Indoor air, human cognition and health

Impact

1 Contribution to science

The existing literature provides evidence of the negative impact of poor indoor air quality on human cognition and health. Studies established an association between indoor air quality and academic achievement of school children and cognitive performance of adults. Additionally, indoor air quality appears to affect health, particularly respiratory health, and well-being of building occupants. Indoor air quality is primarily influenced by ventilation rate, air filtration, and occupancy rates. It encompasses the concentration of air pollutants such as volatile organic compounds, bioeffluents, fine particulate matter, and carbon dioxide (CO_2).

Field studies used CO_2 as a metric of indoor air quality, as it correlates with various air pollutants indoors. These air pollutants typically rise in concentrations when an insufficient amount of fresh outside air is supplied into indoor spaces. However, the mechanisms through which indoor air quality in general, and CO_2 specifically, affect cognitive performance and health outcomes are poorly examined in the scientific literature. Moreover, the influence of CO_2 as an air pollutant, causing adverse effects, is questionable. This thesis contributes to the scientific discussion, focusing on various aspects of indoor air quality in school and university classrooms and the impact of CO_2 exposure on cognition and health.

The thesis extends current understanding of the long-term effect of frequent exposure to a poorly ventilated classroom. Poor indoor air quality leads to worse learning outcomes in the form of exam grades among primary school children, shown in **Chapter 2**. However, the study cannot confirm whether sickness absence explains the relationship between indoor air quality and academic achievement. Instead, the empirical analysis in **Chapter 2** provides evidence that indoor air

quality directly affects academic achievement, independent of sickness absence. The study is the first study that combines indoor air quality data, sickness absence records, and exam scores of school children. This study contributes to the existing literature on indoor air quality and sickness absence by employing a longitudinal design for empirical analysis, that allows to follow the same child over time exposed to different indoor air quality conditions. Former studies solely examined this relationship cross-sectionally. Therefore, they could not establish a causal link between exposure to poor indoor air quality and higher sickness absence rates.

Furthermore, the study in **Chapter 3** provides novel insights on the impact of a renovated, WELL-certified university building, with optimized indoor environmental quality, on students' academic achievement and satisfaction with the built environment. The study investigated students' satisfaction and perception of the indoor environment in the certified and a conventional control building. The results show that students perceived the interior design in the certified building as much more pleasant and they attributed a performance-enhancing effect of the indoor environmental quality. However, despite their beliefs, students in the renovated building did not achieve higher course grades compared to students in the control building. Therefore, this study widens the understanding of the relationship between actual indoor environmental quality, perception of it, and objective changes in school performance. The study shows that a better indoor environmental quality, and higher satisfaction with it, does not necessarily translates into better school performance.

The laboratory study in **Chapter 4** extends the understanding of the role of CO_2 on human cognition and health. Previous work provided mixed results regarding the role of CO_2 on cognitive performance. The study shows that 3,000 ppm CO_2 concentration, compared to 900 ppm, did not lead to a significant decline in cognitive performance of healthy adults. This insights further confirm that CO_2 may not be an air pollutant regarding cognitive performance. The study is also the first study that investigated whether CO_2 influences economic decision-

making. In line with the findings on general cognitive performance, no effects were found on risk behaviour and impatience during economic decision-making. Lastly, this study also measured various physiological parameters during the 8-hours of continuous exposure, showing that no adverse health effects were found. Therefore, a CO_2 concentration of 3,000 ppm is unlikely to have a meaningful impact on cognition performance, decision-making, and health. This seemingly contrasts earlier findings of a significant influence of indoor air quality on a related physiological response. However, earlier studies did not apply statistical methods, such as multiple hypothesis testing, to derive empirically robust results. Therefore, **Chapter 4** extends the understanding of CO_2 as a component of indoor air quality, showing that it does not necessarily harm human cognitive performance or health, for concentration levels typically found indoors.

Lastly, **Chapter 5** reviewed existing literature on the impact of indoor environmental quality on building occupants and the economic benefits of investing in it. This review serves as a starting point for research on the economic value of healthy indoor environments. In contrast to an extensive literature on the business case for energy-efficient buildings, this review testifies a significant knowledge gap regarding the economic benefits of healthy buildings.

2 Contribution to society

The results of this thesis are relevant for multiple stakeholders. Policymakers and the boards of schools and universities can use the insights from **Chapter 2** and **Chapter 3** to make effective decisions on investing in a healthy classroom environment, that fosters learning and health of children and students. Children are often exposed to poorly ventilated classrooms that urgently must be renovated. Lower school performance translates into lower human capital accumulation, which can affect income potential later during adulthood. Lower income is in turn associated with negative health outcomes later in life. Therefore,

policymakers and school boards must be aware of the importance of healthy indoor air quality and investing in school buildings to provide children with an optimal learning environment.

The results in **Chapter 2** and **Chapter 3** also answer the question where money can be spend most effectively to improve learning, in primary and secondary schools, or in university education. Comparing the strong effect of indoor air quality on primary school children, shown in **Chapter 2**, and no significant effect on student grades, shown in **Chapter 3**, investing in the indoor environment of primary school classrooms may be more effective in improving learning outcomes. Improving learning outcomes in primary education is particularly effective, as performance during this phase significantly influences subsequent success in higher education and on the job market. University education already is at an advanced level for adolescences. Therefore, improvements might come to late for children struggling with learning and therefore requiring a supportive environment earlier in their education.

Moreover, architects, building engineers, and real estate developers should use the insights provided in this thesis to better understand the importance of indoor environmental quality, particularly indoor air quality, when designing, constructing, and renovating buildings. There is a narrow focus on the energy efficiency of buildings, which is reasonable due to buildings being a major contributor of greenhouse gas emissions and climate change. However, energy efficiency should not come at the expenses of a healthy indoor environment. Modern, demand-controlled ventilation systems are an example of providing sufficient ventilation during high occupancy and reducing ventilation rates to save energy during low occupancy. Nevertheless, these systems are not perfect, because they use CO_2 as a metric of indoor air quality, despite concerns expressed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) about the reliability of CO_2 as an indoor air quality proxy. Therefore, real estate developers must have a thorough understanding of what indoor air quality consist of and how to achieve a healthy and performance-

enhancing indoor air quality. Especially **Chapter 4** and **Chapter 5** provide insights on the particular role of CO_2 as a proxy of indoor air quality and how indoor environmental quality affects occupants' performance, health and satisfaction in general.

The results in **Chapter 5** are important for tenants of commercial buildings, because the provided insights support an effective decision-making process for the selection of office buildings. Since the COVID-19 pandemic, public awareness of indoor air quality increased drastically. However, businesses renting office space are poorly informed about the importance of indoor environmental quality on employee health and work performance. Having a good understanding of indoor air quality is much needed in order to make informed decisions when renovating a building or choosing office space. Commercial tenants need to make such decision considering associated costs and benefits. Understanding the impact of the indoor environment on employees is crucial to determine the economic value of leasing office space with an enhanced indoor environment. **Chapter 5** helps shedding light on several aspects to support this decision-making process.

Lastly, the results in **Chapter 5** are useful for real estate investors. Investments in real estate needs to be profitable and offer a market-competing return. Real estate investors, such as pension funds, mutual and private equity funds, and investors into real estate investments trusts, need to understand the financial value of investing in healthy and performance-promoting indoor environmental quality. Such a business case has already been provided for green, energy-efficient buildings. However, achieving high energy efficiency in buildings can conflict with the provision of a healthy indoor environment. Therefore, a new balance between energy efficiency and health aspects in building design is needed, which can best be promoted if the capital market is aware of the business case for healthy buildings. **Chapter 5** contributes to this discussion by providing investors with a comprehensive review of existing

literature on the economic value of indoor environmental quality and healthy buildings.