Indoor air, human cognition and health

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Summary

Air quality has often been on the agenda of policymakers aiming to improve public health, primarily focusing on *outdoor* air pollution caused by traffic and economic activities. However, since the COVID-19 pandemic, public awareness of indoor air quality in residential and public buildings has increased. Research on the impact of indoor air quality on human health and cognitive performance is much older than the onset of COVID-19.

This body of research links poor indoor air quality to lower cognitive performance in adults, worse academic achievement in school children, and adverse health effects, which can result in higher sickness absence rates. Nevertheless, some of the evidence is conflicting; much of it relies on self-reported measures of health and performance, and laboratory studies dominate, whereas field studies on the impact of indoor air quality on cognitive performance remain scarce. The aim of this thesis is to extend current research on indoor air quality. This thesis presents two field studies in educational buildings, a laboratory study about the influence of carbon dioxide (CO_2), and a review on the economic implications of better indoor air quality, and to a broader extend, improved indoor environmental quality.

Chapter 2 presents the findings from a field study conducted in seven primary schools. Over the course of one school year, indoor air quality was measured in 61 classrooms, using the concentration of CO_2 as an estimator for indoor air quality. Furthermore, data per child on the test score of a standardized test and the amount of sickness absence days during the school year were collected. The aim of the study is to investigate the relationships between indoor air quality, sickness absence, and test scores. More specifically, it hypothesizes that sickness absence serves as the main pathway through which indoor air quality affects achieved test scores.

Indeed, the results of the study reveal that children exposed to poor indoor air quality, as indicated by high concentrations of CO_2, achieve lower test scores. However, sickness absence is neither influenced by indoor air quality nor related to test scores. Therefore, these findings indicate that indoor air quality impacts academic achievement of school children directly and independently of sickness absence as a potential mechanism. This finding has important policy implications, as it shows that improving the health of children with school interventions is not enough to also improve performance in school. Interventions should consider a broader scope, focusing on improving children's individual health, while also providing them with a healthy and performance-supporting indoor environment in classrooms and school buildings.

Chapter 3 presents a second field study investigating the impact of a renovated university building on students' satisfaction with the indoor environment and their achieved course grades in higher education. A cohort of first-year students was split into two groups: One group attended classes in a conventional university building, while the other group had their classes in a renovated and refurbished university building. The study covered two academic periods, each lasting seven weeks, during Autumn 2022 and Spring 2023, and included five courses across these periods. The renovated building was certified by *WELL* for providing an indoor environment designed to foster occupant health and well-being. Indoor environmental quality was monitored in 31 classrooms across both buildings.

The analysis reveals that indoor air quality in the renovated building was significantly better, with lower concentrations of CO_2 and other air pollutants. In contrast, the conventional building only exhibited favourable indoor air quality conditions on warm summer days, likely due to students and teachers opening windows for ventilation. During colder days, however, pollutant concentrations remained high in the conventional building, whereas the renovated building consistently maintained better indoor air quality. These findings support the effectiveness of the modern ventilation system in the renovated building in maintaining a healthy indoor air quality.

The main analysis of this chapter reveals that students in the renovated building perceived the indoor environment markedly differently compared to students in the conventional building. When specifically asked about the influence of the indoor environmental quality, students in the renovated building reported a positive impact of air quality, temperature, lighting, and noise on their performance in class. Additionally, students found the interior design of the renovated and refurbished building to be much more pleasant and believed it positively influenced their mood and performance during class. Interestingly, despite the improved indoor air quality in the renovated building, no significant differences were found in the achieved course grades between the two student groups. The building in which a student attended tutorial classes had no measurable effect on their course performance.

These findings highlight a discrepancy between students' perceptions of the indoor environment and its actual impact on their performance.On the one hand, students in the renovated building attributed a positive effect of the indoor environment and interior design to their self-rated performance. On the other hand, objectively measured performance indicators, such as course grades, remained unchanged. This suggests that better indoor environmental quality, while improving satisfaction and perceived performance, does not necessarily translate into improved academic outcomes.

This study is relevant for several reasons. First, it demonstrates that findings regarding the relationship between indoor air quality and learning outcomes in primary and secondary schools cannot necessarily be generalized to higher education. While **Chapter 2** identifies a negative effect of poor indoor air quality on test scores among primary school children, **Chapter 3** cannot confirm such a negative relationship between indoor air quality and course grades for university students. This discrepancy may be attributed to differences in exposure time due to different class schedules, learning materials, or the organizational structure of education at the university level.

Additionally, university students differ from school children in terms of age, health behaviours, and other physiological characteristics, which could influence the outcomes.

Therefore, the study suggests that investing in the indoor environmental quality of university classrooms might not be the most effective way to enhance student learning outcomes. In contrast, evidence supporting the positive impact of improved indoor air quality on learning outcomes in primary and secondary school classrooms is more consistent. However, **Chapter 3** underscores the value of investments in the classroom environment of university buildings to improve students' general well-being.

While the two field studies in **Chapter 2** and **Chapter 3** use CO_2 as a metric for general indoor air quality, it remains unclear whether CO_2 directly affects cognitive performance and human physiology at exposure levels commonly encountered indoors. To address this question, **Chapter 4** presents a laboratory study investigating the impact of CO_2 on human cognitive performance, economic decision-making, and health outcomes.

The single-blind randomized crossover experiment involved 20 healthy adults exposed to two concentration levels: 3,000 ppm (parts per million) and 900 ppm CO_2. Participants spent eight hours in an airtight respiration chamber under each condition. Ventilation rates were kept high in both scenarios to maintain the same concentration of other air pollutants and attribute any observable effect to the CO_2 exposure. Chemically pure CO_2 was introduced into the chamber to achieve the 3,000 ppm condition. Such concentration were found in primary school classrooms and university classrooms in **Chapter 2** and **Chapter 3**, confirming that concentrations of 3,000 ppm CO_2 are commonly achieved in educational buildings.

Participants were randomly assigned their starting condition: 10 participants began with the 900 ppm CO_2 condition and transitioned to the 3,000 ppm condition on their second test day, while the remaining

10 participants followed the reverse order. Cognitive tests were conducted twice during each 8-hour test day, assessing psychomotor control, attention, executive functioning, and memory. Additionally, participants answered a series of economic decision-making tasks, where they chose between two payment options with varying probabilities of occurrence. These tests are commonly used in economic research to measure risk behaviour and level of impatience of individuals when faced with choices including monetary payments. Throughout the test day, several physiological parameters were continuously monitored, including heart rate, blood pressure, blood CO_2 levels, oxygen consumption, physical activity levels, and breathing rate.

The results in **Chapter 4** show that exposure to 3,000 ppm CO_2 concentration did not lead to worse performance in the cognition tests, nor did participants show any change in risk behaviour or level of impatience in the economic decision-making tasks. Furthermore, no significant changes in physiological parameters were recorded throughout the day, which would reveal an adverse health reaction. However, a slight increase in breathing rate was noted during the cognitive tests when participants were exposed to the elevated CO_2 concentration, which could be a compensatory mechanism.

These findings seemingly contradict previous studies that reported a negative effect of CO_2 on cognitive performance. Earlier research has indicated that elevated CO_2 levels negatively impact strategic decision-making. However, past evidence points out that the influence of CO_2 on cognitive performance appears to depend on factors such as exposure duration, task complexity, and the characteristics of the studied population. The study in **Chapter 4** contributes to our understanding of CO_2 exposure by demonstrating that concentration levels commonly found indoors do not impair performance on basic cognitive tasks or economic decision-making. Moreover, the findings indicate that elevated CO_2 levels do not necessarily trigger adverse physiological reactions.

Considering the research on the impact of indoor air quality - and, more broadly, indoor environmental quality, including thermal conditions, lighting, and noise levels - on human performance and health, renovating and designing buildings to provide an optimized indoor environment requires a significant financial investment from real estate developers and property owners. Such investments must be financially viable and profitable to incentivize the capital market to support the development of healthier buildings.

To address this issue, **Chapter 5** reviews existing literature on the economic value of investing in an optimized indoor environmental quality. The chapter begins by reviewing studies on the influence of the environmental factors air quality, temperature, light, and noise on building occupants. Mounting evidence shows that exposure to poor indoor air quality, thermally uncomfortable conditions, insufficient indoor lighting, and high levels of noise can lead to adverse health effects and lower cognitive performance. Additionally, studies show that these factors affect occupant well-being with the indoor environment, although it is less clear to which degree, as well as how these factors interact with each other in shaping the well-being of humans.

In the second half, **Chapter 5** summarizes existing literature evaluating the economic costs and benefits of improving the indoor environmental quality of buildings. Although numerous studies document the negative effects of suboptimal indoor environmental quality on performance and health, very few studies attempt to estimate the associated economic costs and benefits. The studies that do exist primarily rely on estimations of energy consumption, insufficient proxies for productivity and work performance, such as salary data, and self-reported health metrics to assess whether investments in indoor environmental quality are cost-efficient.

Overall, **Chapter 5** underscores the need for further research to determine the tangible benefits of improved indoor environmental quality. Current research lacks sufficient investigation into whether the additional costs associated with enhancing indoor environmental quality can be offset by improvements in worker performance, health, and well-being. There is a strong need for studies that collect both objective and subjective measures of performance, health, and well-being to accurately estimate the economic value of such improvements. Understanding how improvements in occupant performance, health, and well-being compare to associated costs, such as increased energy consumption or operational expenses, is essential. Such insights are key to establishing a compelling business case for investing in optimizing the indoor environmental quality.

In conclusion, **Chapters 2 to 5** highlight several key findings: First, the negative effects of poor indoor air quality on academic achievement in primary school children, although these effects were not observed in higher education. Secondly, the potential of improved indoor environmental quality to enhance well-being among university students. Additionally, the included laboratory study demonstrates that CO_2, while a useful proxy for indoor air quality, does not appear to cause adverse health reactions or impair cognitive performance at levels commonly found indoors. Finally, the thesis emphasizes the critical need for further research into the economic value of enhanced indoor environmental quality.