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The impact of face masks on productivity and well-being in the smart building: The role of temperature as a moderating variable

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ABSTRACT

During the COVID-19 pandemic, the widespread use of face masks has become standard practice, raising questions about their impact on work efficiency. This paper examines the relationship between face mask use and subjectively assessed productivity and well-being of people in the smart educational building. A multi-stage approach was used: from hierarchical cluster analysis (HCA) and principal component analysis (PCA) to advance general linear modeling (GLM). Initial cluster analysis revealed significant data segmentation resulting from illuminance, but statistical modeling demonstrated that lighting does not determine work efficiency. A key finding is the dominant effect of ambient temperature on both parameters ($p < 0.01$). After statistically isolating the influence of microclimate, mask use demonstrated a significant negative impact on well-being ($p = 0.045$), but did not significantly impact productivity ($p = 0.125$). The results suggest high adaptation of people who maintain performance despite perceived discomfort and indicate the priority role of thermal regulation in optimizing work in personal protective equipment.

Keywords: productivity, well-being, light intensity, protective masks, smart building, GLM modeling, ANCOVA.

INTRODUCTION

The COVID-19 pandemic in 2020 brought the world to a halt on many economic, industrial, and scientific levels. At that time, people were forced to wear protective masks to minimize the risk of getting sick and spreading the coronavirus. However, many of them have indicated that masks were a source of different types of discomfort issues [1–4]. Although the impact of masks on public health is undisputed, their impact on psychophysical comfort in the work environment is complex and often moderated by environmental parameters such as microclimate or lighting.

Typically, experimental projects on environmental assessment are carried out without face masks (for example [5, 6]). Tests focused on people wearing masks are very rare. In Romania, at the technical university, Rus et al. [7] conducted experiments without masks in 2020 and with masks in 2022. The study sample was male. The conclusions showed that 70% of men not wearing masks felt comfortable, while only 49% of men wearing masks rated their feelings as comfortable.

Research conducted by Tang et al. [8] at the University of Guangzhou in South China showed that masks are a source of discomfort for almost 74% of the study participants. On the other hand, 71% of people indicated that this discomfort mainly concerns the space between the face and the mask. Moreover, the work [9] examined various types of masks and indicated that problems with concentration occurred while wearing the mask. Steinhilber et al. [10] focused on the effects of wearing face masks on physical performance. Thirty-nine participated in the study. The authors reported that wearing face masks did not pose relevant additional physical demands on the people, though some more respiratory effort is necessary. Quite similar findings were presented in [11], where forty individuals participated in tests under different ergometer workloads while wearing a surgical mask, a community mask, and an FFP2 respirator. No considerable impact of mask wearing was detected on cognitive performance. Mgaedeh et al. [12] performed a questionnaire study of workers in retail stores who wore face masks. It was focused on determining how smoking, workload, and wearing eyeglasses while wearing masks impacted the workers' sensations. It was found that smoking and workload interaction resulted in considerably slower motion response, causing itchiness. Moreover, the workload led to a negative influence on the heat buildup within the face mask. Additionally, vision ability considerably declined when eyeglasses and masks were both on the faces. Very recently, Hurley et al. [13] pointed out that the application of a face mask increased the carbon dioxide concentration within this volume, which might affect human sensations. The results showed that almost sixty percent of participants reported that mask-wearing decreased their performance. However, the authors claimed that contextual and psychological factors (rather than mask-induced carbon dioxide exposure alone) play a larger role in shaping self-reported performance.

In indoor spaces, productivity (working or learning productivity) is a major issue. It is dependent on many factors, both physical and psychological [14]. The research [15] indicated that well-assessed productivity is influenced by well-being and the temperature range between 22–24 °C. However, Kaushik et al. [16] claimed that productivity in the office is influenced by air temperature ranging from 22–25 °C, carbon dioxide at a level of about 650 ppm at 60% humidity. However, it remains unclear whether, under conditions of forced use of masks, the optimal temperature ranges remain unchanged or whether the mask becomes an additional factor lowering the employee's thermal tolerance threshold.

Moreover, Liu et al. [17] in New Zealand analyzed the factors affecting the productivity of university workers and postgraduate students. Based on the collected data, five main factors of indoor environmental quality were distinguished: lighting, air temperature, noise, fresh air, and workstations. Additionally, workers indicated exposure to sunlight during work and its impact on productivity, while students claimed that the most important factors were air temperature and air flow, as well as the workspace.

It has been known for a long time that air quality is important for working or studying well in closed rooms [18]. At the University of the United Arab Emirates [19], it was verified how air quality was assessed. It turned out that for 60% of people, the air quality was not good, while 40% of the rest of the people surveyed assessed it as normal. Jaber et al. [20] examined nearly 500 female students in terms of the effect of air temperature and carbon dioxide concentration in two rooms. The results indicated that reducing the temperature from 25 °C to 23 °C, from 25 °C and 23 °C to 20 °C and increasing from 20 °C to 23 °C while reducing the carbon dioxide level from 1800 to 1000 to 600 ppm contributed to improving the quality of memory and increasing concentration on tasks.

No less important is the quality of lighting in rooms during work and study. Its appropriate intensity is important and necessary to be able to read freely from technical aids, books, or other documents. Nevertheless, many studies indicate inadequate lighting in rooms, such as in Aguilar et al. [21], in which the range between 110 and 594 lx was a source of discomfort, or in Aflaki et al. [22], where values below 300 lx in the library were observed. On the other hand, in the case of the study [15], students determined the range between 200 and 400 lx as the most suitable for them during lectures. Variations in lighting intensity in modern open-plan spaces can lead to the creation of unconscious sub-working environments, which require the use of advanced statistical methods, such as cluster analysis, to correctly interpret user perceptions.

It needs to be added that experiments in smart (intelligent) buildings are very rare. It is due to a very small number of such buildings throughout the world. Smart buildings are typically associated with high technical sophistication, the focus on energy efficiency, energy recovery, and the use of renewable energy systems [23–29]. It seems that sensations in such buildings could differ from those determined in traditional buildings.

Although productivity has been the subject of experiments already, a study that compares self-reported productivity ratings in the case of wearing and not wearing face masks in the smart educational building in Polish conditions has not been found in the literature. Moreover, the present study links it to well-being, air temperature, and light intensity, which is also quite rare.

This study fills a gap in the literature by comparing the self-assessed productivity and well-being of individuals wearing and not wearing masks in the specific environment of a smart educational building. Unlike previous work, this analysis is not limited to simple group comparisons. Using advanced statistical modeling (GLM) and exploratory techniques (PCA, clustering), we attempted to isolate the impact of mask use from such dominant environmental factors as temperature and lighting. This allowed us to test the hypothesis of whether mask-related discomfort actually translates into decreased work productivity or merely reduces the user's subjective well-being.

METHOD AND FOCUS OF RESEARCH

The location of the study

The research was conducted in the "Energis" smart building (which is part of Kielce University of Technology – located in the central part of Poland). As an energy-balanced facility, this building is managed by a BMS (Building Management System), which controls heating and lighting parameters, theoretically ensuring optimal working and learning conditions. The building is equipped with renewable energy systems such as heat pumps, photovoltaic panels, and a wind turbine. Such an energy-balanced building should provide thermal comfort and enable high productivity in learning and working. A view of the "Energis" building where the research was conducted is shown in Figure 1.

Experimental setup and data collection

The research methodology involved the simultaneous collection of objective and subjective data. Physical indoor environmental parameters (air temperature, relative humidity, illuminance, and air velocity) were measured across 26 rooms, using a calibrated Testo 400 indoor climate meter. Concurrently, respondents (N=691) completed anonymous questionnaires, rating their perceived thermal sensation, lighting quality, well-being, and productivity. The respondents were mostly men (57.7%), while women constituted 42.3% of the group. The average age was 20.6 y.o. (standard deviation 2.2 y.o.), while BMI (body mass index) amounted to 22.9 kg/m^2 on average (standard deviation 3.9 kg/m^2). There were between 12 and 49 people in each room. The surface area of the rooms ranged from 42.4 m^2 to 460 m^2.

The survey started with placing the microclimate meter in the central part of each room. After the readings stabilized (which usually took 15 minutes), the questionnaire forms were handed over to the respondents. Filling in the forms took a few minutes at most. Each person would participate in the survey more than once, however this frequency was not recorded. Multiple participation could not occur in the same day and it is very unlikely that it occurred at the same environmental conditions.

Figure 1. The smart building "Energis"

In the questionnaire form the respondents were asked about their assessment of current productivity. They could choose from the following answers: "-1" – "poor productivity", "0" – "normal productivity", "+1"– "high productivity". In the form they could also assess their well-being as: "very good" (+2), "good" (+1), "neutral" (0), "bad" (-1), or "very bad" (-2). A question about lighting conditions enabled the assessment ranging from the value "-1" ("too weak"), "0" ("normal") to "+1" ("too strong").

By incorporating previous results obtained in the same building prior to the pandemic (Orman et al. [6]), a total of 67 non-mask-wearing groups and 26 mask-wearing groups occupying the rooms under identical environmental conditions were identified. Two types of masks were worn during the measurements: the surgical one (applied by the majority of the respondents) and the cloth one. The statistical analysis was performed on the subjective ratings averaged within these groups.

Statistical analysis and modeling

Given the high dimensionality of the collected data and potential correlations between physical parameters and subjective sensations, a multi-stage statistical analysis was conducted using Minitab software. Initially, principal component analysis (PCA) [30] and hierarchical cluster analysis (HCA – complete linkage method, Euclidean distance) [31] were employed to identify natural structures and similarities within the dataset. This approach enabled the detection of variables with the highest variance, which could otherwise confound the effects of the primary research factor.

Two hypotheses were tested about the existence of a statistically significant relationship between controlled factors, i.e. lighting, temperature and the fact of wearing/not wearing a face mask, and the observed values assessed subjectively, i.e. well-being and productivity.

During the hypothesis testing phase, an analysis of covariance (ANCOVA) model was applied, treating temperature and illuminance as covariates [32, 33]. This allowed for a precise assessment of the impact of masks while maintaining the ceteris paribus principle for varying environmental conditions – a crucial factor in studies conducted within buildings characterized by dynamic microclimates. Technical details regarding the instrumentation and measurement error analysis are provided in [6].

RESULTS AND DISCUSSION

Initial remarks

The presentation of results is divided into three stages, reflecting the process of reducing statistical noise and identifying the key determinants of productivity. Initially, the focus is on exploratory data structure analysis (PCA and HCA) to verify whether environmental variables form natural clusters that could influence the interpretation of the results. Subsequently, ANCOVA modeling is employed to test the hypothesis regarding the impact of protective masks on objective indicators of work performance (productivity). Finally, subjective well-being is analyzed as an indicator with higher sensitivity to environmental stressors. This multi-stage approach enables the separation of statistically insignificant environmental artifacts from the actual factors shaping well-being and productivity of smart building occupants.

Data structure analysis and cluster identification (HCA and PCA)

The initial stage of the analysis involved identifying the natural structure of the dataset and the relationships between environmental variables and well-being indicators. Principal component analysis (PCA) revealed strong data polarization along the first principal component (PC1), where vectors for temperature, subjective well-being, and productivity pointed in opposite directions, suggesting a strong negative correlation (Figure 2).

Concurrently, a hierarchical cluster analysis (HCA) identified five distinct clusters (Figure 3). Profile analysis of these clusters using Tukey's post-hoc test revealed that illuminance accounted for nearly all the variance determining this division ($R^2 = 93.9\%$). Each of the five clusters represented statistically distinct lux levels, ranging from insufficient lighting (cluster 4: ~67 lx) to extremely bright conditions (cluster 5: ~807 lx) (Table 1).

A key finding from this phase is that although clustering algorithms identified lighting as the primary differentiating characteristic of the study population, further statistical verification did not confirm that this division impacted self-reported productivity (ANCOVA, $p = 0.504$) or well-being (ANOVA, $p = 0.209$). This indicates that the data scatter observed results from the significant technical variation in lighting conditions within the "Energis" building, which merely constituted

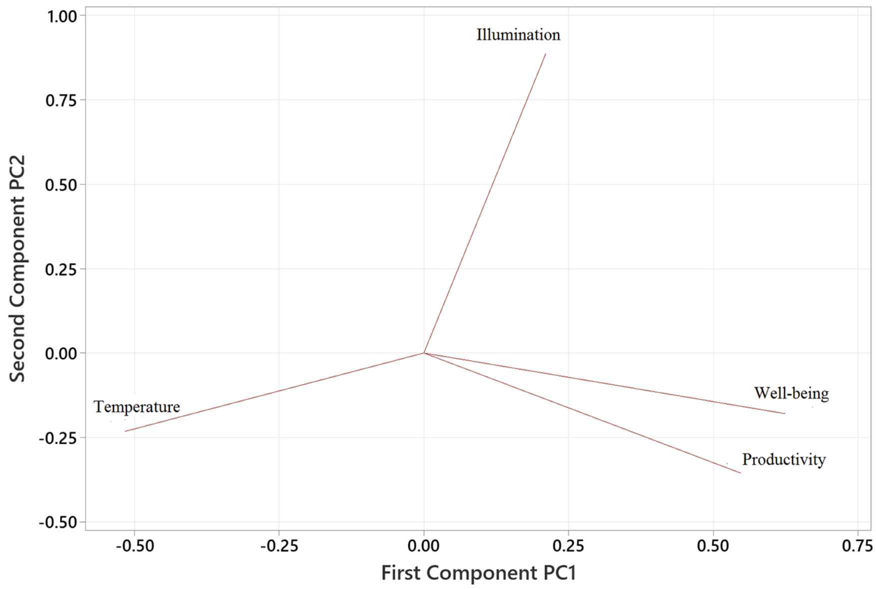

Figure 2. Principal component analysis (PCA) loading plot showing relationships between environmental parameters and subjective indicators of well-being and productivity

Table 1. Results of Tukey's post-hoc test for mean illuminance (lx) across the five identified clusters (means that do not share a letter are significantly different); cluster – cluster number detected in cluster analysis, N – cluster size, Mean – average brightness in a given cluster, Grouping – identification of groups significantly different in relation to the detected clusters – each cluster is an independent group, there is no overlap)

Cluster	N	Mean (lx)	Grouping				
5	1	807	A				
3	11	478		B			
1	14	377			C		
2	31	229				D	
4	36	67					E

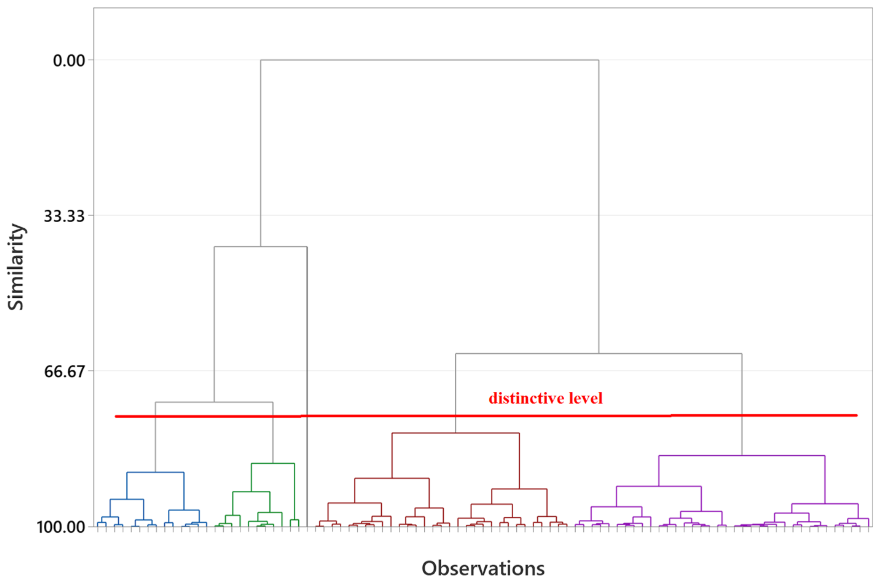

Figure 3. Dendrogram of hierarchical cluster analysis (HCA) identifying groups of observations based on environmental similarities. The vertical axis represents the similarity level between observations, with 100% indicating identical values across measured variables

background noise to the actual processes shaping work efficiency. Consequently, the analytical focus was shifted from lighting aspects to thermal parameters and the impact of protective masks.

The impact of protective masks and thermal parameters on productivity

The primary objective of the analysis was to evaluate the extent to which the use of protective masks modifies self-reported productivity. Although preliminary descriptive analysis suggested minor differences in the distribution of extreme responses (approximately 3% more negative ratings in the mask-wearing group), advanced statistical analysis (ANCOVA) revealed no significant effect of mask use on productivity ($p = 0.122$). This suggests that operational processes and task performance exhibit high resilience to this additional item of protective equipment. Despite potential discomfort, respondents demonstrate adaptive mechanisms that allow them to maintain stable performance levels. In contrast, air temperature emerged as the key determinant of productivity. According to the GLM model, temperature is the strongest statistically significant predictor of performance ($p = 0.009$; $F = 7.14$). This relationship is clearly illustrated by the slope of the regression lines in Figure 4; in both studied cases (with and without masks), a systematic decline in reported productivity was observed as room temperature increased within the range of 20.4–26.8 °C. It needs to be added that the measuring range of the microclimate meter used in the study is from -20 to +70 °C, while the accuracy amounts to ±0.3 °C [34]. Notably, at lower temperature values, the productivity of the respondents without masks was slightly higher; however, as temperatures approached the 25 °C threshold, these differences diminished, and the regression lines converged. This indicates that above a certain thermal threshold, heat stress becomes the dominant factor, effectively marginalizing the impact of wearing a mask. The lack of statistical significance for the Mask × Temperature interaction ($p = 0.539$) further confirms that the negative effect of temperature on productivity is universal and follows a nearly identical pattern for both study groups.

Subjective well-being as a sensitive indicator of mask-related discomfort

The analysis of subjective well-being yielded the most insightful results, contrasting significantly with the findings regarding productivity alone. Unlike work performance, well-being proved to be a parameter highly sensitive to the presence of a protective mask. Only after statistically controlling for environmental covariates (temperature and illuminance) did the GLM model reveal a significant effect of mask use on respondents' well-being ($p = 0.045$; $F = 4.13$).

This result sheds new light on the relationship between comfort and sanitary requirements, which is further confirmed by the visual analysis of the regression lines in Figure 5. The respondents not using masks reported higher levels of well-being across nearly the entire range of studied conditions. A particularly significant discrepancy

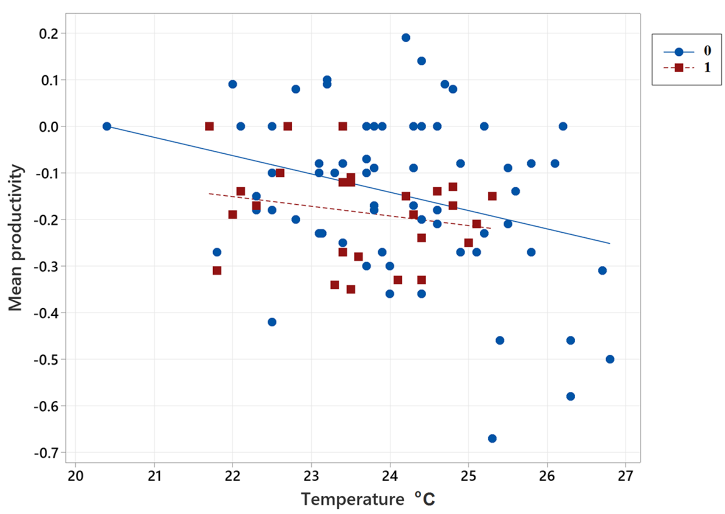

Figure 4. Relationship between air temperature and mean reported productivity, categorized by protective mask use (0 – without face masks [6], 1 – with face mask), including fitted regression lines

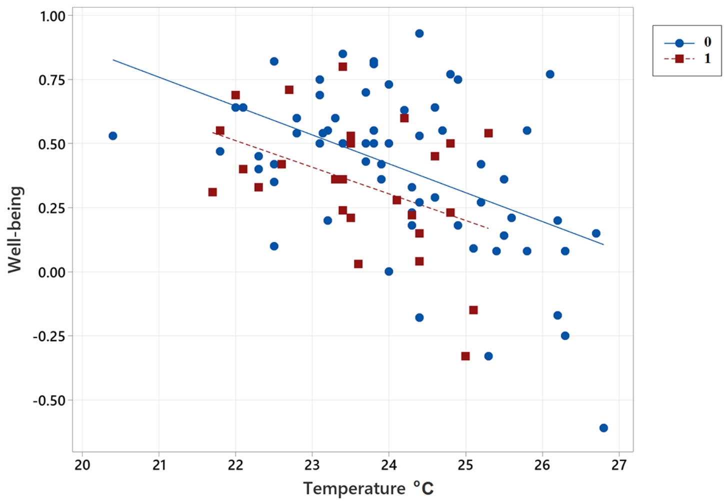

Figure 5. Relationship between air temperature and mean reported well-being, categorized by protective mask use (0 – without face masks [6], 1 – with face mask), including fitted regression lines

is observed in the transition between neutral and positive internal states; the respondents not wearing masks reach a state of high comfort more rapidly as external conditions improve.

Furthermore, the well-being model exhibits a substantially higher goodness-of-fit ($R^2 = 0.23$) compared to the productivity model ($R^2 = 0.089$). This suggests that subjective well-being serves as the body's "first line of response" to environmental stressors. It leads to an important psychological conclusion: the respondents wearing masks maintain stable productivity but do so at a higher psychophysical cost. This relationship suggests the existence of a "performance buffer": the respondents compensate for the discomfort caused by the mask (decreased well-being) to maintain their pace of work or study (stable productivity). However, this compensatory mechanism may lead to accelerated fatigue in the long term. Once again, temperature remained the strongest factor degrading well-being ($p = 0.000$; $F = 23.99$), indicating that the protective mask acts as a cumulative stressor within a suboptimal microclimate.

In summary, the analyses revealed a complex structure of relationships within the "Energis" smart building, where physical environmental parameters predominate over the impact of personal protective equipment. Indoor temperature was demonstrated to be a primary and universal factor reducing both the respondents' productivity and well-being. Although self-reported work performance remained unaffected by mask-wearing, the well-being analysis revealed the real psychophysical cost borne by the respondents. The identification of lighting clusters, despite their high statistical distinctness, ultimately allowed for the exclusion of illuminance as a variable significantly modifying these relationships. These findings emphasize the necessity of employing advanced statistical methods in ergonomic research, as they enable the differentiation of subjective discomfort from the actual operational efficiency of personnel.

A significant limitation of the study is focusing on a specific age group (mostly full time students occupying the educational building). During the survey the type of mask (surgical, cloth ones) was registered in the questionnaire form, however detailed properties of such masks were not recorded. At the same time, it needs to be emphasized that the majority of the respondents wore commercial surgical masks of the same kind. Additionally, no data regarding the exact location of each respondent in a given room was collected, while e.g. the closeness to windows could have influenced the results somehow (for example the airflow speed seems to be an important parameter – as stated in [35]).

CONCLUSIONS

Based on the experimental research conducted within a smart building and the subsequent multivariate statistical analysis (PCA, HCA, and ANCOVA), the following conclusions were drawn.

Thermal factors dominate. Air temperature was identified as the primary determinant of both productivity ($p = 0.009$) and well-being ($p =$

0.000). Within the studied range (20.4–26.8 °C), an increase in temperature leads to a linear decline in both parameters, regardless of whether face masks are worn.

Productivity is resilient to personal protective equipment. No statistically significant effect of a protective mask use on self-reported productivity was found ($p = 0.122$). This suggests a high degree of adaptability among the respondents, who maintain consistent performance levels despite the discomfort associated with facial coverings.

Well-being is sensitive to mask-wearing. In contrast to productivity, subjective well-being is significantly reduced by the use of protective masks ($p = 0.045$). The mask acts as an additional psychophysical stressor, the impact of which becomes statistically prominent once the dominant effect of temperature is controlled.

Illumination intensity is of marginal importance. Although illuminance was the primary factor differentiating the data structure (clustering $R^2 = 0.939$), it demonstrated no significant impact on work productivity ($p = 0.504$) or occupant well-being ($p = 0.209$). The lighting-related trends observed in the data should be regarded as statistically insignificant artifacts.

Smart environments are complex. The study demonstrates that in smart buildings, subjective occupant experiences are the product of multiple, overlapping stimuli. Effective facility management requires prioritizing the control of thermal parameters, as optimal thermal conditions can mitigate the negative effects of other stressors, such as sanitary requirements (e.g., protective masks).

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