Building 4 People: Quantifying the benefits of energy renovation investments in schools, offices and hospitals

METHODOLOGY AND RESULTS

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CONTENTS

1 INTRODUCTION

The health, well-being and performance of people depend to a significant degree on the indoor environmental quality (IEQ) of buildings [1], given that people spend approximately 90% of their time indoors. Our aim in this study was to find quantitative evidence of the beneficial impact of factors that contribute to indoor environmental quality resulting from energy renovation or construction of high energy performance buildings, and then put a value on these benefits. This study builds on the 2017 analysis by Buildings 2030 and BPIE: "People-Centric Buildings for European Citizens"[2].

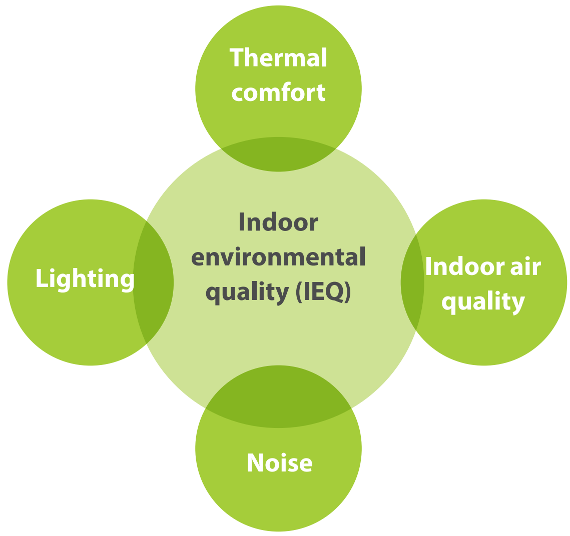
Suitably heated and cooled buildings will avoid drowsiness and help people to stay healthy and focussed. Achieving and even improving upon recommended levels for air quality such as minimum requirements for CO_2, particulate matter and volatile organic compounds reduces the likelihood of sick building syndrome (see box). Adequate lighting improves activity levels, general health and sleep. Noise attenuation enables us to focus better and alleviates stress.

WHAT IS SICK BUILDING SYNDROME?

Some people suffer a range of symptoms as a result of staying a long time in a particular building, typically a workplace, with a poor quality indoor environment. The types of ailments experienced could include one or more of the following: headaches; blocked or runny nose; dry, itchy skin; dry, sore eyes; rashes; tiredness; and difficulty concentrating.

This review covers findings in three indoor environments, namely schools, offices and hospitals. Together, these three types of buildings make up nearly half the EU's stock of non-residential buildings by floor area. Although there are similarities between them regarding the impact of IEQ on performance, absenteeism and health, there is a substantial difference between them in terms of activities in the buildings, air pollutant sources and occupants (e.g. children, healthy adults, sick people). To ensure due consideration of these differences, the studies were assessed individually by building type.

Figure 1 Components of indoor environmental quality (IEQ)



SCOPE OF THE STUDY

This study seeks to answer the following question: **What are the quantified benefits of people-centric renovation of offices, schools and hospitals?** This research takes the first step in defining, measuring, quantifying and monetising the impact of indoor air quality, thermal comfort, acoustics and lighting on students, office workers and patients across Europe.

Even though several components of IEQ have been individually studied in different building types, a common extrapolation methodology and metrics for quantifying the effect of each parameter on human outcomes (performance, absenteeism, health, etc.) has not to date been developed in the international literature.

2 APPROACH

The principal interests in this study are the health, well-being and performance of students, patients and office workers. We adopted a four-step approach, as outlined below.

SECTION	4-STEP APPROACH
METHODOLOGY FOR IMPACT QUANTIFICATION: SCHOOLS, OFFICES, HOSPITALS	**1** IDENTIFYING AND LINKING BENEFICIAL IMPACTS OF IEQ ON PEOPLE Broad literature review **2** QUANTIFYING HEALTH, EDUCATIONAL AND PERFORMANCE BENEFITS In-depth literature selection and calculation
EXTRAPOLATION	**3** EXTRAPOLATING QUANTIFIED BENEFITS TO EUROPE Calculating average impacts over a full year
MONETISATION	**4** PUTTING A MONETARY VALUE ON THE BENEFITS Monetising and interpreting the benefits in terms of time savings and improved performance

3 METHODOLOGY FOR QUANTIFICATION OF THE IMPACT

This study considers performance impacts that are measured in various ways. Performance is the ability of an individual to undertake physically and mentally demanding tasks. Accuracy and speed are the principal aspects of human performance that are usually considered when assessing the relationship between IEQ and performance [3]. It should be emphasised that this study does not take into account discussions on proper measurement of academic or work performance. Nevertheless, it considers educational achievement tests and neuro-behavioural performance tests as relatively objective indicators of learning or performance in schools and offices. Despite their limitations, these tests can be considered more accurate than subjective assessments of performance [4].

Health in schools and offices is measured mainly through the indicator of absenteeism. Some studies differentiate between illness-related and non-illness-related absenteeism. For schools in particular, absence is often used as an indicator of health effects and may be related to asthma, allergies or respiratory illnesses [3]. Absenteeism can have an impact on educational attainment since reduced attendance and missing key lessons may impair learning [4].

Well-being includes the satisfaction and comfort of the people in a building, whether they are working, studying or recuperating from illness. It is measured through surveys and employee turnover rates. Well-being is closely linked to health; the indicators for sick building syndrome, for example, can also be interpreted in the sense of well-being. In this research, we accounted for sick building symptoms in the assessment of health impacts.

To capture the measurement of IEQ on the one hand and its impact on people on the other, we explicitly selected studies providing a quantification (or at least a thorough qualitative association) of both the indoor environment and its impact on people [4], with respect to their health, comfort, performance and absenteeism. Our approach has been to create a robust methodology by collecting findings from strongly designed studies (i.e. controlled, randomised) with quantitative outputs, including meta-analytic reviews. Aggregated results were selected based on the size of the sample (ideally over 100 subjects), the type of outputs (quantitative or qualitative) and their methodology. We focused on the effects of temperature, ventilation rates and CO_2, light and acoustics on performance and health.

The studies differed significantly in methodology and the ways in which findings are expressed, both in terms of human outcomes and environmental factors. In order to synthesise the evidence extracted, we homogenised the findings on the effect of certain per unit changes (e.g. per decibel) in each of the IEQ parameters.

SCHOOLS

The research clearly demonstrates that poor indoor environmental quality can affect students' health, attendance, concentration and learning performance. Students spend a substantial amount of their day indoors and a great amount of that time is spent in school classrooms [5]. Children are highly vulnerable to health effects and indoor air pollution, as they breathe a greater volume of air relative to their body weight compared to adults and their bodies are still developing. In addition, the occupancy density in classrooms is much higher (1.8-2.4 m^2/person) in comparison to offices (10m^2/person). Alongside homes, schools are the most crucial indoor environments affecting children's health, learning and well-being [6].

EFFECT OF TEMPERATURE

There is evidence that elevated indoor temperatures in schools are associated with impaired performance. The European standard for indoor design parameters, EN 15251:2007, recommends values of 20°C and 26°C for winter and summer, respectively. However, individual Member States have values ranging from 15°C to 21°C (winter) and 25-28°C (summer) in their norms.

We identified six studies ([3], [7], [8], [9], [10], [11]) that provided a correlation between certain temperature ranges and students' performance. To synthesise the evidence extracted from these studies, we homogenised the findings on the effect of 1°C decrease in overheating on student performance. To come up with a standard metric from all studies, we used the upper and lower limits across the reported evidence in both temperature and performance. Our synthesis of these studies reveals that:

> ***Every 1°C reduction in overheating increases students' learning performance by 2.3 %***

EFFECT OF INDOOR AIR QUALITY[1]

Effect on performance

In addition to excess temperature, the analysed studies ([3], [7], [9], [12], [13], [14], [15]) associate inadequate ventilation rates with impaired performance. Due to the difficulty and large cost of measuring specific air pollutants, CO_2 concentrations are often used as an indicator of indoor air quality[2]. Because available results for other pollutants are limited, our analysis is based largely on CO_2 concentrations. In addition, the methodology and uncertainty of calculating ventilation rates is not always clear. Certain studies such as [7] and [12] refer to the performance increase per litre per second per person (l/s/p) while others give a range of performance impact across a range of ventilation rates. (low: <6 l/s/p, moderate 6-10 l/s/p, medium 10-15 l/s/p, up to high: 15 l/s/p [16, p. 3]). To synthesise the evidence across these studies, we homogenised the findings on the effect of 1 l/s/p increase in ventilation rates in students' performance.

> ***For every 1 litre per second per person (l/s/p) increase in the ventilation rate up to 15 l/s/p, academic performance increases by 1%***

Effect on absenteeism

Absenteeism is often used as an indicator of students' health condition, even though attendance patterns result from a complex interaction of several parameters [17]. Studies have shown that high CO_2 concentrations corresponding to low ventilation rates result in concentration loss, tiredness and decrease in daily attendance rates. To synthesise the evidence across these studies, we homogenised the findings on the effect of a decrease in CO_2 concentrations of 100 parts per million (ppm) on student absenteeism.

> ***Every 100ppm decrease in CO_2 concentration is associated with a 0.5% decrease in illness-related absence from schools***

EFFECT OF LIGHTING

The benefits of various lighting strategies (active or passive) have been corroborated in multiple studies [18], [19], [20], [21], though only a small portion of the literature aims to link lighting to quantifiable benefits. Typically, studies tested how students performed under different light settings. Performance was measured through reading skills (speed/reading fluency) or a test of their level of concentration. In order to compare different studies with different results, we standardised the performance improvement per 100 lux, as follows:

> ***Every 100 lux in improved lighting in schools is associated with a 2.9% increase in educational performance***

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1 While this analysis looks at ventilation rate and CO_2 concentration, we recognise that indoor air quality covers other aspects beyond these.

2 People exhale CO_2 when breathing, so if the air exchange rate is insufficient, CO_2 concentrations rise, and the air gets stale. Opening windows can increase the air exchange rate and reduce CO_2 concentrations, though potentially at the expense of raising other pollutant levels from outside, depending on the location of the premises.

On daylighting, studies ([22], [23], [24]) typically compared memory tests at different daylight levels. Daylight illumination, which clearly differs in the course of a day and year, is typically measured at desk level. The elimination of glare is essential to benefit from daylight.

Better daylight is associated with a 9% to 18% increase in educational performance

EFFECT OF ACOUSTICS

There has been a great deal of research into the effects of noise/acoustics on children's learning and performance at school. Most of these studies focus on how external noise affects children's cognitive development. In addition, several studies have investigated how noise affects well-being in schools. It has been concluded that *"A major effect of noise in the classroom is the reduction of speech intelligibility, and the hearing and understanding of speech by children of different ages, in various noise and acoustic conditions, is a related important research field"*[25].

In investigating the effects of environmental noise on children, a wide range of attainments and performance factors have been considered. Performance is predominantly measured through reading/literacy, concentration, mathematics and memory. Studies conclude that the effects of *"chronic noise exposure on children are deficits in sustained attention and visual attention; poorer auditory discrimination and speech perception; poorer memory for tasks that require high processing demands of semantic material; and poorer reading ability and school performance on national standardised tests"*[25].

Noise in classrooms comprises both external noise ([26], [27], [28]) transmitted through the building envelope, including windows and doors, as well as noise generated within the school. A renovation can almost fully shut out external noise and alleviate the internal noise.

For every 1 dB decrease in excess noise, academic performance increases by 0.7%

OFFICES

Today, many Europeans working in offices suffer from adverse health effects and lower performance due to an inadequate indoor environment. Over **80 million** adults work in an office environment, meaning that one in every six Europeans spends around eight hours each weekday in an office. Improving office IEQ would not just lead to healthier people and increased well-being, but also boost overall performance. This effect derives from better temperature and air quality, light and noise, as well as the ability to control these elements.

EFFECT OF TEMPERATURE

The literature review identified studies that measured the performance of people under different temperature conditions.[3] The studies differ in setting the temperature (active or just measurement; temperature range), in measuring the performance (during everyday work or specific tests), and in the comparison of the improved temperature with a control setting (same group, different group, or a random distribution of people). There were also studies based on self-assessed performance; however, these cannot be considered within our analysis as we only take measured performance results into account. All of these studies focused on overheating.

To compare the different studies, we derived the performance increase per degree Celsius as a common metric. The studies ([29], [30], [31], [32], [33], [34], [35]) were screened for the high and low temperatures that were used or measured in the study. The total performance increase measured in the study was then divided by the difference between the high and low temperature to obtain the performance increase per degree Celsius.

Every 1°C reduction in overheating increases a worker's performance by 3.6% [36]

[3] Only studies that measured the temperature improvement and the performance change were considered.

EFFECT OF INDOOR AIR QUALITY

The ideal indoor air contains fresh air with low levels of CO_2, particulate matter, volatile organic compounds and other pollutants from either outdoor or indoor sources. Indoor sources may be from machines such as printers and computers but also from carpets, furnishings and exposed building materials. If the source cannot be removed, one way to clean the air is ventilation with a good filtration system. A common ventilation rate in an office would be about 4 l/s/person, up to a maximum of 15 l/s/p. [16, p. 3]. The studies ([14], [37], [33], [38], [39], [40], [41], [42], [43], [44], [45], [46]) showed:

Every 1 l/s/p increase in ventilation increases a worker's performance by 0.8%

EFFECT OF LIGHTING

The literature on lighting is substantial in scope; however, only a small portion seeks to link lighting to quantifiable benefits in health, comfort and performance. The benefits of various lighting strategies (active or passive) have been corroborated in multiple studies. The reports considered in this section are a small proportion of studies that present a significant and quantified relationship between light and health/well-being/performance. Typically, studies tested different light settings and how employees performed under different settings; for example, through how fast workers conduct a certain task.

In order to compare different studies with different results, we standardised the performance improvement per 100 lux, from different studies ([47], [48], [49]), as follows:

Every 100 lux increase in lighting level increases a worker's performance by 0.8%

On daylighting, studies typically compared call times in call centres and memory tests at daylight levels. The daylight component also potentially includes a view. Illumination from daylight and electric light can be quantified separately but both contribute to internal light levels. The elimination of glare is essential to profit from daylight experience and the view. As daylight measurement differs between the studies ([50], [51], [52]), we averaged the performance improvement to conclude that:

Better daylight is associated on average with a 10 % increase in performance

EFFECT OF ACOUSTICS

Literature on acoustics was relatively poor by comparison with other parameters, and frequently focused on the acoustic disadvantages of open-space offices. From the limited results available ([53], [54], [55]), we conclude that:

For every 1 dB decrease in the excess noise, performance improved by 0.3%

HOSPITALS

For hospitals, there was a lack of data connecting the indoor environmental parameters with measurable outcomes. Accordingly, the results presented here are from individual studies.

Among the quantified benefits of improved indoor environmental quality in hospitals, we found:

- Patients' length of stay can be reduced on average by 11% ([56], [57], [58], [59])
- Medication costs are reduced by up to 21% ([61])
- Reducing noise levels has positive effects on heart-rate, pulse, respiration and sleep
- Mortality rate is reduced by up to 19% ([57], [60])
- Employee turnover is reduced by up to 20% ([60])

4 EXTRAPOLATION OF IMPACTS

This section describes how we took the average results presented above and modelled them into achieved and achievable percentage improvements in performance/productivity. The description relates to offices, though a similar calculation was undertaken for schools. As noted earlier, the paucity of results for hospitals meant that it was not possible to carry out the same exercise. Instead, the results for hospitals are based typically on a small number of studies, and in some cases individual studies.

In the discussion below, the "improvement" relates to a comparison between a building with a high IEQ and a standard building. While a number of studies compared "before and after" renovation impacts in the same building, results have also been included that compare the performance of an existing building with that of a new construction, or a newly renovated building. It was not possible to derive a correlation between the level of renovation and the resulting improvements.

Certain impacts are seasonal and geographically specific – for example, overheating would only normally occur in summer months; and full daylighting for normal office hours would not be available in the winter months, particularly in northern latitudes. For such seasonal variables, we applied an average monthly duration for the impact (e.g. reduction of overheating) and applied the percentage improvements identified earlier on a pro rata basis to give an average for the year.

TEMPERATURE

The average reduction in overheating across Europe is assumed to be 6°C during the summer period which, depending on location, varies from four to seven months of a year. When averaged over a year, this equates to 2-3°C. Based on the evidenced tests, each degree-Celsius improvement is associated with a 3.6% increase in performance (see section 3b), so the overall performance increase is 7-12%.

INDOOR AIR QUALITY

The average indoor air quality improvement across Europe is assumed to be an increased ventilation rate of 4-7 litres per second per person throughout the year. Based on the evidenced tests, each 1 l/s/p is associated with a 0.8% increase in performance, so the overall performance increase is 3-6%, depending on location in Europe, with the higher values applicable to buildings with high levels of pollutants, such as those near busy roads or heavy industry, or with significant internal sources of pollution.

LIGHT

The average light improvement across Europe is assumed to be in the range 800-1200 lux during the winter months when there is inadequate daylight throughout the normal working day. On average across Europe, this equates to five months of the year. The light improvement, when averaged over a year, is then 333-800 lux. Based on the evidenced tests, each 100 lux improvement is associated with a 0.8% increase in performance, so the overall performance increase is 3-6%, depending on location in Europe, with the higher values applicable to northern parts of Europe with longer winters and less solar influx.

NOISE

The average noise attenuation across Europe is assumed to be 5-10db for offices throughout the year. Based on the single evidenced test, each decibel improvement is associated with a 0.3% increase in performance, so the overall performance increase is 1.7-3%. Please note that, while many research papers ([62], [63], [64], [65], [66], [67]) argue that noise has a significant impact on health, well-being and performance, they do not quantify the different acoustic environments and their impact and so have not been included in our analysis.

5 MONETISATION OF IMPACTS FOR EUROPE

Having identified the percentage improvements for temperature, indoor air quality, lighting and noise, the next challenge was to extrapolate these results to the rest of Europe and, where possible, derive a monetary value. This section describes the approach taken in the three building types covered by this study. Unless otherwise stated, all data is taken from Eurostat.

OFFICES

In order to quantify the theoretical value, at a European scale, of the benefits of performance increase resulting from renovation of offices, the following steps were taken:

1. Identify the performance improvement (% range) resulting from improved indoor environmental quality (see section 4 above).
2. Multiply this by the average value added per person working in an office environment across the EU to derive a "per person" value of the performance improvement.
3. Multiply this by the number of people across the EU workforce employed in offices.
4. From this figure, net off the proportion of offices already renovated or recently built to high IEQ standards.

Clearly, any attempt to extrapolate from a limited number of case studies to the whole of Europe will be subject to a significant degree of uncertainty. For example, the available literature is only from a limited number of Member States (mainly northern and western countries), and one cannot necessarily assume that the same results will, on average, be achieved in all countries. Furthermore, while the performance improvement may translate, at the level of an individual enterprise, into more output and greater profit, it cannot be assumed that the same impact will be achieved across all enterprises throughout Europe.

Eurostat data was used to identify the value added per person, expressed as gross value added (GVA)[4]. This varies according to the type of employment. Unfortunately, Eurostat does not identify a distinct "office" category. Instead, it was necessary to select those employment sectors where employees are largely office-based. The four sectors are: Information & communication; Financial & insurance; Professional, scientific, technical, administrative & support services; and Public administration, defence, education, human health & social work. Together, these account for 98.9 million EU citizens. The weighted average value added per person equates to €52,000 p.a. The value of a 1% improvement in productivity is then €51.5 billion per year across the whole cohort of employees in these four sectors.

However, as noted earlier, not all employees in these sectors will be office-based. Another source, "Healthy Homes Barometer 2018" published by Velux [19], estimates that 36% of the European workforce is deployed in offices, i.e. 81 million. For the purposes of the present study, we will use the lower figure and scale back the gross performance improvements accordingly. This gives €42 billion p.a. as the theoretical value for every 1% improvement in performance in offices. This is then reduced by 5% to recognise the small proportion of buildings that are already optimal in terms of IEQ. The figure then used in the results is €40 billion p.a. per 1% improvement in performance.

4 Also known as real labour productivity.

SCHOOLS

For schools, we gathered the number of schooldays for the different European countries and found the average to be 185 days per year. This means that each day at school is approximately 0.5% of the school year. Therefore, a performance improvement of 4-7% for air quality, for example, is equivalent to approximately 8-13 school days saved. In other words, the same level of learning could be achieved in an academic year that is approximately two weeks shorter, freeing up time for additional study, extra-curricular activities or holidays.

We considered various ways to monetise the performance improvement, but could not pinpoint sufficient evidence to quantify the school performance benefits. Nor is there any evidence to suggest how the saved time would be used in practice. Among the options we considered were:

- The financial savings from having a school year that is two weeks shorter
- The additional earning potential of students who receive the equivalent of two weeks' additional teaching per year
- The income generated by two weeks' worth of extra-curricular activities such as sport, music/dance lessons or learning a new skill
- The health and well-being benefits of teachers and other staff in the school

We conclude that, while there is a range of potential benefits from improved performance in schools, we are unable to ascribe a financial value to them given the current level of knowledge in this area.

HOSPITALS[5]

For the purposes of determining the value of the benefits in hospitals, the key metric we have selected is the average length of stay (ALOS). This is a recognised parameter used by the sector, with good data over many years covering most EU Member States. It is also a parameter that has been measured within the various studies into the impact of building renovation.

Calculating the theoretical value of the health benefits in hospitals involves the following steps:

1. Quantify the average percentage reduction in ALOS resulting from building renovation.
2. Compare this with current levels of ALOS to determine the actual number of days' reduction in ALOS.
3. Extract data on number of hospital beds and expenditure on hospitals. From this, derive an average cost per bed per day.
4. Extract data on number of in-patients treated annually.
5. Multiply the number of patients by the number of days saved and the daily cost per bed to give the gross value.

The theoretical value of the benefit of improved daylighting, which reduces ALOS by 11%, is €42 billion annually across the EU.[6] The equivalent value for the 10% ALOS reduction from improved indoor air quality is €38 billion.

These theoretical savings assume that the number of hospital beds and the corresponding expenditure are reduced in line with improvements in IEQ. In reality, the benefit is likely to be used at least partially by treating more patients, treating patients more quickly than would otherwise be the case, or enabling greater efficiency in hospital operation. These benefits should also be considered against the backdrop of EU trends that show increasing expenditure on hospitals even though the number of hospital beds and average length of stay are decreasing.

[5] The results presented here refer to hospitals where patients are kept in overnight. They do not include day clinics or other types of healthcare facilities.
[6] Please note that Eurostat did not provide data for Greece, Malta and The Netherlands, so the figures represent the total for 25 EU Member States

GAPS AND AREAS OF FURTHER RESEARCH

Over the course of this project, our research has identified several gaps in the current state of people-centric building research, summarised below:

1. **There is a lack of holistic, longitudinal studies set in real environments that measure all indoor environmental parameters and their impact on people, while excluding other influences.[7]** While a number of studies focus on single technology aspects (e.g. acoustics), few explore the interaction between technologies and their combined impact on people's health, well-being and performance. We have the single technology results but no study that makes sense of how they compare or interact.

2. **People's performance/productivity is defined and measured very differently**. The measurement methods include tests ranging from cognitive performance or ability to memorise, to standardised tests in schools. Cognitive performance tests in real work environments were performed mainly in call centres, where the tasks were relatively standard and less challenging to measure. Moreover, our research identifies only one study [73] set in real work environments, in 10 buildings across 5 cities. Such studies are expensive and resource intensive. Lastly, very little evidence exists for measuring productivity of people engaged in creative tasks such as writing or developing and implementing ideas. Overall, while there are numerous studies quantifying the impact of temperature, indoor air quality and light on workers' and students' performance, the method of measuring and defining performance differ significantly.

3. **The duration of studies varies which results in a lack of consistency when it comes to methodology and impact.** Very few studies quantify the impact over one year to account for seasonal changes.

4. **A large set of evidence comes from outside the EU**, covering a variety of climate zones and building types.

5. **Technologies and building types are not evenly represented in the research.** Numerous studies have quantified the impact of temperature, indoor air quality and light on workers' and students' performance. There is significant evidence that noise impairs student learning and work, but the impact is more difficult to evaluate, as the variation in noise is higher (and combines internal and external factors). Furthermore, the impact on patients and personnel in hospitals remains under-represented within the literature found.

According to a comprehensive book on sick building syndrome [72], there are few experimental or longitudinal studies on health effects of the school environment. In one four-year longitudinal study, it was found that the school environment had an influence on the development of asthma [69]. Meanwhile, two intervention studies in schools have shown the beneficial effect of increasing ventilation ([70]; [71]).

[7] Other factors may be a change in management, varying personal performance

6 CONCLUSION

This study is an important milestone in the monetisation of the sectoral and economic impact of improvements in indoor environmental quality in European public and commercial buildings. A significant body of evidence points to clear, quantifiable benefits in terms of health, well-being and performance resulting from improving the indoor environmental quality of schools, offices, and to a lesser extent, hospitals. Policy makers and professionals in the building sector, from real estate owners to building managers, are advised to factor in these benefits when appraising energy renovations or commissioning new buildings.

There remain significant gaps in the knowledge base, while the extrapolation and monetisation of the impacts is still a new area which requires more research and evidence gathering. We acknowledge the limitations of the results and call for increasing efforts to address the data and knowledge gaps in people-centric buildings research.

BIBLIOGRAPHY

[1] P. V. Dorizas, M. De Groote, and J. Volt, "The inner value of a building: Linking Indoor Environmental Quality and Energy Performance in Building Regulation," http://bpie.eu/publication/the-inner-value-of-a-building-linking-indoor-environmental-quality-and-energy-performance-in-building-regulation/, 2018.

[2] F. Anagnostopoulos, M. de Groote, D. Staniaszek, K. Klimovich, and R. Nicolle, "Building 4 People: Buildings for European Citizens," Brussels, http://www.buildings2030.com, 2017.

[3] L. Chatzidiakou, D. Mumovic, and J. Dockrell, "The Effects of Thermal Conditions and Indoor Air Quality on Health, Comfort and Cognitive Performance of Students," London, 2014.

[4] M. J. Mendell and G. Heath, "Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature," Proc. Indoor Air 2005, vol. 15, no. 1, pp. 27–32, 2005.

[5] US EPA, "Energy Efficiency and Indoor Air Quality in Schools," https://www.energystar.gov/ia/business/k12_schools/Ee&iaq.pdf, 2003.

[6] V. P. Dorizas, A. Margarita-Niki, C. Helmis, and M. Santamouris, "An integrated evaluation study of the ventilation rate, the exposure and the indoor air quality in naturally ventilated classrooms in the Mediterranean region during spring," Sci. Total Environ., doi:10.1016/j.scitotenv.2014.09.060, vol. 502, 2015.

[7] U. Haverinen-Shaughnessy and R. J. Shaughnessy, "Effects of classroom ventilation rate and temperature on students' test scores," PLoS One, doi:10.1371/journal.pone.0136165, vol. 10, no. 8, pp. 1–14, 2015.

[8] J. Park, L. Katz, R. Stavins, A. Shleifer, G. Heal, R. Chetty, J. Aldy, C. Goldin, E. Glaeser, J. Stock, M. Feldstein, J. Miron, J. Liebman, G. Mankiw, D. Keith, J. Goodman, D. Cutler, M. Auffhammer, S. Hsiang, and S. Reardon, "Temperature, Test Scores, and Educational Attainment," Harvard Econ. Job Mark. Pap., p. 166, 2016.

[9] P. Wargocki and D. P. Wyon, "Providing better thermal and air quality conditions in school classrooms would be cost-effective," Build. Environ., doi:10.1016/j.buildenv.2012.10.007, vol. 59, pp. 581–589, 2013.

[10] Z. Bakó-Biró, D. J. Clements-Croome, N. Kochhar, H. B. Awbi, and M. J. Williams, "Ventilation rates in schools and pupils' performance," Build. Environ., doi:10.1016/j.buildenv.2011.08.018, vol. 48, no. 1, pp. 215–223, 2012.

[11] J. Goodman, M. Hurwitz, J. Park, J. Smith, L. Katz, J. Aldy, A. Barreca, O. Deschenes, S. Reber, W. Yin, M. Shah, J. Boomhower, T. Garg, M. Jacobsen, and P. Behrer, "NBER WORKING PAPER SERIES HEAT AND LEARNING Heat and Learning," http://www.nber.org/papers/w24639, 2018.

[12] U. Haverinen-Shaughnessy, D. J. Moschandreas, and R. J. Shaughnessy, "Association between substandard classroom ventilation rates and students' academic achievement," Indoor Air, doi:10.1111/j.1600-0668.2010.00686.x, vol. 21, no. 2, pp. 121–131, 2011.

[13] S. Petersen and M. D. Knudsen, "Method for including the economic value of indoor climate as design criterion in optimisation of office building design," Build. Environ., doi:10.1016/j.buildenv.2017.05.036, vol. 122, pp. 15–22, 2017.

[14] LBNL and Lawrence Berkeley National Laboratory, "Indoor Air Quality Scientific Findings Resource Bank," https://iaqscience.lbl.gov/vent-summary. .

[15] M. J. Mendell, E. A. Eliseeva, M. M. Davies, M. Spears, A. Lobscheid, W. J. Fisk, and M. G. Apte, "Association of classroom ventilation with reduced illness absence: A prospective study in California elementary schools," Indoor Air, doi:10.1111/ina.12042, vol. 23, no. 6, pp. 515–528, 2013.

[16] D. H. Clark, "Ventilation rates in offic ces – mechanical and natural," https://cundall.com/Cundall/fckeditor/editor/images/UserFilesUpload/file/WCIYB/IP-20 - Ventilation rates in offices - mechanical and natural.pdf, 2013.

[17] D. G. Shendell, R. Prill, W. J. Fisk, M. G. Apte, D. Blake, and D. Faulkner, "Associations between classroom CO2 concentrations and student attendance in Washington and Idaho," Indoor Air, doi:10.1111/j.1600-0668.2004.00251.x, vol. 14, no. 5, pp. 333–341, 2004.

[18] M. S. Mott, T. R. Thomas, and J. L. Burnette, "Leveraging Lighting Color, Temperature and Luminosity for Improving Classroom Learning," Networks An Online J. Teach. Res., vol. 15, no. 2, pp. 1–5, 2013.

[19] P. Sleegers, "Lighting affects students 'concentration positively : Findings from three Dutch studies," Light. Res. Technol., https://journals.sagepub.com/doi/abs/10.1177/1477153512446099?journalCode=lrtd, pp. 1–17, 2012.

[20] M. Schulte-Markwort, C. Barkmann, and N. Wessolowski, "Effect of light in schools," in Proceedings of CIE 2010 "Lighting Quality and Energy Efficiency," 2010, pp. 229–231.

[21] C. Barkmann, N. Wessolowski, and M. Schulte-Markwort, "Applicability and efficacy of variable light in schools," Physiol. Behav., vol. 105, no. 3, pp. 621–627, 2012.

[22] L. Heschong, R. L. Wright, and S. Okura, "Daylighting Impacts on Retail Sales Performance," J. Illum. Eng. Soc., doi:10.1080/00994480.2002.10748389, vol. 31, no. 2, pp. 21–25, 2002.

[23] C. Maesano and I. Annesi-maesano, "Impact of Lighting on School Performance in European Classrooms," Clima2016, doi:10.1016/j.tetlet.2008.09.152, pp. 1–14, 2016.

[24] G. Loisos, "Daylighting in Schools," Georg. Loisos Pacific Gas Electr. Co. behalf Calif. Board Energy Effic. Third Party Progr., http://www.nrel.gov/docs/fy00osti/28049.pdf, vol. 1999, no. 1, p. 140, 1999.

[25] S. Gaihre, S. Semple, J. Miller, S. Fielding, and S. Turner, "Classroom Carbon Dioxide Concentration , School Attendance , and Educational," J. Sch. Health, doi:10.1111/josh.12183, vol. 84, no. 9, pp. 569–574, 2014.

[26] M. Klatte, J. Spilski, J. Mayerl, U. Möhler, T. Lachmann, and K. Bergström, "Effects of aircraft noise on reading and quality of life in primary school children in Germany: Results from the NORAH study," Environ. Behav., vol. 49, no. 4, pp. 390–424, 2017.

[27] S. Pujol, J. Levain, H. Houot, R. Petit, M. Berthillier, J. Defrance, J. Lardies, C. Masselot, and F. Mauny, "Association between Ambient Noise Exposure and School Performance of Children Living in An Urban Area : A Cross-Sectional Population-Based Study," doi:10.1007/s11524-013-9843-6, 2013.

[28] P. Barrett, F. Davies, Y. Zhang, and L. Barrett, "The impact of classroom design on pupils ' learning : Final results of a holistic , multi-level analysis," Build. Environ., doi:10.1016/j.buildenv.2015.02.013, vol. 89, pp. 118–133, 2015.

[29] R. Niemelä, M. Hannula, S. Rautio, K. Reijula, and J. Railio, "The effect of air temperature on labour productivity in call centres - A case study," Energy Build., doi:10.1016/S0378-7788(02)00094-4, vol. 34, no. 8, pp. 759–764, 2002.

[30] C. C. Federspiel, G. Liu, M. Lahiff, D. Faulkner, D. L. Dibartolomeo, W. J. Fisk, P. N. Price, and D. P. Sullivan, "Worker performance and ventilation: Analyses of individual data for call-center workers," doi:10.2172/795377, 2002.

[31] O. Seppänen, W. J. Fisk, and D. Faulkner, "Cost Benefit Analysis of the Night-Time Ventilative Cooling in Office Building," doi:10.1016/j.jflm.2010.04.012, p. 12, 2003.

[32] J. Repenning, D. K. Schumacher, T. Bergmann, R. Blanck, D. H. Böttcher, D. V. Bürger, D. J. Cludius, L. Emele, W. Jörß, K. Hennenberg, H. Hermann, C. Loreck, D. S. Ludig, D. F. Matthes, C. Nissen, M. Scheffler, K. Wiegmann, C. Zell-ziegler, D. T. Fleiter, B. Fries, L. Sievers, M. Pfaff, N. Thamling, D. Rau, D. J. Hartwig, S. Welter, O. Lösch, and A. Wirz, "Folgenabschätzung zu den ökologi- schen , sozialen und wirtschaftlichen Folgewirkungen der Sektorziele für 2030 des Klima- schutzplans 2050 der Bundesregierung," Berlin, Freiburg, 2018.

[33] K. W. Tham, "Effects of temperature and outdoor air supply rate on the performance of call center operators in the tropics," Indoor Air, vol. 14, no. Suppl 7, pp. 119–125, 2004.

[34] X. Ye, Z. Lian, Z. Zhou, J. Feng, C. Li, and Y. Liu, "Indoor environment, thermal comfort and productivity," Proceeding Indoor Air 2005, https://www.isiaq.org/docs/PDFs/0407.pdf, no. Ashrae 1993, pp. 407–502, 2005.

[35] O. Seppänen, W. J. Fisk, and Q. H. Lei, "Ventilation and performance in office work," Indoor Air, doi:10.1111/j.1600-0668.2005.00394.x, vol. 16, no. 1, pp. 28–36, 2006.

[36] P. Wargocki and D. P. Wyon, "The Effects of Outdoor Air Supply Rate and Supply Air Filter Condition in Classrooms on the Performance of Schoolwork by Children," HVAC&R Res., doi:10.1080/10789669.2007.10390950, vol. 13, no. March 2007, pp. 165–191, 2007.

[37] C. C. Federspiel, W. J. Fisk, P. N. Price, G. Liu, D. Faulkner, D. L. Dibartolomeo, D. P. Sullivan, and M. Lahiff, "Worker performance and ventilation in a call center: analyses of work performance data for registered nurses," Indoor Air, doi:10.1111/j.1600-0668.2004.00299.x, vol. 14, no. s8, pp. 41–50, 2004.

[38] I. Air, B. Munksgaard, and I. Air, "The effects of indoor air quality on performance and productivity," vol. 14, no. Suppl 7, pp. 92–101, 2004.

[39] P. MacNaughton, J. Pegues, U. Satish, S. Santanam, J. Spengler, and J. Allen, "Economic, environmental and health implications of enhanced ventilation in office buildings," Int. J. Environ. Res. Public Health, doi:10.3390/ijerph121114709, vol. 12, no. 11, pp. 14709–14722, 2015.

[40] R. Maddalena, M. J. Mendell, K. Eliseeva, W. R. R. Chan, D. P. P. Sullivan, M. Russell, U. Satish, W. J. Fisk, J. K. Eliseeva, W. R. R. Chan, D. P. P. Sullivan, M. Russell, U. Satish, and W. J. Fisk, "Effects of ventilation rate per person and per floor area on perceived air quality, sick building syndrome symptoms, and decision-making," Indoor Air, doi:10.1111/ina.12149, vol. 25, no. 4, pp. 362–370, 2015.

[41] J. S. Park and C. H. Yoon, "The effects of outdoor air supply rate on work performance during 8-h work period," Indoor Air, doi:10.1111/j.1600-0668.2010.00700.x, vol. 21, no. 4, pp. 284–290, 2011.

[42] J. G. Allen, P. MacNaughton, U. Satish, S. Santanam, J. Vallarino, and J. D. Spengler, "Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: A controlled exposure study of green and conventional office environments," Environ. Health Perspect., doi:10.1289/ehp.1510037, vol. 124, no. 6, pp. 805–812, 2016.

[43] WGBC, "Health, Wellbeing & Productivity in Offices," http://www.worldgbc.org/sites/default/files/compressed_WorldGBC_Health_Wellbeing__Productivity_Full_Report_Dbl_Med_Res_Feb_2015.pdf, no. September, 2014.

[44] D. K. Milton, P. M. Glencross, and M. D. Walters, "Risk of Sick Leave Associated with Outdoor Air Supply Rate, Humidification, and Occupant Complaints," Indoor Air, doi:10.1034/j.1600-0668.2000.010004212.x, vol. 10, no. 4, pp. 212–221, 2000.

[45] J. G. Allen, P. Macnaughton, U. Satish, S. Santanam, J. Vallarino, and J. D. Spengler, "Associations of cognitive function scores with Carbon Dioxide, Ventilation and Volatile Organic Compound Exposure in Office Workers," http://ehp.niehs.nih.gov/wp-content/uploads/advpub/2015/10/ehp.1510037.acco.pdf, vol. 124, no. 6, pp. 805–812, 2016.

[46] U. Satish, M. J. Mendell, K. Shekhar, T. Hotchi, D. Sullivan, S. Streufert, and W. J. Fisk, "Is CO2 an indoor pollutant? direct effects of low-to-moderate CO2 concentrations on human decision-making performance," Environ. Health Perspect., doi:10.1289/ehp.1104789, vol. 120, no. 12, pp. 1671–1677, 2012.

[47] H. Juslén, Lighting , Productivity and Preferred Illuminances - Field Studies in the Industrial Environment. 2007.

[48] P. R. Mills, S. C. Tomkins, and L. J. Schlangen, "The effect of high correlated colour temperature office lighting on employee wellbeing and work performance," J. Circadian Rhythms, doi:10.1186/1740-3391-5-2, vol. 5, no. 1, 2007.

[49] AT Kearney, "Quantified benefits of Human Centric Lighting," http://www.lightingeurope.org/uploads/files/Market_Study-Human_Centric_Lighting._Final_July_2013.pdf, no. April, 2015.

[50] A. Hedge, "The Workplace Study," 2017.

[51] Heschong Mahone Group, "Appendix of Windows and Offices: A Study of Office Worker Performance and the Indoor Environment," Calif. Energy Commision, doi:10.1175/1520-0450(1998)037<0414:TDFBIM>2.0.CO;2, vol. 37, no. 4, pp. 414–435, 2003.

[52] M. G. Figueiro, M. S. Rea, A. C. Rea, and R. G. Stevens, "Daylight and Productivity – A Field Study," ACEEE Summer Study Energy Effic. Build., pp. 69–78, 2002.

[53] HermanMiller, E. Lewis, P. H. Lemieux, and D. Sykes, "Sound Masking in the Office," whatweknow.aaas.org, 2003.

[54] A. L. Jones, "Is it time for a European market surveillance coordination body ? Redefining monitoring , verification , and enforcement of European product policy," pp. 1511–1518.

[55] E. Lewis, D. M. Sykes, and P. H. Lemieux, "Using a Web-Based Test to Measure the Impact of Noise on Knowledge Workers' Productivity," Proc. Hum. Factors Ergon. Soc. Annu. Meet., doi:10.1177/154193120304701805, vol. 47, no. 18, pp. 1972–1976, Oct. 2003.

[56] T. L. Buchanan, K. N. Barker, J. T. Gibson, B. C. Jiang, and R. E. Pearson, "Ilumination and errors in dispensing," Am J Hosp Pharm, vol. 48, pp. 2137–2145, 1991.

[57] K. M. Beauchemin and P. Hays, "Dying in the dark: Sunshine, gender and outcomes in myocardial infarction," J. R. Soc. Med., doi:10.1177/014107689809100703, vol. 91, no. 7, pp. 352–354, 1998.

[58] K. M. Beauchemin and P. Hays, "Sunny hospital rooms expedite recovery from severe and refractory depressions," J. Affect. Disord., doi:10.1016/0165-0327(96)00040-7, vol. 40, no. 1–2, pp. 49–51, 1996.

[59] J. H. Choi, L. O. Beltran, and H. S. Kim, "Impacts of indoor daylight environments on patient average length of stay (ALOS) in a healthcare facility," Build. Environ., doi:10.1016/j.buildenv.2011.10.010, vol. 50, pp. 65–75, 2012.

[60] Thiel, C. L., Needy, K. L., Ries, R., Hupp, D., & Bilec, M. M. (2014). "Building design and performance - A comparative longitudinal assessment of a children's hospital". Building and Environment, 78, 130-136..pdf".

[61] J. M. Walch, B. S. Rabin, R. Day, J. N. Williams, K. Choi, and J. D. Kang, "The effect of sunlight on postoperative analgesic medication use: a prospective study of patients undergoing spinal surgery," Psychosom. Med., doi:10.1097/01.psy.0000149258.42508.70, vol. 67, no. 1, pp. 156–163, 2005.

[62] G. W. Evans and D. Johnson, "Stress and open-office noise," J. Appl. Psychol., doi:10.1037/0021-9010.85.5.779, vol. 85, no. 5, pp. 779–783, 2000.

[63] J. Toftum, L. Soren, J. Kristiansen, and G. Klausen, "Effect of open-plan office noise on occupant comfort and performance," 10th Int. Conf. Heal. Build., http://orbit.dtu.dk/en/publications/effect-of-openplan-office-noise-on-occupant-comfort-and-performance%28cdb06883-48bc-40df-a5b6-05496e4eb854%29.html, 2012.

[64] M. A. Yousef Al Horr Amit Kaushik, Ahmed Mazroei, E. E. Martha Katafygiotou, Y. Al horr, M. Arif, M. AK, K. A, and E. Elsarrag, "Occupant productivity and office indoor environment quality : a review of the literature Occupant Productivity and Office Indoor Environment Quality : A Review of the Literature," Build. Environ., doi:http://dx.doi.org/10.1016/j.buildenv.2016.06.001, vol. 105, p. 45, 2016.

[65] U. Ayr, E. Cirillo, I. Fato, and F. Martellotta, "A new approach to assessing the performance of noise indices in buildings," Applied Acoustics, vol. 64, no. 2. doi:10.1016/S0003-682X(02)00075-0, pp. 129–145, 2003.

[66] E. Sundstrom, J. P. Town, R. W. Rice, D. P. Osborn, and M. Brill, "Office Noise, Satisfaction, and Performance," Environ. Behav., doi:10.1177/001391659402600204, vol. 26, no. 2, pp. 195–222, 1994.

[67] S. P. Banbury and D. C. Berry, "Office noise and employee concentration: Identifying causes of disruption and potential improvements," Ergonomics, doi:10.1080/00140130412331311390, vol. 48, no. 1, pp. 25–37, 2005.

[68] VELUX, Ecofys, Fraunhofer, and VELUX, "Healthy Homes Barometer," https://velcdn.azureedge.net/~/media/com/hhb 2018/healthyhomesbarometer2018.pdf, 2018.

[69] G. Smedje and D. Norbäck, "Incidence of asthma diagnosis and self-reported allergy in relation to the school environment—a four-year follow-up study in schoolchildren," Int. J. Tuberc. Lung Dis., vol. 5, no. 11, pp. 1059–1066, 2001.

[70] G. Smedje and D. Norbäck, "New ventilation systems at select schools in Sweden—effects on asthma and exposure," Arch. Environ. Heal. An Int. J., vol. 55, no. 1, pp. 18–25, 2000.

[71] D. Norbäck and K. Nordström, "Sick building syndrome in relation to air exchange rate, CO 2, room temperature and relative air humidity in university computer classrooms: an experimental study," Int. Arch. Occup. Environ. Health, vol. 82, no. 1, pp. 21–30, 2008.

[72] S. A. A. Wahab, Air Quality: Monitoring and Modeling Protocol for Urban School Buildings. doi:10.1007/978-3-642-17919-8_4, 2011.

[73] P. MacNaughton, U. Satish, J. G. C. Laurent, S. Flanigan, J. Vallarino, B. Coull, J. D. Spengler, and J. G. Allen, "The impact of working in a green certified building on cognitive function and health," Build. Environ., doi:10.1016/j.buildenv.2016.11.041, vol. 114, pp. 178–186, 2017.

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