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Changes in work environment parameters in relation to the comfort and factors influencing productivity of office workers: comprehensive literature review

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Abstract. The implications of indoor air quality on human health are well-documented and extensively studied in several researches, encompassing an augmented susceptibility to airborne infections and enduring consequences attributed to diverse chemical pollutants. The repercussions of insufficient air parameters within occupational environments on employee health and productivity are predominantly correlated with perceptions of comfort, satisfaction, the incidence of occupational diseases, and the concentration and decision-making levels. The aim of the study is to develop a causal model of air quality and productivity parameters, based on theoretical analysis, which can be used to assess changes in work environment parameters and their impact on the comfort and productivity of office workers. The theoretical analysis highlighted the significance of employee productivity and the growing importance of well-being in assessing workers' productivity. Factors such as temperature, humidity, airflow, and especially CO_2, were identified as crucial in creating a conducive working environment that influences employee productivity. The research results in the developed indoor air quality parameter matrix as causal model and emphasises the complexity of the relationship between work environment parameters and employee productivity.

Key words: causal model, cognitive tests, indoor air quality, productivity, wellbeing.

INTRODUCTION

The services sector now employs the largest number of people after industry, manufacturing, construction and agriculture (OECD, 2022). Many service sector jobs are now located in office buildings, which are often characterised by airtight facades, increased use of air conditioning and mechanical ventilation systems, and are equipped with several types of electronic equipment such as computers, monitors, printers and audiovisual conferencing equipment (Sakellaris et al., 2016). Changes in the structure of modern economies and the shift towards a smarter and service-oriented business model in developed countries have led to more time being spent indoors, particularly working at a computer. Office design has changed in recent decades, with individual offices increasingly being replaced by open-plan offices. The fact that employees spend long periods of time in the same room with other people highlights the importance of ensuring good indoor air quality for everyone in the office environment. These changes, together with the effects of increasing climate change and the risks of air quality and pollution, make indoor air quality more important than ever. It is well known and widely researched that poor indoor air quality can have negative effects on human health, ranging from increased risk of airborne infections to long-term effects of various chemical pollutants (Bluyssen et al., 2011). The impact of inadequate workplace air parameters on employee health and productivity is most commonly associated with feelings of comfort, satisfaction, occupational diseases, concentration and decision-making ability (Wargocki et al., 2000; Wargocki et al., 2002; Satish et al., 2012). Recently, with the rising costs of building management due to energy costs and the need to ensure adequate air quality, this aspect has become as important as health impacts. Business owners and building managers have a new and important challenge: to find a balance between investment in air quality, energy efficiency of buildings and productivity and health of employees.

The aim of the study is to develop a causal model of air quality and productivity parameters, based on theoretical analysis, which can be used to assess changes in work environment parameters and their impact on the comfort and productivity of office workers.

The study involved a literature analysis to identify the indoor air parameters that have the greatest impact on employee comfort and productivity. The impact of these parameters on employees' cognitive abilities was also analysed, as well as their sub-activity under changes in the selected parameters. The study developed a causal model to assess changes in work environment parameters on office workers' comfort and productivity by establishing a causal relationship between air quality and productivity parameters. A pilot study was conducted to validate the theoretical concepts of the model. This study presents significant literature findings on the indoor air quality parameters that have the most significant impact on productivity. It also provides recommendations on which indoor air quality parameters should be prioritised to achieve the optimal balance between cost and employee productivity.

MATERIALS AND METHODS

Systematic literature review with PRISMA guidelines. Systematic literature review was performed to gain the latest research results from scientific studies on work environment parameters in relation to the comfort and productivity of employees in the working environment. A survey of the literature was conducted to identify the variety of indoor air quality aspects that have potential to influence the office workers' productivity and health (as it affects productivity). Research papers were selected from the following electronic databases: Cochrane Library, Clinical Key and Science Direct. The review was conducted in accordance with PRISMA guidelines 2020 (Page et al., 2021) for systematic reviews. For the selection of scientific articles and publications, authors chose the following keywords - thermal comfort, temperature, humidity, indoor air quality, ventilation, CO_2, pollution, office workers, cognitive load and productivity. Keyword searches in the selected databases led to selection of 196 papers. After deleting duplicates, the authors selected 128 documents. Of the 128 publications that were selected by title, several were excluded because they did not satisfy all the selection criteria in that the texts were not available in total and free of charge. 84 full-text papers that satisfied all the criteria were analysed and used to create a systematic review of the literature, including the analysis summarises the results of 37 experimental studies that performed objective cognitive tests with fixed CO_2 concentrations, either by adding pure CO_2 or by adjusting ventilation rates (the latter also affects other indoor air pollutants).

Case study as pilot-research project. A small case study (pilot-research) was performed in order to test the causal model and used 3 types of cognitive tests to assess the impact of different factors on workers productivity. Study involved 21 participants, males and females with the mean age 35.05 years (22–62 years, SD = 11.68). All participants consent to participate and where exposed to the indoor environment factors. Following cognitive tests were used in the study: 'Corsi test' (Kessels et al., 2008), 'Visual Choice reaction test' (Deary et al., 2011) and 'Stroop test' (MacLeod et al., 1991; Lamb et al., 2018). Measurements with tests were performed in one week cycle each morning, mid-day and evening. Each day in the working cycle there were changes in the effects of temperature, humidity and CO_2 levels and in such a way cognitive performance was observed in the time frame from 9:00 till 17:00. Research has been approved by the Ethics Committee of Riga Stradins University. According to the neurobehavioral framework for evaluation of productivity of office workers, behaviour depends on persons' emotion, cognition and executive functions (e.g. purposive action, effective performance and motor performance). While, cognitive functions include persons' perception (visual and auditory), learning and memory (short-term or working memory, and long-term memory), thinking (e.g. problem solving), expression (e.g. speaking, writing). In the pilot-study 3 cognitive tests were included to check different cognitive functions and performance. To increase the quality of data, the participants were asked to perform tests that require no longer than 20 minutes of time per one attempt. Corsi test evaluates visual spatial short-term memory and includes spatial attention (Brunetti et al., 2014). Visual Choice reaction test requires continuous attention and characterises the participant's reaction time to visual signals. The test evaluates the level of mental fatigue of the respondents, which is one of the main reasons for the decrease in response. At the beginning, there is a single task that measures an individual's reaction time when performing non-decisional cognitive tasks, while the second part is a more complex task that measures an individual's ability to react when the choice is necessary (Gumasing & Castro, 2023). The Stroop test evaluates the participant's visual perception along with the ability to perceive meaning (Lamb et al. 2018). The gathered data from each test was analysed separately to determine how the changes in parameters impacted each participant. Correlation tests were used to determine if the impact of indoor environment factor changes is statistically significant. Data analytics and visualisation were done in IBM SPSS and Microsoft Excel.

RESULTS AND DISCUSSION

Justification and description of the choice of parameters in relation to the working environment

Air quality characteristics and work productivity are affected by various environmental factors. Several factors were analysed in this study: thermal comfort described by temperature (t, °C) and relative humidity (RH, %), the air quality according to carbon dioxide level (CO_2, ppm), that depends on the effectiveness of ventilation, including air ventilation rate (L s^{-1}). It is important to understand that the microclimate and air quality cannot directly improve productivity, but rather facilitates the performance of work, which accordingly allows employees to work with maximum efficiency. In a real work environment, it is impossible to find 100% satisfaction of employees with occupational parameters due to subjective definition of comfort. However, comfortable conditions for the maximum number of employees must be provided in each workplace. The indicators and recommended values analyzed in this study serve as a starting point for the analysis of the influence of indoor air environment parameters on employee performance and productivity. Hence authors further will describe the main parameters and inclusion justification in the research.

Changes in the physical environment raise certain physiological (e.g., sweating to reduce body temperature) and psychological (e.g., increased effort in the event of a challenge) reaction of the body (Parsons, 2000). Work productivity depends on the human motivation that helps to achieve the result despite the challenges (Lamb et al. 2018). While, motivation decreases during thermal stress, especially at warm environmental temperatures (above 26 °C vs. below 22 °C). A decrease in motivation provides a better explanation for the decrease in productivity than the direct effect of heat stress (Cui et al., 2013).

Temperature perception is influenced by the microclimate, which is described by relative humidity and air velocity. Additionally, indoor temperature is affected by heat radiation from heating systems, electrical devices, sunlight, and ventilation effectiveness. Latvian national requirements specify the following parameters for office workers classified as light work employees: a temperature range of 19–25 °C during winter and 20–28 °C during summer, with an air relative humidity of 30–70% and air velocity of 0.05–0.15 m s^{-1} for both seasons that is stated in Latvian legislation (Cabinet of Ministers Regulation No. 660).

National research indicates that 15.8% of Latvian employees were dissatisfied with their work conditions, including inappropriate air temperature (Vanadzins et al., 2023). According to European data, the highest number of reported illnesses related to working environment conditions, including exposure to cold and heat, occur in outdoor work, manufacturing companies, and the transport sector. Office work is generally considered to have relatively favourable microclimatic conditions.

Providing one optimal microclimate may change the value of another microclimate, e.g. increasing the temperature may reduce humidity or increasing the speed of air movement may be perceived as reducing the air temperature. Relative humidity between 40 and 60% ensures optimal functioning of the body. Increased relative humidity combined with increased temperature slows the evaporation of sweat from the skin surface and can cause the body to overheat. Low relative humidity increases water evaporation from the skin surface, which is not associated with sweating. This can lead to changes in thermoregulation and respiratory problems that dry the skin and mucous membranes, reducing the body's defences against infectious agents. Maintaining a relative humidity between 40% and 60% can reduce the ability of bacteria and viruses to survive. Relative humidity affects the distribution of gaseous substances and the rate of evaporation from indoor furnishings and furniture materials, which in turn affects chemical pollution in the air. Increased humidity and temperature lead to higher rates of evaporation of gases (HEVAC, 2016).

Depending on the body's condition, an adult at the optimal air temperature emits 100–200 kcal of heat, 40–45 g of water vapour, and 20–50 L of CO_2 h^{-1}. If the temperature of the air increases, the amount of water excreted from the body in the form of sweat may increase to 100–150 g h^{-1} (Eglite, 2008). As a result, even at optimal CO_2 concentration (800 ppm) there is an odour in the room's air that causes subjectively unpleasant feelings. Carbon dioxide level in the outside air usually is less than 400 ppm, while the concentration could be higher near vehicle traffic areas, industry and sources of combustion. In rooms where the main source of CO_2 is people, CO_2 does not reach concentrations that could cause severe damage to health (< 5,000 ppm) (ASHRAE, 2022). The National Institute of Occupational Safety and Health recommendation for the indoor CO_2 level is less than 1,000 ppm. When CO_2 is above 1,000 ppm could be noticed the following feelings and symptoms: the feeling of stale air, increased concentration of dust, and air relative humidity, the heat exchange could be deteriorated, person could feel malaise, headache, dizziness and reduced productivity (Eglite, 2008; ASHRAE, 2015). High CO_2 concentrations affect high-level decision-making. Low ventilation efficiency and high indoor pollutant concentrations, including CO_2, may reduce the speed of various functions but not obligatory change the accuracy (Du et al., 2020).

Most ventilation systems re-circulate a part of the indoor air to maintain thermal comfort and decrease energy costs. CO_2 works as an indicator of ventilation systems efficiency according to the recommended minimal volume of fresh air supply. In many cases, the main CO_2 pollution source is people. In this case, parallelly with the increase of CO_2 concentration, increases the amount of anthropo-toxins - end products of metabolism processes - different toxic organic and inorganic chemicals (e.g. ammonia, indole, mercaptans). As well increases the number of microorganisms in the air, dust concentration, number of positively charged aero-ions, increases the air temperature and relative humidity (Eglite, 2008).

The main purpose of the ventilation system is to maintain good indoor air quality in buildings by removal and dilution of pollutants, and fresh air supply. Insufficient air change or ventilation leads to the accumulation of chemical, biological, mechanical contaminants and moisture problems. It is important to remember that heating, ventilation and conditioning influence indoor air quality in different ways. In order to save energy, natural indoor ventilation systems (with the possibility of adjusting the amount of air exchanged according to the changing parameters of the outdoor air) are preferred. If it is not possible to ensure air quality requirements with natural ventilation, additional mechanical ventilation systems are used (installed directly in windows/walls /via air ducts). Mechanical ventilation systems shall be provided for rooms or areas of rooms where natural ventilation is not possible (e.g. windows cannot be opened or not present). Mechanical ventilation systems allow recirculating air to reduce energy consumption if harmful chemicals, bacteria, or unpleasant odours are not emitted into the room. Reduction of energy consumption should be balanced with optimal CO_2 level.

Ventilation can be described via ventilation rate (supply or exhaust) or the volume of outdoor air that is provided into the space/ is exhausted out from the space. Airflow direction shows the overall airflow direction in a building, which should be from clean zones to dirty zones. And finally, air distribution or airflow patterns state that the external air should be delivered to each part of the space in an efficient way and the airborne pollutants generated in each part of the space should also be removed in an efficient way (Atkinson et al., 2009). Ventilation rates below 5 L s^{-1} per person are likely to cause indoor air pollution problems in non-industrial facilities with high emission rates and the minimum air ventilation rate for office buildings is recommended to be 2.8–4.2 L s^{-1} per person.

Latvian Building Standard LBN 231–03 'Heating and ventilation of residential and public buildings' stipulates that the absolute minimum supply of fresh air when it is assumed that people are the only source of air pollution in a room amounts to 4.2 L s^{-1} (or 15 m^3 h^{-1}) per person (Cabinet of Ministers, 2015). A ventilation rate's recommendation from ASHRAE for office workers of 8.5 L s^{-1} per person is made to contribute to optimal CO_2 levels below 1,000 ppm (ASHRAE, 2015). The ASHRAE ventilation rate's recommendation of 8.5 L s^{-1} per person was increased to 10 L s^{-1} per person after calculations of the necessary air exchange frequency (NAEF) for people who are not physically active (office employees belonging to the mental workers' group). The formula is following: NAEF = n * (22.6 L 1–0.4 L m^{-3}) / room volume, where n is the number of people in the room; 22.6 L is the average volume of exhaled CO_2 by an adult person who is at rest (not physically active, and performs mental work; the value is average for women and men); 1 L m^{-3} (or 1,000 ppm) is maximum recommended CO_2 level indoor; 0.4 L m^{-3} or (400 ppm) is CO_2 level in outdoor air that is provided through ventilation system (Eglite, 2008). If calculations for the right side of the formula are made, NAEF is calculated as the number of people multiplied by 37 m^3 h^{-1} and divided by room volume (m^3), therefore 36 m^3 h^{-1} or 10 L s^{-1} are mentioned as a borderline between a moderate and good level of air ventilation rate per person per hour in Table 1.

Even the air quality parameters like temperature, relative humidity, CO_2 level and ventilation rate can be easily evaluated, the parameters always should be analysed in complexity. Because the presence of the ventilation system does not obligatory mean that will be appropriate microclimate in the work environment (may be affected, e.g. by the layout of the premises, furniture). Mechanically treated air that is heated/ cooled, humidified/ dehumidified does not mean that it is clean and fresh. The workplace placement could be unsuitable and leading to discomfort - under air conditioners, air supply openings. The location of air intake for ventilation supply at workplaces also plays a role, that the air is not taken from basements or the street side. Maintenance and repair of ventilation systems also could be crucial.

Working environment parameters and impact on productivity

Effect of temperature on productivity. The productivity of office workers plays a key role in both the quality and efficiency of the work done and in reducing costs for the company. In order to ensure employee productivity and thermal comfort, the permissible indoor air temperature shall be set within a range with small tolerable daily and seasonal variations. The relationship between temperature and work performance has often been described as an inverted U-shape (Seppanen & Fisk 2006). This means that maximum productivity is achieved at the optimum temperature and any deviations from the optimum temperature will have a negative impact on performance. Increasingly, productivity is being studied in relation to thermal sensation, generally confirming the inverted U-shaped model with maximum performance in the vicinity of neutral thermal sensation. Optimal relative productivity is often at neutral and/or cool air temperatures (thermal sensation vs. relative productivity) (Geng et al., 2017). However, productivity decreases at elevated air temperatures (26–28 °C), even when thermal comfort is achieved by adjusting clothing and/or room air movement speed (Lan et al., 2020). In contrast, Hancock's maximum adaptive model emphasises the ability of humans to maintain constant productivity under changing moderate indoor thermal conditions (17–25 °C). Consequently, productivity is influenced by the physical work environment (intensity of thermal stress), the worker (his/her work motivation) and the task (work content and conditions) (Luo et al., 2023).

Analysing different literature on the effect of air temperature on human work efficiency, the obtained results are similar and comparable, which on average show a 2% drop in work efficiency in relation to 1 °C when the temperature is above 25 °C (Kirilovs & Emsiņš, 2010). The above statement is supported by research showing that indoor productivity will decrease as temperatures increase by more than 25 °C (Seppanen et al., 2002).

Temperatures above 25 °C cause a decline in mental alertness, and temperatures above 30 °C cause a decrease in concentration. Compared to 18 °C, 26 °C, and 30 °C, the optimal temperature for executive brain function precision was found to be 22 °C (Abbasi et al., 2019; Wei, 2020). At 26.2 °C compared to 22.4 °C, at 27 °C compared to 23 °C, and at 26.3 °C compared to 21.4 °C (Laurent et al., 2018; Barbic et al., 2019; Lan et al., 2020), there was a statistically significant decline in cognitive test performance. In several research findings approximately 25 °C was determined to be the optimal temperature for cognitive test performance, as opposed to 18.7 °C and 28.8 °C and 22–23 °C. Also 25 °C was associated with higher cognitive test performance, as opposed to 18.7 °C and 28.8 °C and 22–23 °C (Hong et al., 2018; Yeganeh et al., 2018). According to one study, there was not a significant difference in cognitive test performance at 22 °C and 25 °C (Zhang et al., 2017). According to Zhang & de Dear (2017), cognitive function either stayed mostly unchanged or even slightly improved at 22 °C as opposed to 24 °C. 20 to 26 degrees Celsius was shown to be the ideal range for productivity, with 22 to 24 degrees Celsius being the most productive (Geng et al., 2017). According to Maula et al. (2016) and Vimalanathan & Babu (2014), work performance was considerably worse at 29 °C compared to 23 °C and at 17 °C and 28 °C compared to 21 °C. According to one study, people's mental loads were comparatively higher in a 28.6 °C environment than in 21.7 °C or 25.2 °C (Wang et al., 2019). In the study conducted by Xiong et al. (2018), the highest learning efficiency was recorded at 22 °C as compared with 17.3 °C and 27.1 °C. Based on this data, the ideal temperature range for performance is typically between 22 and 24 °C, and brain activity is extremely sensitive to even minute variations in Interactive Response Technology (IRT). Though the function of the transient receptor potential melastatin 8 (TRPM8) neuron has been postulated, the underlying biological process has not been studied (Wei, 2020).

Gender sensitivity to cold and hot environments differed significantly. An increase in temperature from 24 °C to 27 °C caused an increase in thermal discomfort in men by 1.18 points on the scale, which is 0.67 points higher than in women (0.51 points), while lowering the temperature from 24 °C to 21 °C, thermal discomfort increased by 0.48 scale points for women, twice that of men (0.24 points) (Rajat et al., 2019).

CO_2 impact on productivity. Poor indoor air quality, as evidenced by elevated indoor CO_2 concentrations, is associated with impaired cognitive function, however, current research findings on the cognitive effects of CO_2 are conflicting. Looking at various scientific publications, the amount of carbon dioxide that does not meet the recommendations is considered one of the main types of indoor pollution. In Latvia, at the moment, such a recommendation (regulatory requirement) in public buildings is 1,000 ppm (specified in Regulation No. 310 of the Cabinet of Ministers Regulations on the Latvian building code LBN 231-15 'Heating and ventilation of residential and public buildings' clause 95 (adopted on 16.06.2015, with as amended from 13.05.2021) (Cabinet of Ministers, 2015). There is little accurate information about the real situation (separate measurement series, school monitoring data, etc.). The world of data is relatively abundant, for example, in general office spaces in the United States, CO_2 concentrations tend to be much lower than schools. In a representative survey of 100 US offices (Persily & Gorfain, 2008), only 5% of measured maximum indoor CO_2 concentrations exceeded 1,000 ppm, assuming an outdoor concentration of 400 ppm. One very small study found that in meeting rooms in offices, where important decisions are sometimes made, CO_2 concentrations may be elevated, for example up to 1,900 ppm during 30- to 90-minute meetings (Fisk et al., 2019).

Previous studies of CO_2 exposure, mostly at higher levels, have focused on physiological effects. CO_2 is a key arousal regulator of human respiratory and behavioural states (Kaye et al. 2004). However, at lower CO_2 levels and when it comes to productivity, the effects of CO_2 on cognitive abilities come to the fore.

In a subset of 37 experimental studies that met objective criteria for robustness and certainty according to chosen methodology, CO_2 concentrations were found to affect high-level decision making. On the other hand, lower ventilation efficiency and higher concentration of indoor pollutants, including CO_2, accumulation can reduce the speed of various functions, but not change the accuracy. The main confounding factors are differences in cognitive assessment methods, study designs, individual and population differences in subjects, and uncertainties about exposure doses. Accordingly, future studies are proposed to use direct air delivery to precisely control CO_2 inhalation, incorporate brain imaging techniques to better understand the underlying mechanisms linking CO_2 concentration and cognitive function, and investigate potential interactions between CO_2 and other environmental stimuli (Bowen et al., 2020).

In the study, 22 participants who were exposed to 3 different CO_2 concentrations - 600, 1,000 and 2,500 ppm in an office-like room performed cognitive load tests, looking at changes in 9 decision-making abilities. They are basic activity, applied activity, focused activity, task orientation, initiative, information search, information usage, activity that requires a wide range of approaches (breadth of approach), basic strategy (basic strategy). The results of the study confirmed that at a CO_2 level of 1,000 ppm there were moderate but statistically significant reductions in six of the nine decision-making performance scales. At 2,500 ppm CO_2, there was a large and statistically significant reduction in seven scales of decision-making performance. Contrary to the above, performance scores (concentrated activity) increased with CO_2 pollution, suggesting a mixed decline in cognitive abilities with increasing CO_2 levels. The scalar results show that at a CO_2 level of 600 ppm vs. 1,000 ppm cognitive ability decreases by 11–23%,

CO_2 600 ppm vs. 2,500 ppm - by 44–94%, while CO_2 1,000 ppm vs. 2,500 ppm decreases cognitive abilities by 35–93% (Satish et al., 2012).

Effect of relative humidity on productivity. A working environment with a humidity range between 40 and 60% is recommended for optimum productivity. Optimum relative humidity increases the stability of the precorneal tear film and reduces the risk of dry eyes and fatigue, which significantly improves productivity (Wolkoff et al., 2021). Regarding efficiency aspects, the highest reading accuracy (97%) was observed at a relative humidity of 40% (at a temperature of 24 °C). As the relative humidity decreased to 20%, the reading accuracy decreased by 1.44% (Chao et al., 2021). Despite the fact that there is an increase in productivity with an increase in relative humidity, this trend is not infinite. When humidity exceeds 70%, the absorption of sweat by the human body is hampered, which blocks the body's cooling mechanism and can lead to overheating. Overheating, in turn, will lead to excessive sweating, intense elimination of body fluids and minerals through sweat, which can lead to dehydration, dizziness, cognitive impairment, which reduces productivity (Wolkoff et al., 2021). In contrast, two studies on the production environment confirm trends observed in previously mentioned studies. In a study of automobile production shops, worker productivity increased by six units of product produced per 30 minutes with an increase in relative humidity from 63% to 78% (Ismail et al., 2009). Similar results were observed among workers in the electronics industry. Employee productivity increased by 15 units of product produced per 30 minutes with an increase in relative humidity from 55% to 61%. In this case study, the following relationship was expressed by formula $Y = 2.5863X – 28.896$, where X is relative humidity and Y is productivity (number of product units produced). The resulting equation model is only applicable to show the productivity at the time of the study at the selected assembly workplace in the Malaysian electronics manufacturing plant (Ismail et al., 2007).

Relative humidity affects not only productivity but also the health of the workers. In European offices (167 buildings), a voluntary employee survey (n = 7,440) found that almost half (47%) of employees found the air to be dry, leading to symptoms such as dry skin (15%) and dry eyes (16%) (Wolkoff et al., 2022).

Effect of air ventilation rate on productivity. Air exchange frequency refers to the rate at which air is exchanged in a workspace. Workers report more discomfort in the form of dryness in the throat, difficulty in thinking clearly, and feeling uncomfortable at low air exchange rates (3 L s^{-1} per person in the room) than at higher air ventilation rates (10 L s^{-1} and 30 L s^{-1}) (Wargocki et al., 2002).

Specifically, workers showed improved writing speed, insertion of numbers into the text, and speed of rereading when air exchange rates were improved (Wargocki et al., 2002). The study found that increasing air ventilation rates from 3 L s^{-1} per person to 30 L s^{-1} per person resulted in a 1.7% improvement in employee text processing productivity.

A study analysing scientific literature found that increasing air exchange from 6.5 L s^{-1} per person to 12 L s^{-1} per person improves productivity by 1%. Raising it to 24 L s^{-1} per person improves productivity by 2.4% compared to the original 6.5 L s^{-1}per person productivity measure (Seppanen & Fisk, 2006).

It is important to note that increasing air exchange also reduces the risk of workers becoming ill. Research conducted by Seppanen & Fisk (2006) has shown that employees who work in environments with an air ventilation rate of 12 L s^{-1} per person are sick for an average of 5 days per year. Increasing the air ventilation rate to 24 L s^{-1} per person would reduce the number of sick days to an average of 3.8 per year.

Several studies analysing air environment parameters in a complex way are also appearing in the scientific literature. In these cases, the results are more dispersed and provide a more accurate picture of the workplace conditions, but the findings are less universally applicable. It can be concluded that indoor temperature, relative humidity and CO_2 are the most influential factors on productivity at the work environment. One study offers an accessible target oriented approach by determining optimal parameters to maximise productivity would be as follows: temperature: 21–25 °C, relative humidity: 30–55%, CO_2: up to 700 ppm (Kaushik et al., 2020).

In this case the values for air exchange frequency are not specified, meaning that the actual room air exchange frequency is automatically optimal, when temperature, relative humidity and CO_2 parameters are compliant as these parameters can be easily adjusted also in case of not advanced technology. Accordingly, when these recommended values are reached, the actual room air exchange frequency is automatically optimal, so there is essentially no need to set it differently. A similar study compared different levels of microclimate parameters to determine their impact on productivity. It concluded that productivity is the best at a temperature of 21–25 °C, a relative humidity of 21–40% and a CO_2 concentration of up to 600 ppm (in this study, the air exchange frequency was 18.87 L s^{-1} per person and only outside air was used without recirculation (Allen et al., 2016).

Since there are not many publications for complex analysis of air quality parameters impact on employee productivity, the choice was made to base findings on a single parameter metrics from many other parameters. Meaning that one parameter being out of bounds would indicate reduction in productivity. The impact of parameter metrics on productivity and condition graduation are derived from multiple case studies. Four levels of conditions are based on case study recorded impact.

Indoor air quality (IAQ) parameter optimization for productivity

Authors developed an IAQ parameter risk matrix with four main categories: *good*, moderate, bad, not acceptable (See Table 1). The choice of such categories was based on several research studies due to the topic of risk matrix design remains controversial, despite their widespread use in practice and various methods have been proposed to aid in the design of risk matrices (Duijm, 2015; Bao et al., 2017; Jensen et al., 2022).

It is important to note that productivity levels can be influenced by various individual factors. For instance, previous research has highlighted gender and age, as well as individual sensitivity to indoor work conditions and office environments. Indoor workers may complain about draughts and cold temperatures. Static work (sitting or standing) can lead to low heat production, making employees more sensitive to small fluctuations in temperature. To compensate for the lack of heating, office spaces are insulated with appropriate materials. Office workers often wear formal clothing, which limits their ability to adapt to changes in temperature. Uncovered body parts emit heat radiation, which increases air flow. Higher air temperature can create a feeling of poor air quality and stagnant air. However, not only thermal factors play a role in self-perception and work efficiency (Toomingas et al., 2011).

Some studies show gender differences in optimal microclimate conditions, where women's optimal microclimate conditions have higher air temperature and relative humidity than men's (Liu et al. 2021). Gender differences are explained by factors such as lower body mass in women, higher subcutaneous fat content, lower physical abilities in women (which affect heat production), and other factors.

Table 1. Risk matrix for indoor air quality parameters (Author`s developed matrix)

IAQ parameters	Risk levels with categories from I – IV			
	Good (I)	Moderate (II)	Bad (III)	Not acceptable (IV)
CO_2, ppm	< 800	800–1,500	1,500–2,500	> 2,500
% productivity	100	89–77	77–65	< 65
Temperature, ℃	21–23.9	19–20.9 / 24–25.9	17–18.9/26–27.9	< 17 or > 27.9
% productivity	100	98	96	94
Relative humidity, %	40–60	30–40 / 60–70	20–30 / 70–80	< 20 or > 80
% productivity	100	100–98.6	98.6	< 98.6
Air ventilation rate, L s^{-1}	10–20	4.16–10	0.27–4.16	< 0.27
Air ventilation rate, m^3 h^{-1}	36–72	15–36	1–15	< 1
% productivity	100	99	98	< 98

However, in normal working conditions (with slight variations in microclimate), gender differences have little significance. As a person ages, the sensitivity of their organs and temperature-regulating structures (sweat glands, blood vessels) to temperature changes decreases, and structural changes in the skin occur. In older people, the 'protective reaction' to cold and heat with vasoconstriction or vasodilation begins later, and sweat production is lower. Considering physiological changes and lifestyle differences, the elderly have a decreased tolerance for adapting to environmental changes (Toomingas et al., 2011).

Pilot-research project results

The practical case study with pilot testing of the causal model was carried out. The main results are summarised in Table 2.

Table 2. Microclimate parameter planned (P) and factual (F) values in pilot-research study (Author`s developed table)

Parameter	23 P	23 F	24 P	24 F	25 P	25 F	26 P	26 F	27 P	27 F
t, ℃	18–22	22.7	18–22	23.3	18–22	23.9	20***	20.8	26–28****	22.6
RH, %	40–60	42	40–60	47	40–60	49	40–60	35	40–60	34
Velocity, m s^{-1}	< 0.05		< 0.05		< 0.05		0.15 average	0.15 average	< 0.05	
CO_2, ppm	< 800	600	> 900*	931	> 1,200**	1,166	< 800	517	< 800	490

Originally planned: *1,000; **1,500; ***17–20; ****23–28. Represented average values for each day from 08:00 to 17:00 in the 5 full day period.

The pilot research found that increasing the temperature from 20.5 °C to 24.5 °C led to a slight increase in reaction time (affecting the productivity of several office workers), but overall data analysis showed that gained results are not statistically significant. Despite this fact the use of cognitive tests showed better cognitive ability results for some office workers when the relative humidity increased from 34% to 49% and by increasing the CO_2 level also led to a decrease in reaction time.

When it comes to test result differences between Corsi, Deary simple and Deary Choice tests, for CO_2 impact on productivity, the Deary Choice test showed the biggest impact on test subjects. It had the biggest correlation (-0.13) between all test subject scores and CO_2 levels, but this relationship is too small to be considered impactful. Relative humidity analysis illustrated that this parameter is very subjective. For most participants relative humidity did not have a statistically significant impact, but for some participants this parameter was critical. In this niche group, one exhibit performed better in a more humid environment (40–50%) and another one had better results in a dryer environment (30–40%).

During the experiment the assessment process was set up to be as self-sustaining as possible to reduce potential anomalies. The setup contained a schedule for employees taking performance tests, heat, ventilation and air conditioning (HVAC) systems were aligned to the determined parameters for specific days, the management and employees were briefed on the experiment's goal to make sure all employees who participated in the study were informed and their priorities were aligned. The preparations were carefully planned and made, but there were some setbacks:

1. The office HVAC and temperature systems were unsuccessful in reaching predetermined non optimal micro climate parameter values, since the installed HVAC systems are built to make an optimal working environment and are not designed for simulating extreme environments.

2. Testing employees on a voluntary basis leads to inconsistency in the data pool, making it less trustworthy. In total there were 15 periodic testing sessions (three times a day (morning, afternoon, evening) for 5 days) but the average employee only submitted 9 testing sessions and from all 21 participants only 5 submitted a full data set of 15 testing sessions. To guarantee a maximised data set it is critical to find ways to enforce testing. Some examples for this enforcement:

a) booking dedicated time (15 min) in their calendar, this can also be done collectively for example after a meeting;

b) monitoring responses and progress live to ensure people finish their test session;

c) restricting access to any other work before testing is done by deploying IT tools.

To avoid such obstacles, the researchers recommend for other scientists and practitioners adding a testing phase before the data collection phase to practise reaching goal parameter values.

If the test subjects are compliant then usually reminding employees to take the test at the specific time could be enough, but our experience taught us that testing in most cases is deprioritized for other work. For any type of enforcement it is crucial that you have cleared these operations with management and stand your ground in all situations to result in any conflict. In general it is good to inform all stakeholders, divide responsibility and get positive feedback for performing testing so you do not waste time on negotiating but can focus on delivery.

CONCLUSIONS

Research has shown that there is no single formula for measuring the impact of indoor air quality on office workers' productivity or cognitive performance. However, various studies have highlighted the importance of workers' productivity and well-being, and the impact of indoor air quality. It is important to maintain good indoor air quality to ensure the well-being and productivity of office workers. Temperature, humidity, ventilation (air exchange frequency), CO_2 concentration are all key components that can influence and ensure a favourable working environment, which in turn affects employee productivity. Further research is needed to refine the developed causal model (see Table 1) and improve its relevance to reality and individual characteristics. Additionally, it is important to highlight the cognitive capacity of each individual and their ability to adapt to the various factors that determine air quality. Productivity is linked not only to short-term exposure to external factors but also to long-term lifestyle, including physical activity, sleep quality, a balanced diet, and emotional well-being. The impact of indoor air quality on individual and business productivity is difficult to accurately research due to the importance of an individual's ability to maintain cognitive abilities in the face of short-term deterioration in air quality and adapt to low indoor air quality. The impact of indoor air quality on individual and business productivity is difficult to accurately research due to the importance of an individual's ability to maintain cognitive abilities in the face of short-term deterioration in air quality and adapt to low indoor air quality. This can lead to a significant reduction in health over a long period of time. Therefore, it is crucial to consider these factors when studying the effects of indoor air quality. The impact of indoor air quality on individual and business productivity is difficult to accurately research due to the importance of an individual's ability to maintain cognitive abilities in the face of short-term deterioration in air quality and adapt to low indoor air quality. After analysing the available and selected studies, the research team recommends the use of temperature, humidity, air exchange frequency, and CO_2 concentration as the most relevant and practical indicators with the best-proven impact on employee productivity. Among these parameters, CO_2 levels have the most significant impact on productivity, as supported by extensive research.

To predict the impact of indoor air quality on employee productivity and determine the most cost-effective and optimal regime, we recommend using CO_2 levels as the primary indicator, as shown in the table above. Other parameters should be used as additional indicators, ensuring that their levels do not exceed the recommended average values. Future research will explore additional factors and conditions to validate the developer causal model and enhance its practical applicability.

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