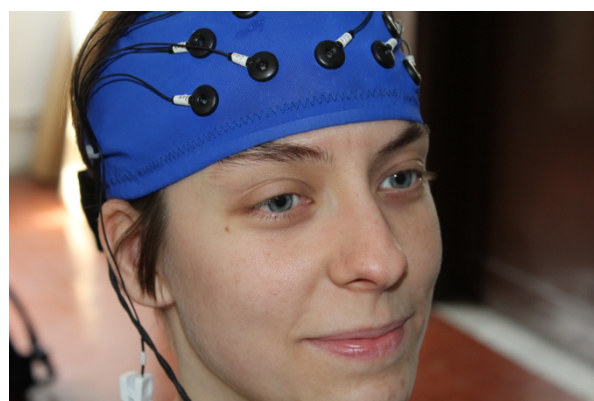


Fig. 4. Experimental tester during a neuroscience experiment wearing an EEG cap



Fig. 5. Experimental tester during a neuroscience experiment wearing HR and GSR measurement devices.



Fig. 6. A neuroscience experiment using a fixed eye-tracker (Tobii).

3 Results

3.1 The added value of integrating Neuroscience in assessing employees' comfort

Therefore, neuroscience can give us a measure of the level of cognitive stress of an individual during a task and in a certain conditions: this has been studied in several working fields (including the most stressing ones) where studies of neuroscience [35] [36] [37], have been able to test the mental fatigue of pilots and people working in the aviation field.

On the other hand, with neuroscientific methods we can infer if an individual is interested or not in the task that he/she is performing: this, which is assessed through the index of cognitive interest, is a measure that does not only depend from the nature of the task itself, but also from contextual variables [38].

At the same time, neuroscience is capable of giving us a hint about the comfort or discomfort of a person in terms of emotion/pleasantness towards a stimulus or an environment (also when an individual is subject to extreme temperatures, high or low): this is given by the index of the approach/withdrawal.

Finally, another measure of the individual's attention can be collected via eye tracking (in this case, the index is called "visual attention").

A last remark about the added value of integrating neuromarketing in the experiments about comfort and productivity is the possibility of lowering the number of testers in the sample, with the same reliability of large numbers that are usually needed in traditional research: in consumer neuroscience, studies have shown that the effect on a few people is representative of the effect on larger populations, clearly at the cost of measurement variability leading to a loss of statistical power [39, 40].

4 Conclusions

4.1 An interdisciplinary view: importance and limitations

In view of this, we might suggest therefore that, in order to have a more complete comprehension of the level of comfort and wellbeing of an individual, as well as of the productivity level of a worker, we should take into account not only the variables coming from the literature of the environmental comfort, but also interdisciplinary literature coming from the results of neuroscience and, in a broader sense, also social sciences.

However, many limitations and issues may arise from merging different disciplines together, starting from the difficulties in matching data of experiments conducted on the same sample but in different conditions that, even if vary slightly, can generate discrepancies (e.g. let us imagine that an experiment is conducted when a person has assumed caffeine: this would alter the results of the neuroscientific experiment but would not be diriment for the multi-domain experiments).

Therefore, in order to conduct experiments that integrate different methods coming from different

disciplines, a preliminary shared protocol should be studied: first theoretically, and then corroborated by empirical tests.

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