Indoor air, human cognition and health

Doctoral thesis

INDOOR AIR, HUMAN COGNITION, AND HEALTH

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INDOOR AIR, HUMAN COGNITION, AND HEALTH

Dissertation

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Contents

1 Introduction

1.1 General introduction

In 2022, the United Nations passed a resolution that having access to a clean, healthy, and sustainable environment is a human right, as well as having clean air [367]. This step supports efforts to define good air quality and how it can be achieved. However, providing good indoor air quality is a much older topic in building design. A prime example is the Pantheon, as shown on the cover of this book. The Pantheon, supposedly built under the Roman emperor Hadrian between 118 and 125 A.D. [163], provides a passive ventilation system which distributes cold air from the entrance into the Pantheon, and rises through natural convection until it exists as warm air through the Oculus on the top. The resulting change in air pressure ensures a consistent ventilation of the indoor environment [397].

Nowadays, numerous studies provide evidence of the detrimental impact of *outdoor* air pollution on human health and cognition [36, 319]. However, *indoor* air quality became an increasingly important topic for researchers and public health policymakers, even prior to the onset of the Covid-19 pandemic, which substantially increased public awareness of indoor air quality. Humans in the Western world spend the majority of their time indoors, either working, sleeping, eating, or exercising [110]. This makes indoor air quality, and in a broader sense the indoor environment in buildings, a profound determinant of human cognitive performance, health, and well-being [375, 260, 12]. However, providing a healthy indoor space was not always the main motivator to ensure good indoor air quality in buildings.

In Germany, for example, a tenant in a residential building has a so called "*Sorgfaltspflicht*", or duty of care, to maintain the quality of the building, as stated in the German Civil Code[1]. Part of this obligation is to frequently air the indoor space to reduce the risk of mould or other damage to the building materials. The German terms "*Stoßlüften*" and "*Durchlüften*" describe the act of *impact ventilation* and *shock ventilation*, when the windows on both sides of a building are opened to create a wind flow through the building. However, this rule is mainly motivated by the need to maintain the quality and value of the property, avoid the onset of mould or high humidity levels, but does not account for the important implication of indoor air quality for occupant health.

Recently, indoor air quality in buildings has become a public health concern [255]. Numerous studies show the negative effects of insufficient ventilation on the health of occupants, associated with high concentrations of indoors air pollutants [391, 352]. Exposure to poor indoor air quality affects cognition performance and learning in adults and children [98, 385]. This makes indoor air quality not just a determinant of human health, but also a productivity and economic growth factor, affecting human capital accumulation and income potential [231, 38]. However, with the increasing pressure to construct energy-efficient buildings comes the opportunity to redesign them in a way that promotes a healthy and performance-enhancing indoor environment.

[1] Bürgerliches Gesetzbuch (BGB), paragraph 541 and 543 section 1, number 2.

1.2 From green to blue buildings - The transition in the real estate sector

The real estate sector is a major contributor of greenhouse gas emissions and therefore an important sector to take into account when tackling climate change [221]. Thus, there is a demand for energy efficient buildings, often referred to as *green* buildings. International agreements such as the Paris Climate Agreement of the United Nations [366], and the subsequent Green Deal of the European Union [105], further increase the pressure for the real estate sector to transition towards green and sustainable building design. Fortunately, green buildings provide an excellent business case for real estate investors and tenants. They provide investors with premium rents and higher property value, showing that the capital market and tenants value green buildings [100, 168].

However, a green building is not necessarily a healthy building for its occupants [86]. While a higher ventilation rate is needed to maintain good air quality, higher fan speeds lead to higher energy consumption. Additionally, if the outside air is cooler or hotter than the indoor temperature, the air must be heated up or cooled down before entering the room. This leads to a higher energy demand from heating and cooling the air. In response, common green building certification schemes have began to expand their focus to include providing a healthy and comfortable indoor environment while minimizing energy use [237]. Furthermore, new building certification schemes such as WELL and Fitwel were introduced, with a primary focus on creating a healthy indoor environment [213, 237]. New technology, such as modern heating, ventilation, and air conditioning (HVAC) filtration systems, combine ventilation with air filtration and purification to remove air pollutants and pathogens from the air while maintaining energy efficiency. These air filtration systems can effectively reduce the risk for airborne infections [25], while minimizing energy consumption [32, 30].

I refer to buildings, which combine energy efficiency and a healthy indoor environment, as *blue buildings*, derived from the term *blue zones*, which are regions where life expectancy is highest among the population due to their exceptional health conditions [54]. Such buildings can be seen as the much-needed evolutionary step towards transitioning the real estate sector to sustainability for both, humans and the planet. However, to effectively design such buildings, some unanswered questions remain with regards to the impact of the indoor air quality on humans, and financial performance.

1.3 Indoor air quality - More than just fresh air

Indoor air quality is, along with temperature, acoustics, and lighting, one of the four factors determining indoor environmental quality [213]. Indoor air quality encompasses the concentration of air pollutants such as volatile organic compounds, carbon dioxide (CO_2), and fine particular matter. High concentrations of these pollutants in indoor spaces increase as a consequence of insufficient ventilation of the room with fresh outside air [14, 65]. Bioeffluents and CO_2 are exhaled by humans and other air pollutants are emitted by the building material itself [355]. CO_2 is often used as an easy-to-measure metric to determine indoor air quality, because its concentration correlates with other human-emitted indoor air pollutants [292, 355].

Numerous laboratory studies have shown that increased ventilation rates and better indoor air quality, as determined by low CO_2 concentrations, are associated with better cognitive performance in adults [98]. Field studies in schools confirm the impact of indoor air quality, finding negative associations with poor indoor air quality and low ventilation rates on school performance of primary and secondary school children [385, 380]. Moreover, indoor air quality affects health of occupants [391, 352], causing respiratory symptoms [120] and potentially increasing sickness rates [340, 241, 137, 91]. This evidence showcases the importance of indoor air quality to provide a healthy and performance-enhancing indoor environment.

However, despite extensive research on indoor air quality and CO_2 on humans, many questions remain. It is still unclear for which mechanism indoor air quality affects cognitive performance and long-term learning outcomes in schools. While multiple mechanisms are proposed on how indoor air quality affects these outcomes [380], there are no studies that extensively investigate the underlying drivers of the impact of indoor air quality on human cognitive performance and health. Additionally, field studies on indoor air quality and learning are mostly done in primary and secondary schools. Findings from these studies should not be generalized to a university setting, due to differences in the educational setting and population. Moreover, the role of CO_2 as an air pollutant itself is still unclear. The aim of this thesis is to answer some of these questions, specifically, how and by which mechanism frequent exposure to indoor air quality affects learning in school children and university students, and the role of CO_2 on cognition, the related physiological response, and general health.

1.4 Indoor air quality - A factor of human capital accumulation

A recent study provides evidence that ex-ante exposure to poor indoor air quality during the learning period prior to the testing date impacts ex-post exam grades [280]. However, the underlying mechanism of this relationship is unknown. Wargocki and Wyon [380] propose sickness absence as a potential mediator between indoor air quality and school performance. This assumption is plausible, given that several studies found a cross-sectional association between sickness absence rate and ventilation rate in classrooms [340, 241, 137, 91]. Spending more time in class is important to achieve better academic outcomes in school, while missing school, even for a couple of days, negatively affects achieved test grades [225, 196, 142].

To examine if sickness absence explains the relationship of indoor air quality and academic achievement, **Chapter 2** presents the results of a field study conducted in seven schools in the south of the Netherlands. This study confirms a negative effect of ex-ante exposure to poor indoor air quality on ex-post achieved test scores. However, indoor air quality is not significantly associated with sickness absence, nor does sickness absence affect test scores. Thus, the results cannot empirically support the assumption made in previous literature that indoor air quality affects academic achievement via sickness absence [380]. The findings in **Chapter 2** rather show that indoor air quality affects academic achievement and long-term learning outcomes directly and independently of sickness absence rates.

1.5 From primary school to university: Heterogeneity of the indoor air quality impact between educational levels

Past studies on the impact of indoor air quality on academic achievement cannot be directly generalized to university education. Primary and secondary education differs in terms of the organizational structure of classes, which influences the exposure time to the classroom environment. University students spend less time in class than school children; they do the majority of their learning in other places, such as libraries, dedicated learning spaces, or at home. Laboratory studies have shown that exposure time to certain indoor air quality conditions is an important driver of how strongly it affects cognitive performance [98].

To address the question of how indoor environment affects student performance, **Chapter 3** investigates the impact of indoor environmental quality and, more broadly, the effect of a newly renovated and refurbished building with a modern ventilation, heating, and air conditioning (HVAC) system, on the academic achievement of university students. Objective measures of the indoor air quality confirm that the renovated building contained lower concentrations of air pollutants.

Interestingly, the presented results show that students were more satisfied with the interior design of the newly renovated building and believed that it had a positive effect on their mood and performance in class. When asked specifically about the impact of indoor environment quality - including air quality, temperature, light and noise in the classroom - on their performance, students in the renovated building perceived a positive effect.

However, the study revealed that having tutorial classes in the renovated building did not lead to higher course grades among students. Therefore, students' beliefs about the impact of the indoor environment on their performance were not an accurate estimation for actual performance improvements. **Chapter 3** also demonstrates that findings from primary and secondary education cannot necessarily be directly generalised to a university setting. This may be due to differences in exposure time, population characteristics, and cognitive demand of the learning material and class structure in higher education.

1.6 The role of carbon dioxide - Is it an air pollutant?

Many field studies, including the studies presented in **Chapter 2** and **Chapter 3**, use CO_2 as a metric of indoor air quality. However, past laboratory studies have contradicting results of the role of CO_2 on cognitive performance [345, 7, 322, 331, 313, 404, 402]. Moreover, a recent study provides results that CO_2 itself can be an important modulator for the risk of indoor airborne infections [151]. Therefore, CO_2 is not just a metric for indoor air quality, but it may be the cause of higher sickness rates, which is observed among school children in poorly ventilated classrooms [241, 340, 137]. Additionally, the physiological mechanism for which indoor air quality affects cognition are widely unknown and need to be further investigated [403, 15]. Understanding the role of CO_2 also has practical implications for operating building management systems.

Air filtration systems are not able to remove CO_2 from the air [255]. Therefore, a position paper by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) emphasizes the need to further research the effect of CO_2 in order to understand if it is an air pollutant causing adverse effects for humans [15].

To investigate the role of CO_2, **Chapter 4** presents results from a laboratory study on how it influences cognitive performance and human physiology. The study shows that 3,000 ppm CO_2 did not affect attention, executive functioning, and memory. Additionally, no effect on economic decision-making was found. Notably, no physiological stress reactions, changes in human metabolism, or adaptations in respiration rate and blood CO_2 concentrations were recorded throughout the day. Thus, the findings did not confirm that a CO_2 concentration of 3,000 ppm caused any effect on cognition, decision-making or adverse health effects. The study raises doubts about whether associations between CO_2 and cognitive performance, found in previous field studies, are causal.

1.7 Is blue also gold? - The business case of healthy buildings

After investigating specific aspects of indoor air quality on human cognition within the wider context of indoor environmental quality, it is important to emphasize the need for capital from the private sector to finance the transition from green to healthy (*blue*) buildings. In other words, there has to be a willingness from tenants and real estate investors to rent and invest in real estate dedicated to a performance-enhancing and healthy indoor environmental quality. However, making a healthy building a profitable investment depends on several factors. This discussion is the topic of the review in **Chapter 5**. In the first part, the paper summarizes existing evidence about the impact of indoor air quality, temperature, acoustics, and lighting on human performance, health and satisfaction. The second part reviews literature that aims to establish the economic value of improved indoor environmental quality and healthy buildings.

The paper shows that, despite the documented relationship between indoor environmental quality and occupant work performance and health, there is insufficient research on whether healthy buildings can be a profitable business case. Most papers only include "*back-of-the-envelope*" cost estimations. The literature on the economic value of healthy buildings is not as mature as for *green* buildings [100, 168]. Additionally, the role of indoor environmental quality in occupant satisfaction is not yet well understood. Several papers indicate that *green* and healthy buildings do not always lead to higher satisfaction rates among occupants [10, 212]. Therefore, further research is needed to identify how the determinants of a healthy indoor environmental quality can provide tangible value for real estate investors and commercial tenants.

1.8 Outline of the thesis

Chapter 2 presents the findings from a field study in seven elementary schools. The study shows that children who attend classes in insufficiently ventilated classrooms with poor indoor air quality achieved lower scores in standardized exams. However, sickness absence did not explain the relationship of indoor air quality and test scores, indicating that indoor air quality directly affected academic achievement, independent of sickness absence.

Chapter 3 continues with a second field study on the impact of indoor environmental quality in a newly renovated and refurbished university building on student grades and satisfaction. The study shows that students perceived the indoor environmental quality and interior design of the renovated building more positively, attributing an enhanced effect on their self-reported performance. However, despite these beliefs, students did not achieve significantly higher course grades.

Chapter 4 presents the results of a laboratory study on the impact of indoor carbon dioxide on cognitive performance, economic decision-making and physiological response. The study shows that for a commonly occurring concentration level of 3,000 ppm, carbon dioxide does not cause any cognitive impairment or adverse health effect compared to a carbon dioxide concentration of 900 ppm.

Lastly, **Chapter 5** reviews existing literature on the effects of the four indoor environmental quality parameters on work performance, health and occupant satisfaction. This chapter also reviews literature on the economic costs and benefits of investing in indoor environmental quality, aiming to answer whether healthy buildings can become a profitable investment.

This thesis closes with **Chapter 6**, which discusses the main findings, methodologies, and provides an outlook for future research.

2

Indoor air quality, sickness absence and academic achievement in primary school children

Abstract

Academic achievement in primary school is an important factor for human capital accumulation, productivity, and health outcomes in adulthood. A substantial share of public expenses is devoted to the renovation, refurbishment, and modernization of school buildings. Indoor air quality in school buildings has a profound influence on children's academic achievement and learning performance. Evidence confirms a negative impact of insufficient ventilation and poor indoor air quality on cognitive performance and learning outcomes in primary and secondary school children. However, no study has investigated the pathways that explain the effect of indoor air quality on learning outcomes. Understanding the underlying mechanisms is crucial for developing effective interventions that foster the academic performance of children. This study combines indoor air quality measurements in classrooms, daily absence data, and test scores from standardized exams in primary schools, to investigate if sickness absence explains the relationship of indoor air quality and academic achievement. The results confirm a negative effect of frequent exposure to poor indoor air quality, determined by elevated carbon dioxide concentrations, during the learning phase, on subsequent test scores. However, sickness absence was not affected by indoor air quality, neither did sickness absence influence test scores. Therefore, the empirical analysis could not confirm a mediating role of sickness absence between indoor air quality and academic achievement. The findings illustrate a direct impact of indoor air quality on academic achievement, independent of absenteeism of primary school children.

This chapter is co-authored with Nicolás Durán[1], Piet Eichholtz[2], Nils Kok[2], and Guy Plasqui[2]

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2.1 Introduction

Academic achievement in school is an important determinant of productivity and earning potential in adulthood [295, 38]. Skill development during the schooling period improves economic mobility, reduces inequality and promotes economic growth [24, 155]. In return, higher income and earning potential are associated with better health outcomes later in life [350, 232].

A school's indoor environment plays an important role for learning outcomes, because children spend a majority of their time indoors in school [363, 318]. However, school buildings often have a deficient level of infrastructure and insufficient ventilation inside classrooms [273]. This leads to unhealthy indoor air quality conditions, because humans and indoor materials emit various air pollutants, which could be removed through proper ventilation [101, 65, 355]. Past evidence shows that the indoor environmental quality, including indoor air quality, can substantially affect cognitive performance, learning outcomes, and health of children [385, 50, 120]. Numerous studies provide evidence that insufficient ventilation and accumulation of air pollutants lead to poor indoor air quality and therefore reduce test scores of school children [385].

Despite mounting evidence on the negative effects of exposure to poor indoor air quality in schools on academic achievement, there is no understanding on what explains this relationship. Laboratory studies on indoor air quality confirm an immediate effect of high concentrations of air pollutants and carbon dioxide on cognitive performance during time of exposure [98]. However, children in classrooms are repeatedly exposed to the same indoor air quality condition prior to the actual testing. Therefore, results from laboratory studies should not be generalized to explain why past studies have identified a negative relationship of frequent exposure to poor indoor air quality on subsequent exam grades [242, 280]. These studies do not provide insights into a possible mechanism of this long-term effect.

The presented study aims to close this research gap by investigating sickness absence as a mediator to explain the negative impact of indoor air quality on test scores. It is essential to understand if sickness absence explains the impact of indoor air quality on learning outcomes. This will be important for designing effective school interventions, which successfully promote learning among children. Wargocki and Wyon (2017) [380] hypothesize that increased sickness absence is a possible mechanism that drives the impact of indoor air quality on performance outcomes. It is reasonable to assume that sickness absence mediates the relationship of indoor air quality and academic achievement, given that insufficient ventilation and high indoor concentrations of carbon dioxide promote the spread of airborne infections and increase the prevalence of respiratory health symptoms [272, 151, 120]. Additionally, according to the Faucet theory, skill development and learning in children happens through regular exposure to schooling [191, 197]. Spending more time in class is associated with better academic outcomes in school, while missing school, even for a couple of days, negatively affects test grades [225, 196, 142].

Four studies reveal that insufficient ventilation and poor indoor air quality lead to higher absence rates among school children [340, 241, 137, 91]. However, none of these studies extend their analysis towards learning outcomes and academic achievement. Therefore, this study hypothesises if poor indoor air quality, determined by carbon dioxide concentration, leads to higher sickness absence rates and thereby, higher sickness absence predicts worse test scores. Thus, the direct effect of indoor air quality on test scores would be reduced, once controlled for sickness absence, confirming the mediating role of sickness absence on the relationship of indoor air quality on test scores.

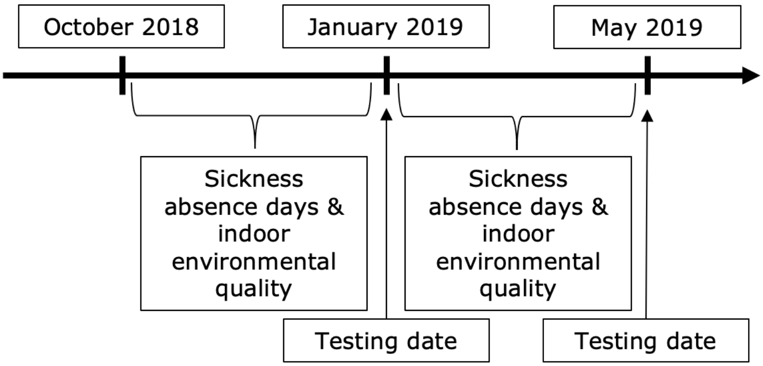
To examine this hypothesis, we used data from two independently conducted field studies, that recorded data on indoor environmental quality, including air quality, thermal conditions, and noise, as well as test scores and absenteeism in primary schools, located in the Netherlands [359, 388]. Our results show that exposure to poor indoor air quality, during the learning period preceding the testing date, predicted lower test scores. The recorded effect size in our study for improving indoor air quality on test scores is substantially higher than the effect of class size reduction, measured in previous work [342]. This comparison supports the effectiveness of indoor air quality improvements in classrooms to improve academic achievement. However, in our analysis, sickness absence rates among children were unrelated to indoor air quality conditions. Furthermore, absence rates did not significantly influence test scores. Therefore, our analysis cannot confirm that sickness absence explains the relationship of indoor air quality on learning outcomes. Instead, the analysis shows that indoor air quality impacts test scores independent of sickness absence, indicating a direct long-term effect of indoor air quality on learning.

2.2 Methods

2.2.1 Data Description

This paper used data from two field studies that were independently conducted in seven elementary schools located in the south of the Netherlands. Individual data on absence days, test scores on standardized nationwide exams, and indoor environmental quality were collected and matched to classrooms from October 2018 to May 2019. Figure 3.2 shows the timeline of our study. The number of days each child was absent due to sickness in a specific classroom, along with indoor environmental quality measures for that classroom, was aggregated for the 3-month learning period prior to each testing date. The data was then matched with the test score the child achieved at the end of the learning period. This approach leads to two learning periods during the school year: One from October 2018 to January 2019 and one from February 2019 to May 2019. Daily absence and indoor environmental quality data allow us to examine the ex-ante, long-term impact of exposure to indoor environmental quality and number of sickness absence days in the 3-month learning period on ex-post test scores for each period.

Figure 2.1: Timeline of data collection in the study sample



Note: The indoor environmental quality data collected, consists of: CO_2, temperature, relative humidity, noise, and PM_{10}. The indoor environmental quality data and days being absent and its reason have been collected during the three months preceding the testing date.

The number of absent days and reasons for absence, whether sickness related, were collected for each child as part of the first field study, the Healthy Primary School of the Future Project. A detailed description of the study protocol can be found in Willeboordse et. al. (2016) [388]. This study is registered in the database ClinicalTrials.gov with the reference number *NCT02800616*, and received medical ethical approval from the Medical Ethics Committee Zuyderland in Heerlen (Registration number: *MEC 14-N-142*)[1]. The second field study collected data on test scores for each child and matched this data with continuous indoor environmental quality measures during the school year. A detailed overview of the field study protocol is available in Palacios et. al. (2020) [359]. This study received medical ethical approval from the Medical Ethical Committee azM/UM at Maastricht University Hospital, registered under the number *METC 2018-0681*. Data on children's academic performance is recorded based on standardized school exams taken by all primary school children in the Netherlands, referred to as CITO Tests (Centraal Instituut voor Toetsontwikkeling). These

[1] All participants were required to complete an informed consent form, signed by both parents or caregivers, and by the children in case they are 12 years or older.

tests are administrated twice per year, in January and May, and consist of several domains, including spelling, mathematics, and reading. For our study, the sample consists of children in grades 3-6, with an age range of 6 to 12 years old. Additional data on the number of children of each group, further referred as class size, has been collected in [359].

To measure indoor environmental quality in each classroom, commercially available monitors (Aclima Inc, California, USA) were deployed. These monitors measured the concentration of carbon dioxide (CO_2), aggregated to the minute level, the amount of coarse particles (PM_{10}), aggregated at 10-minute frequency, indoor temperature, relative humidity, and noise, aggregated to a 1-minute frequency. The monitors were deployed in autumn of 2018 in the schools and measured continuously throughout the school year. As is widely practised in the literature [174, 242] and recommended by indoor air quality guidelines [15], we used peak CO_2 concentration within a classroom as a proxy for indoor air quality.

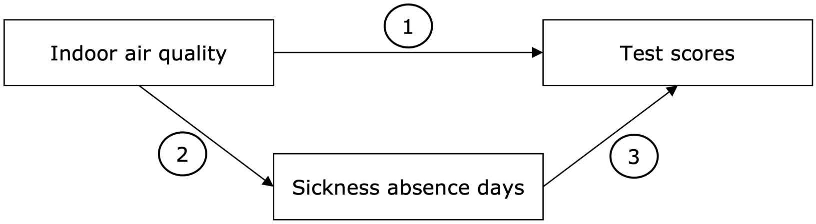
2.2.2 Empirical Strategy

To examine whether sickness absence explains the relationship between indoor air quality and test scores, a three-step approach was used, following the mediation analysis approach described by Baron and Kenny (1986) [27]. Figure 2.2 shows the three relationships to be examined.

The first step was to examine the relationship between indoor air quality and test scores (indicated by arrow (*1*) in Figure 2.2) using the following fixed-effect regression model:

$$Score_{iycdt} = \beta_1 CO2_{ct} + \beta_2' IEQ_{ct} + \beta_3' ClassSize_{ct} + \Theta_{iycdt} + \varepsilon_{iycdt} \quad (2.1)$$

Figure 2.2: Relationship between IAQ, sickness absence, and test score



In Equation 2.1, the dependent variable $Score_{iycdt}$ is the standardized test score (z-score) achieved by child i with y years of schooling, belonging to classroom c, in testing domain d (spelling, math, reading), for the testing period t (January 2019 or May 2019). The variable $CO2_{ct}$ describes the daily average peak carbon dioxide concentration as an estimator for indoor air quality in classroom c during the 3-month period t, expressed as standard deviations (z-score). In line with other studies [50], vector IEQ_{ct} includes the daily average peak temperature, relative humidity and noise in classroom c during the three months period t, expressed in standard deviations (z-score). We excluded the measurements for fine particles PM_{10}, because of the significant and high correlation with CO_2 concentrations, which could lead to a multicollinearity problem (0.73, $p < 0.001$, see Supplementary Table A1).

The vector $ClassSize_{ct}$ includes both the number of children, and number of children squared in classroom c during the 3-month period t. The vector Θ_{iycdt} includes fixed effects of child i, years of schooling y, classroom c, testing domain d (spelling, math, reading), and testing period t. Lastly, the variable ε_{iycdt} describes the error term. Standard errors are clustered at classroom and period level to account for the dependency of observations within a classroom and testing period [293], following standard practice to cluster standard errors at treatment level [1].

After examining the impact of indoor air quality, in terms of peak carbon dioxide concentration, on test scores, the second step in the mediation analysis by Baron and Kenny (1986) [27] is to investigate whether there is a significant influence of indoor air quality on sickness absence (indicated by arrow (2) in Figure 2.2). We used the following fixed-effect regression model:

$$Sickness_{ict} = \delta_1 CO2_{ct} + \delta_2' IEQ_{ct} + \delta_3' ClassSize_{ct} + \Omega_{ict} + \varepsilon_{ict} \quad (2.2)$$

In Equation 2.2, the dependent variable $Sickness_{ict}$ consists of the total days child i has been absent due to sickness, belonging to classroom c, during the three months learning period t. Sickness absence has been standardized and expressed as a z-score. The variables $CO2_{ct}$, IEQ_{ct}, and $ClassSize_{ct}$ are defined as in Equation 2.1. The vector Ω_{ict} includes fixed effects for child i, classroom c, and testing period t.

Lastly, we examined the combined effect of indoor air quality and sickness absence on test score (indicated by arrow (1) and (3) in Figure 2.2). For this purpose, the following extension to Equation 2.1 was applied:

$$Score_{iycdt} = \gamma_1 CO2_{ct} + \gamma_2 Sickness_{ict} + \gamma_3' IEQ_{ct} + \gamma_4' ClassSize_{ct} + \Theta_{iycdt} + \varepsilon_{iycdt} \quad (2.3)$$

Compared to Equation 2.1, the variable $Sickness_{ict}$ was added to Equation 2.3 to regress test scores on the number of days being absent due to sickness of child i, in classroom c, during the 3-month learning period t, preceding the testing date, standardized and expressed as a z-score. The variables $CO2_{ct}$, IEQ_{ct}, and $ClassSize_{ct}$ are equally defined in Equation 2.1. Additionally, the same fixed effect vector Θ_{iycdt} is included. A mediation effect through sickness absence is statistically proven if the coefficient δ_1 in Equation 2.2 is significantly positive, and γ_2 in Equation 2.3 is significantly negative [27]. A partial mediation through sickness exists if coefficient γ_1 is smaller than the coefficient β_1 in Equation 2.1, and a full mediation of sickness absence exists if the coefficient γ_1 in Equation 2.3 becomes insignificant, compared to coefficient β_1 in Equation 2.1.

2.3 Results

2.3.1 Description of the study sample

Table 2.1, Panel A shows the indoor environmental quality in the classrooms across the seven schools. The daily peak CO_2 concentration was 1,447 ppm (standard deviation of 798 ppm), while daily average CO_2 concentration in the sampled classrooms was at 1,067 ppm, with a standard deviation of 478 ppm. The average CO_2 concentration was slightly above the recommended threshold of 1,000 ppm set by standards of the European Union [95]. However, the peak CO_2 concentration markedly exceeded this threshold on average by 447 ppm.

Peak temperature and relative humidity were relatively stable at 22° Celsius (71.6° Fahrenheit) and 44%, respectively, which lie within the range recommended by building guidelines [22]. The average classroom size was 53 square meters (570 square feet), with a standard deviation of 9 square meters (97 square feet). The largest classroom was 96 square meters (1,033 square feet), while the smallest classroom was 42 square meters (452 square feet).

Six out of the seven schools had mechanical ventilation installed on average 8 years before data collection started. There was a large variation with the installation year of each ventilation system, with relatively new systems installed not more than 3 years ago, to systems which were installed 20 years ago. A similar picture emerges for the average age of the school buildings. While the average building age in the sample was 16 years, one school building was relatively new at the time of data collection (3 years), while another school building was already built 41 years ago.

Table 2.1: Summary statistics

Panel A: Indoor environmental quality	Mean	Median	St. Dev.	Min	Max
Daily peak CO_2 (in ppm)	1447	1107	798	736	3990
Daily average CO_2 (in ppm)	1067	871	478	616	2788
Daily peak temperature (in °C)	22	22	1	20	26
Daily peak relative humidity (in %)	44	43	6	35	58
Size of classrooms in square meters	53	51	9	42	96
Number of schools with mechanical ventilation	6				
Age of ventilation system (in years)	8	5	7	3	20
Age of school buildings (in years)	16	6	13	3	41
Panel B: Absence days	**N**	**Mean**	**St. Dev.**	**Min**	**Max**
Total absence days	1215	3	3	1	22
Sickness absence days	1215	3	3	0	21
Non-sickness absence days	1215	1	2	0	21
Panel C: Test score distribution	**N**	**Mean**	**St. Dev.**	**Min**	**Max**
All test subjects	3024	112	41	25	200
Mathematics	694	108	39	31	200
Spelling	1279	120	42	40	200
Reading	1051	105	42	25	200

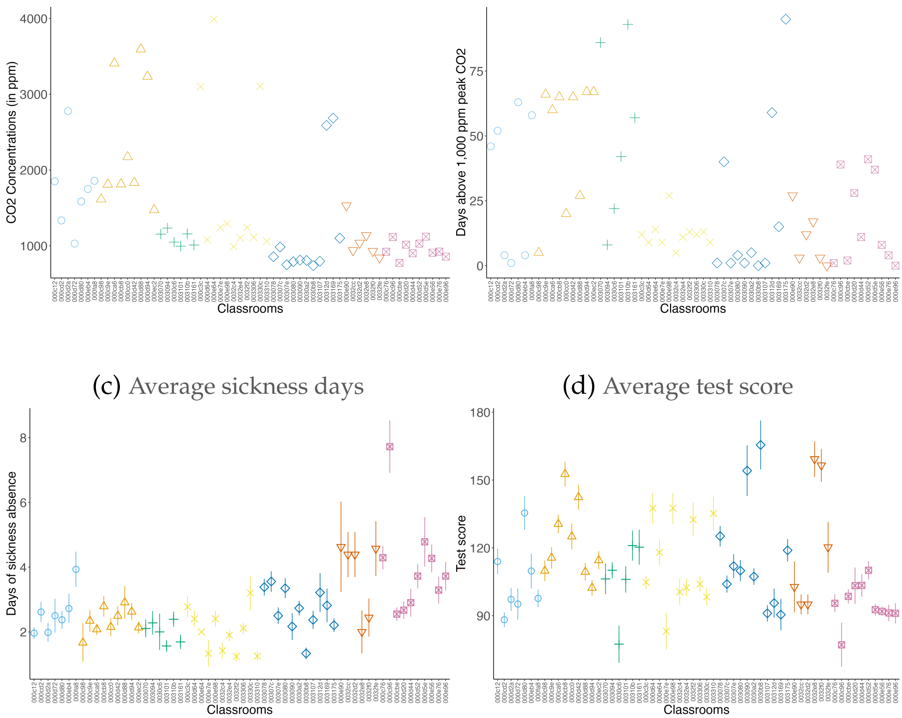
Note: The table shows the indoor environmental quality in classrooms and building characteristics of 7 schools in Panel A, the prevalence of absence in days in Panel B, and the distribution of test scores in Panel C. The summary of the indoor environmental quality parameters are based on the distribution of daily averages over the school year. The column "N" presents the sample size.

To further illustrate the variation in indoor air quality between the 60 classrooms, Figure 2.3 shows the daily average peak CO_2 concentrations in Panel 2.3a, and the amount of days for which the peak CO_2 concentrations exceeded 1,000 ppm in Panel 2.3b. The two panels illustrate a large variation in indoor air quality between the schools, indicated by different colour and point shapes, but also noticeable variation within schools.

Five schools had classrooms with average peak CO_2 concentrations of around 1,000 ppm and below (see Panel 2.3a), fulfilling indoor air quality guidelines [95]. However, some classrooms recorded daily average peak CO_2 concentrations which were 2-3 times higher than the 1,000 ppm threshold. The two panels 2.3a and 2.3b also show two school buildings with particularly poor indoor air quality, as indicated by an average peak CO_2 concentration of up to 2,000 ppm.

The classrooms in the sample of schools recorded a substantial number of days in which 1,000 ppm was exceeded. 11 out of the 60 classrooms recorded between 50 and 75 days in which children were exposed to peak CO_2 concentrations above 1,000 ppm. There were 4 classrooms where peak CO_2 concentrations did not exceed 1,000 ppm.

Figure 2.3: Indoor air quality, sickness days and test scores in classrooms



(a) Daily average peak CO_2 concentrations (b) Days of peak CO_2 above 1,000 ppm

(c) Average sickness days (d) Average test score

Note: Each point represents one classroom out of a total of 60 classrooms with the colour and shape of the point identifying the school. All schools expect for the blue school with the dot (○) have mechanical ventilation. Panel 2.3a shows the daily average peak CO_2 concentrations in a classroom over the two sample periods while panel 2.3b shows the number of days during the sample period exposed to more than 1,000 ppm peak CO_2 concentrations. Panel 2.3c shows the daily average sickness days in each classroom over the sample period. Panel 2.3d shows the average test score per class over both periods. The dot (●) indicate the mean and the bar indicates the 95% confidence interval around the mean.

The only school without mechanical ventilation is indicated in Figure 2.3 on the very left in light blue and the shape of the circle (○), showing that this school did not have strikingly higher CO_2 concentrations. This could indicate that natural ventilation in this school was frequently used, while it also shows that the schools with mechanical ventilation did not necessarily have better air quality, which could be due to insufficient or old ventilation systems.

Additionally, Panel B in Table 2.1 shows summary statistics for absence days. Children were, on average, 3 days absent during the 3-month learning period prior to the testing date, of which the average days of sickness-related absence was also 3 days. Children were absent for reasons other than sickness for one day on average, during the 3-month learning period. The sample size was 654 children, of which 319 were female (49%) and 335 were male (51%). The age ranged from 6 to 12 years, with an average age of 9 years.

Lastly, Panel C in Table 2.1 shows the distribution of the main test score and by test domain. Overall, a maximum test score of 200 points could be reached with an average achieved score of 112 points in the sample population. The lowest standard deviation in test scores was recorded for the mathematics domain with 39 points, while the standard deviation in test scores for spelling and reading was fairly similar at 41 and 42 points, respectively.

Figure 2.3 also shows the distribution of sick days in Panel 2.3c and the distribution of test scores in Panel 2.3d. The figures show a large variation of sick days and in average achieved test scores between schools and classrooms, but also a wide variation within classrooms, indicated by the bars around the points.

Notably, the classrooms with a particularly high rate of sick absence days, on the right side of Panel 2.3c, did not particularly record high daily average peak CO_2 concentrations in Panel 2.3a. However, Panel 2.3b shows that these classrooms exceeded the 1,000 ppm concentration threshold for several days.

2.3.2 Indoor air quality, sickness absence and test scores

Table 2.2 shows the results of the mediation analysis described in section 2.2.2. The first column regresses achieved test scores on average peak CO_2 concentrations during the 3-month learning period prior to the testing date, as described in Equation 2.1.

Table 2.2: Indoor air quality, sickness absence, and test scores

	DV: Test score	DV: Sickness absence	DV: Test score
	(1)	(2)	(3)
Daily peak CO_2 (z-score)	-0.369^{***}	0.073	-0.369^{***}
	(0.107)	(0.093)	(0.107)
Days of sickness absence (z-score)			0.002
			(0.042)
Daily peak temperature (z-score)	0.014	−0.053	0.014
	(0.077)	(0.147)	(0.078)
Daily peak relative humidity (z-score)	0.334^{*}	−0.186	0.335^{*}
	(0.149)	(0.236)	(0.152)
Daily peak noise (z-score)	−0.015	0.028	−0.015
	(0.104)	(0.127)	(0.104)
Class size	−0.027	−0.012	−0.027
	(0.025)	(0.041)	(0.025)
Class size^2	0.000	0.000	0.000
	(0.000)	(0.001)	(0.000)
Fixed Effects			
Classroom	Y	Y	Y
Testing period	Y	Y	Y
Child	Y	Y	Y
Test domain	Y	N	Y
Years of schooling	Y	N	Y
Observations	3,024	1,215	3,024
R^2	0.780	0.872	0.780
Adj. R^2	0.713	0.705	0.713

Note: The dependent variable (DV) in column (1) and column (3) is the standardized test score (z-score). The dependent variable in column (2) is the standardized sickness absence days (z-score). The model for column (1) is described in details in equation 2.1, for column (2) in equation 2.2 and for column (3) in equation 2.3 in section 2.2.2. All models include fixed effects on child, classroom and testing period. The models in column (1) and column (3) additionally include fixed effects on test domain (spelling, math, reading) and years of schooling. Clustered standard errors at the classroom by period level are shown in parentheses and significance levels are indicated as $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

The results indicate a significantly strong ($p < 0.001$) and negative impact of elevated CO_2 concentration in the classroom on a child's test score. A one standard deviation increase in peak CO_2 concentrations, corresponding to 798 ppm in our sample, leads to a 0.369 standard deviation decrease in test score, which is a fairly large effect size. In our sample, this would correspond to 15 out of 200 points lower, or a 7.5% decrease of points, in the exam score.

Column (1) controls for the impact of temperature, relative humidity, noise, and class size, showing that only relative humidity has a positive effect on test scores ($p < 0.05$). A one standard deviation increase in relative humidity, corresponding to a 6% increase in humidity levels, leads to a 0.334 increase in test scores, or approximately 13 points more in the test score. This model accounts for variation between classroom, testing period, child, testing domain and years of schooling of a child by adding respective fixed effects.

Column 2 in Table 2.2 regresses sick days during the 3-month learning period on daily average peak CO_2 concentrations, temperature, relative humidity, noise and class size. This model corresponds to Equation 2.2, described earlier. The analysis did not record a significant effect of peak CO_2 concentrations, as a proxy of indoor air quality, on sickness absence, nor did one of the other parameters predict sickness absence. Thus, controlling for variation in classrooms, testing period, and child with fixed effects, a mediation effect of sickness cannot statistically be confirmed.

Column 3 shows the results of the model described in Equation 2.3, which is similar to the model in column 1, except that test score is regressed on sickness absence as well as peak CO_2. Comparing Columns 1 and 3, the effect of indoor air quality, in terms of daily average peak CO_2 concentrations, stays persistent in both magnitude and significance level. Additionally, sickness absence was not a significant predictor of test scores. Supplementary Table A2 shows the regression of test scores on sickness absence excluding the variable of peak CO_2 concentrations. Once we control for variation between children, absence of any form did not significantly affect test scores, even when

CO_2 as confounder is excluded. Thus, sickness absence does not appear to explain the relationship between indoor air quality, measured by CO_2 concentrations, and test scores. These findings cannot confirm the initial hypothesis of a mediation effect of sickness absence.

2.3.3 Sensitivity analysis

In order to further analyse the results shown in section 2.3.2, a sensitivity analysis with several model specifications was conducted, to examine how the statistical significance and magnitude of the relationship between sickness absence, CO_2, and test score differ across a variety of model specifications.

Table 2.3 presents different specifications for the model described in Equation 2.3, which regresses test scores on daily average peak CO_2 concentrations and sickness absence during the 3-month learning period before the testing date. Columns 1 to 4 replicate the analysis by gradually adding fixed effects to control for variation across classrooms and testing periods (Column 2), test domains and years of schooling (Column 3), and between children (Column 4).

The analysis shows that after adding fixed effects for classroom and testing period, the initially positive association between CO_2 concentrations and test scores (0.124 standard deviations, $p < 0.05$, in Column 1) becomes negative. This supports the hypothesis of a negative impact of indoor air quality on test scores. Furthermore, this negative relationship between peak CO_2 concentrations and test scores remains persistent in Columns 5 and 6, where only non-sickness related absence or total absence are included in the model, respectively.

Notably, when a fixed effect for children is added in Column 4, the R^2 substantially increases. Before adding a fixed effect for children, the model in Column 3 explains only 21% of the variation in test scores. However, once variations between children are controlled, the model explains 78% of the variation in test scores. This makes the model with a child fixed effect the dominant model, as it applies a longitudinal analysis that follows the same child over time, exposed to different indoor air quality conditions.

Furthermore, this specification analysis shows that, before controlling for variation between children with a child fixed effect, sickness absence during the 3-month learning period significantly and negatively impacts test scores ($p < 0.01$). Column 3 indicates that a one standard deviation in sick days, equivalent to 3 additional days of absence, reduces test scores by 0.063 standard deviations, or about a 2.5 point reduction in the test score. This effect is fairly small, reducing test scores by just 1.25% of the overall achievable test score of 200 points. It is also much smaller than the effect of peak CO_2 on test scores in the related model in Column 3 (-0.202, $p < 0.05$). This model controls for variations between classrooms, testing period, testing domain, and years of schooling. However, once a child fixed effect was added, the impact of sickness absence on test scores becomes insignificant ($p > 0.05$).

Supplementary Table A2 shows the same picture. When CO_2 is excluded as a predictor for test scores, sickness absence significantly explains test scores without adding a child fixed effect, with a relatively low explanatory power of just 3.5% for the model's R^2. After a child fixed effect, the effect of sickness absence becomes insignificant and the explanatory power in terms of the R^2 increases to 78%. Columns 4 and 5 in Table 2.3 show the results when regressing test scores on non-sickness related absence and total absence, respectively. The analysis shows that, independent of the inclusion of different absent days and its reasons, the effect of absent days on test scores stays insignificant, including all fixed effects indicated in Column 4.

Overall, this sensitivity analysis shows that the insignificant relationship between sickness absence and test scores is driven by controlling for variations between children, thus observing the same child over time. Given the R^2 of 0.780 after adding a child fixed effect, compared to 0.213 without a child fixed effect, this explains a major proportion of the observed variation in test scores.

Table 2.3: Sensitivity analysis of indoor air quality and absence on test score

	DV: Test score					
	IV: Sickness absence				IV: Non-sickness absence	IV: Total absence
	(1)	(2)	(3)	(4)	(5)	(6)
Daily peak CO_2 (z-score)	0.124*	−0.354***	−0.202*	−0.369***	−0.369***	−0.367***
	(0.055)	(0.069)	(0.087)	(0.107)	(0.108)	(0.106)
Days absent (z-score)	−0.105***	−0.061**	−0.063**	0.002	0.032	0.016
	(0.023)	(0.021)	(0.021)	(0.042)	(0.028)	(0.041)
Daily peak temperature (z-score)	0.042	−0.063	0.067	0.014	0.012	0.014
	(0.042)	(0.085)	(0.061)	(0.078)	(0.077)	(0.078)
Daily peak relative humidity (z-score)	−0.141	0.235	0.172	0.335*	0.321*	0.337*
	(0.079)	(0.150)	(0.091)	(0.152)	(0.152)	(0.148)
Daily peak noise (z-score)	−0.139**	−0.352**	−0.095	−0.015	−0.002	−0.011
	(0.048)	(0.116)	(0.088)	(0.104)	(0.105)	(0.101)
Class size	0.034	0.001	0.009	−0.027	−0.025	−0.026
	(0.023)	(0.019)	(0.026)	(0.025)	(0.025)	(0.025)
Class size^2	−0.000	0.000	−0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Fixed Effects						
Classroom	N	Y	Y	Y	Y	Y
Testing period	N	Y	Y	Y	Y	Y
Test domain	N	N	Y	Y	Y	Y
Years of schooling	N	N	Y	Y	Y	Y
Child	N	N	N	Y	Y	Y
Observations	3024	3024	3024	3024	3024	3024
R^2	0.043	0.187	0.213	0.780	0.780	0.780
Adj. R^2	0.041	0.169	0.190	0.713	0.713	0.713

Note: The dependent variable (DV) in all column is the standardized test score (z-score). Column (1) to (4) show the model described in equation 2.3, gradually adding fixed effects on classroom and testing period in column (2), testing domain and years of schooling in column (3) and a child fixed effect in column (4). Column (5) replaces the independent variable (IV) "Days absent" from days being absent due to sickness to days being absent for other reasons than sickness. Column (6) regresses all days of absence, due to sickness and non-sickness related, on test scores. Clustered standard errors at the classroom by period level are shown in parentheses and significance levels are indicated as $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

Furthermore, the impact of absent days persistently remains insignificant for different absence reasons. Additionally, the significantly negative association of indoor air quality, in terms of daily average peak CO_2 concentrations, is robust against different model specifications and fairly similar in its magnitude when gradually adding fixed effects to control for variations.

Lastly, Table 2.4 shows the model specifications for the impact of CO_2 on sick days. The analysis gradually adds fixed effects for classroom, testing period and child, starting without fixed effects in Column 1 and ending with a comprehensive set of fixed effects included in Column 4.

The findings show that, despite different model specifications, daily average peak CO_2 concentrations during the 3-month learning period prior to a testing date was not significantly correlated with sickness absence during this time frame. The insignificance stays robust across different model specifications, supporting the conclusion that sickness absence does not function as a mediator between indoor air quality and test scores in our sample. The model in Column 4, which includes all fixed effects, explains up to 87% of the observed variation in sickness absence days, as indicated by the R^2, while the model in Column 3, excluding a child fixed effect, explains only a small proportion of the variation (R^2 of 10%).

2.4 Discussion

This study investigates if sickness absence functions as a mediator to explain the relationship between indoor air quality and test scores. The findings confirm that ex-ante exposure to poor indoor air quality has a significantly negative effect on ex-post test scores. However, the main hypothesis that sickness absence explains this relationship cannot be confirmed. There is no significant association between CO_2 and sickness absence, and neither does sickness absence predict test scores. In this section, these findings will be discussed in the light of previous studies and potential study limitations.

Table 2.4: Sensitivity analysis of indoor air quality on sickness absence

	DV: Sickness absence			
	(1)	(2)	(3)	(4)
Daily peak CO_2 (z-score)	0.031	−0.012	−0.009	0.073
	(0.043)	(0.088)	(0.092)	(0.093)
Daily peak temperature (z-score)	−0.009	0.003	0.005	−0.053
	(0.031)	(0.088)	(0.088)	(0.147)
Daily peak relative humidity (z-score)	−0.147**	−0.051	−0.067	−0.186
	(0.056)	(0.062)	(0.100)	(0.236)
Daily peak noise (z-score)	0.068	0.028	0.032	0.028
	(0.040)	(0.060)	(0.070)	(0.127)
Class size	−0.014	−0.021	−0.021	−0.012
	(0.025)	(0.026)	(0.026)	(0.041)
Class size^2	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.001)
Fixed Effects				
Classroom	N	Y	Y	Y
Testing period	N	N	Y	Y
Child	N	N	N	Y
Observations	1215	1215	1215	1215
R^2	0.015	0.098	0.098	0.872
Adj. R^2	0.010	0.047	0.046	0.705

Note: The dependent variable (DV) is the standardized sickness absence days (z-score) during the three months learning period prior to the testing date. Column (1) shows the model described in equation 2.2, but without any fixed effects. Column (2) adds a fixed effect on classroom, column (3) adds an additional fixed effect on testing period and column (4) an additional fixed effect on child. Clustered standard errors at the classroom by period level are shown in parentheses and significance levels are indicated as $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

Indoor air quality and test scores: Existing literature confirms a negative impact of indoor air quality on school performance and cognitive performance of school children [385]. This negative relationship is repeatedly reported using a variety of metrics to estimate indoor air quality, including average CO_2 concentrations [383, 382], peak CO_2

concentrations [280], and the difference between outdoor CO_2 and indoor CO_2 concentrations to determine ventilation rate [242, 158]. Wargocki et. al. (2020) [385] summarized 37 existing studies, indicating a 5% increase in test performance for a decrease of CO_2 concentration from 2,300 ppm to 900 ppm. Our analysis shows a 7.5% increase in test score for a 798 ppm reduction in peak CO_2 concentrations, showing that children in our sample responded much stronger to a change in indoor air quality, as compared to the average effect size in previous work. Nevertheless, our results were expected to be in line with previous evidence, confirming the negative impact of indoor air quality on academic achievement.

The recorded effect size of 0.369 standard deviations for a one standard deviation change in CO_2 concentration highlights a significantly stronger impact of indoor air quality improvement on academic achievement compared to other common school policy measures. For instance, a meta-analysis on the effectiveness of class size reduction in improving school performance reported an effect size of only 0.2 standard deviations [342]. Additionally, teacher quality appears to play a crucial role. If class size reduction necessitates the hiring of less qualified teaching staff, the benefits of this measure on learning outcomes may be substantially diminished [182]. A related study on school building renovations aimed at improving indoor air quality and academic performance further suggests that enhancing indoor air quality may be a more cost-effective and impactful strategy for improving school performance than reducing class sizes [348].

Our study specifically confirms the impact of frequent exposure to specific indoor air quality conditions on learning abilities prior to the actual testing date. While past laboratory studies measure the immediate effect of exposure to poor indoor air quality, in terms of high concentrations of air pollutants, on cognitive performance [98], our analysis considers the indoor air quality that children were exposed to during the learning period. Their test scores can therefore be considered as a measure of their learning progress. Our analysis reveals that frequent exposure to an insufficiently ventilated room with poor indoor air quality consistently harms learning, and ultimately academic achievement.

Sickness absence as a mediator: Considering long-term effects allows the possibility of multiple pathways by which exposure to elevated air pollutant concentrations can harm learning outcomes. While it is assumed that an effect from immediate exposure could be due to a heightened state of physiological stress [403], Wargocki and Wyon (2017) [380] propose that sickness absence is an additional mechanism that drives the long-term effect of indoor air quality exposure on performance. The aim of our study is to investigate this hypothesis, confirming whether sickness absence, in part or entirely, explains the negative impact of indoor air quality on test scores. However, we cannot confirm a mediating role of sickness absence based on our analysis. Rather, our results indicate that indoor air quality directly affects test scores, independent of sickness absence.

Notably, our results neither support or reject the hypothesized mechanism of immediate physiological stress during time of exposure [403, 98], leading to a recurring impairment of cognitive performance, and ultimately reducing long-term learning abilities. If children cannot concentrate well every day while in school, then even a small reduction in cognitive performance can accumulate to a substantial impact on academic achievement in the long-run. Therefore, exposure time and frequency play a crucial role in the overall impact, which has already been observed in laboratory studies [98, 185]. As a consequence, marginal changes in indoor air quality conditions, which might not lead to an immediate, significant reduction in cognitive performance, can still be harmful if exposure occurs frequently. Furthermore, Wargocki and Wyon (2017) [380] suggest that factors other than physiological stress (not examined in this study), such as acute health symptoms, reduced attention, and low motivation, can all potentially explain the impact of indoor air quality on school performance.

Considering earlier evidence, assuming a mediating role of sickness absence seems to be plausible. Previous studies associate low ventilation rates with an increased number of sick days among school children [340, 241, 137, 91]. CO_2 itself may be an important factor rather than just a proxy for indoor air quality, as the accumulation of CO_2 can increase the survival rate of airborne viruses [152]. This would explain why proper ventilation of indoor spaces reduces the risk of airborne infections [272]. Therefore, it seems contradicting that our analysis did not find a relationship of CO_2 concentrations with sickness absence, despite using various model specifications. However, using a child fixed effect allows us to follow the same child over time, in a longitudinal design, while previous studies applied cross-sectional examinations.

Regarding the sensitivity analysis of indoor air quality on sickness absence, it is important to rule out any reverse causality between CO_2 concentrations and absence rate, leading to an endogeneity problem. Humans are the main source of indoor CO_2 accumulation, since CO_2 is exhaled as a byproduct of human metabolism [291]. Therefore, the accumulation of CO_2 in a room is highly dependent on occupancy rate per room size (keeping ventilation rate unchanged) [292]. If more children are absent, this could affect CO_2 accumulation, thus CO_2 concentrations and absence can be reversely correlated. A statistical approach to account for reverse causality is to use an instrument variable [287], such as the presence of mechanical ventilation. However, six of the seven schools in our sample had mechanical ventilation in classrooms, thus the variation of the presence of mechanical ventilation was too low to allow for an instrument variable approach.

However, in our study design, we considered continuously measured daily peak CO_2 concentrations, averaged over the 3-month learning period, and sickness absence during this period. Children in our sample were on average 3 days absent within these months, while the CO_2 concentrations were averaged over a period of approximately 90 days. Our indoor air quality metric is therefore representing the equilibrium CO_2 concentrations in a classroom, which makes it less sensitive to daily variation in occupancy rate and reduces the influence of a possible reverse causality problem.

A difference of our analysis compared to previous work is the sample size of only 60 classrooms. Previous studies included between 144 and 434 classrooms [340, 241, 91]. However, these studies use absence counts at classroom levels as an outcome variable, while we consider individual sick days per child, using a child fixed effect to follow the same child over both test periods. Thus, the sample size in previous studies, measured by number of classrooms, needs to be compared with our sample of 654 children for which we have individual absence data.

Existing studies did not apply a child fixed effect to follow the same child longitudinally for different levels of indoor air quality exposure, as done in our study. Therefore, we can control for any within-individual differences which can explain random variations in sickness absence, showing that if the same child is exposed to different air quality conditions, the number of sickness days did not change as a response to changing exposure to indoor air quality conditions.

Notably, our data includes one academic year with two testing periods. The absence of a significance association of CO_2 with sickness absence can simply be due to the short period observed in our data, which does not provide enough within-child variation of CO_2 exposure to allow an accurate estimation after applying a child fixed effect. To illustrate the conditional variation, Appendix Figure A1 shows a histogram of the residuals from regressing daily peak CO_2 concentration on the child fixed effect. The figure shows that a notable variation of within-child CO_2 exposure can be recorded, supporting the robustness of our fixed effect approach. Nevertheless, future research should include a longer time frame, including several school years, to allow for a large exposure variation within a child when conducting a longitudinal, intra-individual analysis.

Sickness absence and test scores: Our analysis could not reproduce a significant effect of absence on test scores, at least not after applying a child fixed effect. Model specifications without controlling for the variation between children show a negative effect of increased sickness absence on achieved test scores, as shown in previous work [191, 199, 198, 253]. However, a possible explanation for the lack of statistical significance in our sample could be that there seems to be a threshold of a certain number of absence days, after which it starts to affect academic achievement [191]. In our sample, the average number of sick days is just 3 days during the 3-month learning period, thus it is possible that children in our sample were simply not absent enough to lead to any significant effect on test scores.

Possible role of teaching quality: Our analysis has an important limitation that could not be addressed with the given dataset. While the mediation analysis applied, based on Baron and Kenny (1986) [27], is widely used in the literature to identify potential mediation effects, Imai et al. (2011) [178] highlight the limitations of this approach for investigating causal mechanisms. Their paper introduces the sequential ignorability assumption, which is essential for deriving causal inferences. This assumption requires, first, that the treatment is independent of the potential mediator and the outcome variable. In our context, this means that the distribution of exposure to indoor air quality should be independent of the distribution of sickness absence and test scores. In other words, CO_2 concentration, as a determinant of indoor air quality, needs to be exogenous. Furthermore, the sequential ignorability assumption also requires that no unobservable factor exists which is influenced by the treatment (indoor air quality exposure) and simultaneously affects the mediator (sickness absence).

Regarding the exogeneity of CO_2 concentration, it can be argued that teacher and student behaviour, such as regularly opening windows to ventilate the classroom, influences indoor air quality. Consequently, CO_2 concentration is an endogenous variable. In our analysis, we use a child fixed effect to account for any child-specific behaviour that might impact indoor air quality, thereby strengthening the robustness of our results. However, as in previous studies on this topic [385], we lack data on teacher or teaching quality, which prevents us from applying a teacher fixed effect to control for teacher-specific behaviour. It can be assumed that particularly engaged teachers deliver higher teaching quality, which positively affects test scores, and that these teachers are also more likely to pay attention to air quality by frequently ventilating the classroom. In such cases, teaching quality would influence both indoor air quality and test scores, making indoor air quality a dependent factor of teaching quality.

Considering teaching quality also allows for another possible causal connection between indoor air quality and academic achievements of school children, as already proposed in former work [385]. Numerous studies have shown negative effects of poor indoor air quality on cognitive performance and work performance in office workers [98]. Therefore, poor classroom air quality can potentially also reduce cognitive performance of teachers, leading to lower teaching quality and ultimately worse learning outcomes of pupils. Furthermore, a relationship of indoor air quality and sickness absence would not just affect children, but also teachers, potentially leading to increased sickness absence of teachers, which in turn affects learning quality of children.

In contrast, a previous study confirmed a positive effect of the presence of mechanical ventilation on test scores [280]. Mechanical ventilation is unlikely to be influenced by student or teacher behaviour, yet it has a significant impact on indoor air quality. Therefore, the presence of mechanical ventilation can be considered an exogenous proxy for indoor air quality. However, as already mentioned earlier, the schools included in our study do not provide sufficient variation in the presence of mechanical ventilation to allow for a robustness analysis using mechanical ventilation as an alternative proxy for indoor air quality.

In our analysis, we applied a classroom and test domain fixed effect. While we do not have data on which class had which teacher, assuming that the same teacher taught the same test domain to the same class throughout the academic year, we would also partly control for teacher-specific factors in our analysis. Nevertheless, future research should collect data on teaching quality and teacher behaviours to shed more light on multiple possible mechanisms explaining the relationship of indoor air quality and learning outcomes in schools.

The second part of the sequential ignorability assumption posits that no unobserved factor exist, which is influenced by indoor air quality and, in turn, affects sickness absence. Confirming this assumption is important for providing a robust estimation of a significant mediation effect. In our analysis, we did not find any evidence of a significant mediating role of sickness absence in the relationship between indoor air quality and test scores. A potential reason for the absence of significance could be an unobservable factor which influences the mediator sickness absence in the opposite way than CO_2 exposure affecting sickness absence. Opposing effects could equal each other out, leading to an insignificant relationship of CO_2 on sickness absence if not controlled for the unobservable factor. Therefore, we cannot fully confirm that sequential ignorability is fulfilled in our analysis, given the limited data we have. Further research is needed to explore other potential mechanisms through which indoor air quality impacts academic achievement in schools. These mechanisms may involve sickness absence as a secondary mediating factor or alternative pathways, for example via teaching quality, that have not been identified yet.

2.5 Conclusion

This study investigated the ex-ante impact of exposure to poor indoor air quality, determined by elevated concentration levels of carbon dioxide (CO_2), on ex-post test scores on standardized exams of primary school children. Children who were exposed to poor indoor air quality, during the 3-month learning period prior to the testing date, achieved significantly lower test scores. Furthermore, this study did not confirm the hypothesis that increased sickness absence explains the negative relationship between indoor air quality and test scores. Classroom CO_2 concentrations were not significantly associated with sick days of children. Additionally, sickness absence, during the 3-month learning period, did not significantly influence subsequent test scores. Therefore, these findings suggest that indoor air quality directly affects academic achievement in the form of test scores, independent of sickness absence as a potential mediator of this relationship.

Overall, our findings have important policy implications for school boards, because they show the importance of providing good indoor air quality to optimize the academic performance of primary school children. Interventions which aim to reduce sickness absence and improving academic achievement through a healthy lifestyle have a major shortcoming if they do not include improvements of the classroom indoor environment in their intervention plan. Policy makers that aim to improve the learning outcomes of school children should therefore apply a holistic approach. They should focus on children-specific health and learning improvements and investing in the school environment to provide sufficient ventilation of indoor spaces. Importantly, investing into improving the school built environment is not just improving the academic achievement of children, but it has been shown to be cost-effective on a macroeconomic level [384, 381].

3

Indoor environment, student satisfaction, and performance: Evidence from a large-scale field experiment in university classrooms

Abstract

This study examines the effect of a renovated university building with optimized indoor environmental quality on satisfaction and learning performance of students. We conducted a single-blind, randomized treatment-control experiment to compare the satisfaction and performance of two student cohorts over 14 weeks: one in a renovated, WELL-certified university building, and the other in a building without recent renovations. Indoor air quality and thermal conditions were measured in both buildings using a sensor network, confirming that the renovated building had lower concentrations of air pollutants and a more stable indoor thermal environment. Students were more satisfied with the interior design of the renovated building, and reported more support from the indoor environmental quality in that building, believing that it positively affected their self-assessed performance in class. However, we did not find statistically significant differences in course grades between the student cohorts exposed to the two different buildings, confirming students' belief of a positive effect of the indoor environment on their learning performance.

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3.1 Introduction

Indoor environmental quality, which encompasses a range of factors, including indoor air quality, lighting, thermal condition, acoustics, aesthetics, and ergonomics [4], has emerged as an important factor influencing the cognitive performance, health, and well-being of building occupants [376, 260, 12]. Several studies document that poor indoor environmental quality can cause health complaints among occupants [251, 390, 55] and increase the risk of respiratory symptoms [223]. Indoor environmental quality can also affect cognitive performance of adults [98] and school performance of children [51, 50].

Given these findings, there is a growing emphasis on improving indoor environmental quality in educational settings to enhance student well-being and learning outcomes, especially after the COVID-19 pandemic [101]. Academic achievement in school and university is an important determinant for productivity and income potential in adulthood [295, 38]. Educational development improves economic mobility, reduces inequality, and promotes overall economic growth [24, 155]. This potentially makes indoor environmental quality in classrooms an important factor in learning, and ultimately, accumulation of human capital.

Despite the importance of indoor environmental quality in educational buildings, there remains a gap in empirical evidence quantifying the actual impact of indoor environmental quality improvements on student satisfaction and learning outcomes in higher education settings. Past studies on occupant satisfaction were conducted in an office setting, but it is not clear whether improved indoor environmental quality conditions lead to higher satisfaction levels [323, 129]. Moreover, studies on indoor environmental quality often did not consider non-environmental quality factors, such as interior design and general appearance of the indoor environment. Aspects such as ergonomics and aesthetics can also influence the satisfaction with the indoor environment and general well-being, beyond the effects of indoor air quality, temperature, or lighting conditions [126, 323]. Building certification schemes like WELL and Fitwel incorporate a holistic approach of the indoor environment [237], however the evidence on the effectiveness of these schemes on occupants' well-being and objective improvements of the indoor environmental quality is scarce and exist only for office workers [211, 212, 189].

Furthermore, most research on the effect of indoor environmental quality on academic performance is performed in primary and secondary education [385, 379]. Evidence shows that poor indoor air quality, thermal discomfort, insufficient lighting, and background noise, can reduce cognitive performance and learning outcomes, including course grades [376]. These effects are typically documented in field studies on primary and secondary school children [280, 284, 50].

However, there is a lack of evidence on how the indoor environment affects college and university students. University education differs from primary and secondary education due to the organizational structure and complexity of the learning material. Exposure to the classroom environment is shorter and less frequent for university students, compared to primary and secondary education. In addition, college and university students represent a distinct population in terms of age and lifestyle habits. These differences are important to consider, because the complexity of cognitive tasks, exposure duration and frequency, and population differences can moderate the effect of indoor environmental quality [98, 286]. Thus, evidence on the impact of indoor environmental quality on satisfaction of office workers and on learning performance in primary and secondary schools cannot be generalized to a university setting.

Meanwhile, there is a widespread trend to renovate and retrofit the existing building stock [115, 172], primarily focusing on enhancing energy efficiency, addressing climate concerns [294]. Investments in renovating and modernization of school and university buildings substantially contribute to public spending on school infrastructure. In the USA, more than $60 billion is spent annually every year on improving schools, making it the second largest public investment in the country [81, 273]. In the European Union, public expenditure on schools accounts for up to 3% of the EU GDP [113]. However, it is unclear where the money should be spent to effectively improve learning, in primary and secondary or rather in higher education.

The trend towards a more energy efficient and sustainable school infrastructure presents an opportunity to improve the quality of the indoor environment in educational buildings, by integrating indoor environmental quality improvements into climate and energy-related renovation efforts. Furthermore, many energy efficiency renovations directly enhance indoor environmental quality, such as improvements of lighting and heating, ventilation, and air conditioning systems [213]. By integrating indoor environmental quality enhancements into these energy-focused renovations, educational institutions have the opportunity to create learning environments that not only are more efficient in their operations, but also promote the learning, health, and well-being of students and teachers.

To close these research gaps, our study investigates how a holistic building renovation, and improving indoor environmental quality and interior design affects satisfaction with the classroom environment and learning outcomes of university students. A randomized treatment-control field experiment was conducted, in which a cohort of first-year Bachelor students was split into one half with classes in a conventional university building, and the other half assigned to the newly renovated and refurbished building. This renovated building is certified with the WELL certificate following its improved energy efficiency standards and indoor environmental quality conditions with the aim of supporting the health and well-being of occupants [180]. Students' self-reported satisfaction with the indoor environment, their perceived impact of the indoor environmental quality on learning performance, and their achieved course grades, were compared between the treatment and control group. Based on previous literature on occupant satisfaction in office buildings [12, 212] and primary and secondary education on learning outcomes [50], this study investigates the hypothesis that university students who have their classes in the renovated, WELL-certified building are more satisfied with the interior design and the indoor environmental quality and achieve higher course grades, compared to students in the control building.

Indoor environmental quality measures show lower concentration levels of air pollutants and a more stable thermal environment in the treatment building. The empirical analysis confirms that students perceived the indoor environment in the renovated building as a more pleasant experience and attributed a positive effect on their self-assessed performance in class. However, contrary to their beliefs, students in the renovated building did not achieve a significantly different course grade, than students from the conventional building.

This paper is structured as follows. Section 3.2 describes the buildings, the experimental setup, and the data collection procedure. In addition, a description of the statistical model is included. Section 3.3 provides descriptive statistics of the indoor environmental quality measures in both buildings and the results of the statistical analysis. Section 3.3 also shows how the renovated building influenced students satisfaction with the interior design and indoor environmental quality and course grades. This section is followed by a discussion in section 3.4, which contextualizes the findings in light of previous evidence. The paper concludes in section 3.5.

3.2 Methods

This field study took place in two buildings at Maastricht University's School of Business and Economics during Autumn 2022 and Spring 2023. The study includes the two buildings of the school, of which one is a newly renovated, refurbished and WELL-certified building (treatment condition). The treatment buildings' renovation was finalized in

2020. During the COVID pandemic, the building was mostly unoccupied and the ventilation was set at maximum rates due to COVID regulations. Thus, volatile organic compounds, which are often elevated shortly after renovation [166], were assumed to be removed before students entered the building for their classes. The control building was renovated and refurbished in the early-2000s, without any specific focus on indoor environmental quality. For the purpose of this study, the first year cohort of 1,256 students was randomly split into two groups, of which one group had their classes in the treatment building and one group had their classes in the control building.

3.2.1 Study setup

Teaching system at Maastricht University

The educational system at Maastricht University follows the problem-based learning approach [337]. The majority of teaching takes place in small tutorial meetings with a maximum of 15 students plus a teacher. Students attend their 2-hour tutorial meetings twice a week, for each course for a 7-week long period. During each tutorial meeting, students work on a case study, which stimulates discussions and knowledge exchange between them.

Exams are written in the 8^{th} week. The final course grade is a weighted average of partial grades from the exam, in-class presentations, and course assignments during the 7-week teaching period. The exam is taken inside a large hall outside the university campus, which is not part of our measured sample of rooms[1].

Teachers explicitly do not fulfill the role of a lecturer during the tutorial meetings, but guide students during the learning process and

[1] All students are exposed to the same conditions when writing their exam - in the same room at the same day. As such, this study does not focus on the concurrent effect of indoor environmental quality on student performance.

discussions, ensuring they cover the learning objectives. In each tutorial session, one student is selected as the chairman or chairwoman, in which case they must lead the tutorial group through the answers for the learning objectives. Students derive these answers via self-study during the time between the tutorial meetings.

Therefore, education at Maastricht University is organized in small groups, instead of large groups attending a lectures, which is often the case for university education. However, university students spend less time per week in classrooms compared to primary and secondary pupils. In our case, the students had 2-hour long tutorial meetings for two courses each, twice per week. The teacher plays a less prominent role.

Description of the buildings

The treatment group had their tutorial meetings in a newly renovated building (henceforth: treatment building). The structure of the building is from 1919 when it was constructed as army barracks. It has been in use by the university since 2020 after major renovations (see Figures 3.1a and 3.1c).

The control group had their tutorial meetings in an existing university building (henceforth: control building), which was built as a monastery in the 1930s and was renovated in the early 2000s. It has been in use by the university since the 1970s (see Figures 3.1b and 3.1d).

Both buildings provide similar-sized tutorial rooms with a maximum of 15 students assigned to a tutorial group. Classrooms were distributed over two levels in the treatment building and three levels in the control building. The buildings are located 500 meters apart from each other. Both buildings each face a park with trees and grass on one side of the building, and a busy road with car traffic on the other side.

Figure 3.1: Treatment and control building

(a) Treatment building from the outside

(b) Control building from the outside

(c) Treatment building from the inside

(d) Control building from the inside

Note: The circle in Figure 3.1c and 3.1d indicates the position of the indoor environmental quality monitor which was installed for the purpose of this study. Figure 3.1a and 3.1c show the treatment building and a typical classroom in it, respectively. Figure 3.1b and 3.1d show the control building and a typical classroom in it, respectively.

The major difference between the two buildings is the renovation and refurbishment of the treatment building. The treatment building is equipped with a new HVAC (heating, ventilation and air conditioning) system. A balanced demand-controlled ventilation system was installed to adjust the ventilation rate for different occupancy rates, based on real-time measured carbon dioxide (CO_2) concentration, ensuring low concentrations of CO_2, volatile organic compounds and fine particles. The temperature is automatically controlled via heating and cooling, using a Building Management System.

As part of the renovation, the treatment building was certified with the WELL Silver standard [180]. The WELL standard consists of four levels of which the Silver standard is the third highest (other levels include Bronze, Gold and Platinum certification). This certification scheme is different from other building certifications such as LEED and BREEAM; its scoring system emphasizes the creation and maintenance of a healthy indoor environment, fostering the well-being of occupants [299].

With regards to indoor environmental quality, the treatment building received WELL credits for meeting indoor air quality standards, such as low levels of CO_2, air pollutants, having a demand-controlled ventilation, and reduced exposure to outdoor air pollution. Credits were also awarded for reducing the emissions of volatile organic compounds and semi-volatile organic compounds from the materials used in the building. Options for users to open windows are limited in the treatment building, to avoid any disturbances for the HVAC system.

Furthermore, WELL credits were also awarded for ensuring adequate light exposure, with high levels of visual acuity, lighting for the circadian rhythm and control of solar glare and glare from electric light. For thermal comfort, the treatment building received WELL credits for monitoring thermal parameters and ensuring thermostat control, but no attempts were made to enhance thermal comfort. Credits were also given for managing and limiting background and outside noise, and providing acoustical privacy.

The control building does not have any specific certification for energy efficiency or for maintaining a healthy indoor environmental quality. Some classrooms are equipped with mechanical ventilation, radiators for heating, but no air conditioning. The investigated classrooms are also of different size and shape. Some rooms in our sample were added in recent years to extend the building and create more rooms, while other rooms are part of the original building shape.

In all classrooms, windows can be opened either fully or partially. Furthermore, the exterior wall insulation is less advanced than in the treatment building due to the previous renovations being more than 20 years ago. The furniture and interior design of the control building has been in use for several years.

Randomization procedure

The first-year cohort of the Business Economics and International Business programs, including 1,256 students[2], was randomly split into two groups: A treatment group with tutorial meetings in the treatment building, and a control group with tutorial meetings in the control building. Five courses were included in the study: During period 1, both programs followed the same two courses, which were Quantitative Methods I and Management of Organisation and Marketing. Quantitative Methods is a mathematically focused course where students are taught the basics of statistical calculations. The other course, Management of Organisation and Marketing, focuses on the transfer of knowledge with regards to the functioning of companies and management in a business context.

In period 2, students of both programs only followed one common course (Quantitative Methods II) and had a program-specific course next to it. Students of the Business Economics program followed the course Macroeconomics, where they learned the basic theories of macroeconomic models. Students of the International Business program followed the Strategy course, which aims to transfer knowledge about the concepts, frameworks, and analysis techniques of strategic decision-making for managers.

All courses consist of lectures every Monday in a lecture hall where no environmental measurements were conducted. The two-hour tutorial meetings took place from Tuesdays to Fridays. Each course consisted of two tutorial meetings per week, so students had four tutorial meeting hours per week, per course. The tutorial meetings started at four

[2]The exact number of students differ between courses due to including students who retook the course.

different times during the day, at 08:30 am, 11:00 am, 1:30 pm, or 3:30 pm. Teachers have several tutorial meetings per day, and an equal amount in both buildings within a day, as well as each course. This controls for possible variation in course grade due to teaching quality. Students and teachers were unaware of the study purpose and the monitoring of indoor environmental quality.

Ethical approval procedure

Ethical approval was given by the Ethical Review Committee Inner City Faculties (ERCIC) of Maastricht University, to conduct this study and to collect the described data, within a setting in which participants are unaware of the study purpose. The Ethical approval is stored under the identification number ERCIC-371-21-08-2022. The approval was provided on September 19^{th}, 2022, prior to data collection of student grades and the responses to the satisfaction questionnaire.

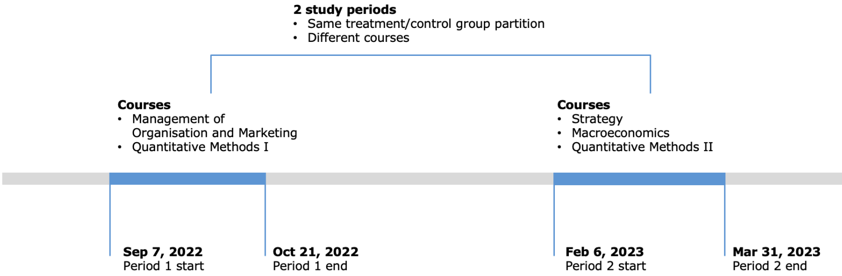
3.2.2 Data collection

Educational outcomes

Two terms during the academic year are included, both lasting 7 weeks of on-campus classes (see Figure 3.2 for a timeline). The first period took place from September 7^{th}, 2022 until October 21^{st}, 2022 (period 1). Exams were written during the week of October 24^{th}, 2022. The second measurement period took place from February 6^{th}, 2023 to March 31^{st}, 2023 (period 2). Exams for period 2 were made in the week of April 3^{rd}, 2023[3].

[3]There was one week of holidays in between (February 20^{th} to February 26^{th}) and no education took place on March 8^{th} and March 9^{th} due to an internal event at the university.

Figure 3.2: Timeline of data collection



Student performance is based on the final course grade as retrieved from the administrative system of the university. Individual characteristics of students, such as age and sex, could not be derived from the administrative system, which ensures that the data for the grades remains anonymous.

The grade was linked to a random subject number for each student, which we matched to the particular classroom and tutorial group. This allows us to relate the environmental data of each room to the final grades for every student of each tutorial group that had classes in each particular classroom. Student evaluation of the teacher's performance was collected as a measure of teaching quality.

Questionnaire about satisfaction of the indoor environment

Students answered the questionnaire about their satisfaction with the interior design and the indoor environmental quality as part of the usual course evaluation questionnaire they receive during the last week of tutorial meetings. They answered the questionnaire in class, during the last tutorial meeting. Thus, the answers are linked to the particular tutorial group and therefore the particular indoor environment of the classroom. However, student responses were anonymized and the answers to the questionnaire could therefore not be related to the grade of a particular student.

To determine satisfaction, we asked students on a 7-point Likert scale if they regularly had difficulty to concentrate in the tutorial room, rated with (1) for ″Never″ to (7) for ″Always″. Additionally, we collected information on whether students liked attending the tutorial meetings (1 for “not at all″ to 7 for “very much″), and whether they perceived the interior of the tutorial room as appealing (1 for “not appealing at all″ to 7 for “very appealing″), and finally, whether the interior of the classroom affected their mood and performance during the tutorial meetings (both with 1 for “negatively affecting″ to 7 for “positively affecting″).

We measured satisfaction with indoor environmental quality using an adapted version of the Berkeley's Center for the Built Environment questionnaire [398, 147]. The four questions asked the students how much they think the following parameters supported or hindered their ability to perform well during the tutorial sessions of the corresponding 7-weeks period: Air quality, lighting conditions, noise levels, and temperature. Students indicated their satisfaction on a 7-point Likert scale, ranging from (1) for ″Hinder″ to (7) for ″Support″.

Data on indoor environmental quality

The indoor environmental parameters of 31 classrooms for 324 tutorial groups were collected during the two teaching periods. This includes the concentration of CO_2, total volatile organic compounds, fine particular matter ($PM_{2.5}$), temperature, and relative humidity. These parameters were measured on a 5-minute basis, using commercially available Foobot SAT monitors (Foobot EnergyWise SAS, Luxembourg). The monitors were mounted on the wall at 1.5 meters above the ground (see Figures 3.1c and 3.1d).

Because of the dynamic nature of the classes, this height has been chosen as a balance between the standard height of 1.1 meter for sitting and 1.7 meter for standing activities, according to ASHRAE Standard 55 [22]. The monitors were not positioned close to a window, a ventilation outlet, or a door, ensuring that the air quality and temperature measurements were not affected by air flow and direct solar radiation. The monitor was validated and compared to other low-cost sensors [405].

The indoor environmental quality data was cleaned to only include the measurements during the time of the tutorial. Therefore, measurements during holidays, weekends, nights, and the 30 minute break between tutorial meetings were excluded from the dataset. Daily maximum and average outdoor temperature data in Maastricht during the two study periods for each day of class was derived from the *European Climate Assessment & Datasets* database (weather station ID: 168) [316].

3.2.3 Empirical strategy and statistical model

We investigated the effect of exposure to the treatment building on the study outcomes using the following fixed-effect regression model:

$$Y_{i,c,t,j} = \beta_1 Treatment_i + \tau_c + \lambda_t + \theta_j + \varepsilon_{i,c,t,j} \tag{3.1}$$

$Y_{i,c,t,j}$ represents a set of variables for student i for course c, who has the tutorial session in time-slot t, given by teacher j. Therefore, the tutorial group is identified by 3 fixed effects(c, t, and j). The dependent variables of the individual regression analysis are therefore:

- Whether the student feels supported to perform well in class - from air quality, light, noise, and temperature, indicated as 1 for "Hinder" to 7 for "Support";

- Whether the interior affects the student's self-perceived performance or mood, defined as 1 for "negatively affecting" to 7 for "positively affecting";
- Whether the student likes to attend the tutorial session, defined as 1 for "not at all" to 7 for "very much";
- Whether the student finds the tutorial room appealing, defined as 1 for "not appealing at all" to 7 for "very appealing";
- Whether the student feels difficulty to concentrate during the tutorial session, with 1 for "Never" to 7 for "Always";
- Student course grade, ranging from 1 for the worst to 10 for the best grade;
- The evaluation grade for the teacher given by the students, ranging from 1 for the worst to 10 for the best grade.

The outcome variable $Y_{i,c,t,j}$ is standardized and expressed in terms of standard deviations (z-score). The binary variable $Treatment_i$ is equal to *1* if student i is in the treatment group, and *zero* otherwise. As students and tutorial groups are randomly assigned to the new or old building, the coefficient β_1 captures the overall (causal) effect of the treatment. We used a fixed-effects approach to control for the course τ_c, the tutorial schedule λ_t (time of day), and which teacher θ_j hosted the tutorial group. Using this approach, we also correct for group size and room volume because each tutorial group had its meetings in the same room during the 7 week period for each course. Lastly, $\varepsilon_{i,c,t,j}$ is the error term that is clustered at the tutorial group level.

3.2.4 Treatment validation

To examine whether the randomization of students and teachers between buildings was successful, we compared the distribution of teachers and students between the treatment and control buildings. The randomized assignment of teachers and students is crucial to ensure that the findings are attributable to the building environment, rather than pre-existing disparities.

Panel A of Table 3.1 shows the distribution of teachers having their first tutorial group of the day either in the treatment or control building. Teachers for all courses in Period 1 exhibit a nearly even split between control and treatment building, indicative of a balanced approach to the initial building assignment. For period 2, teachers are only unequally distributed for the macroeconomics course with 20% starting in the control building and 80% starting in the treatment building, however only 10 teachers taught this course.

In Panel B, we illustrate the switching of teachers between buildings within periods, which is crucial to ensure a proper teacher fixed effect between tutorial groups of the same teacher. This switching is indicative of a robust randomization process, designed to mitigate potential biases arising from initial building assignments. This ensures a diverse exposure to both buildings that is independent of teaching quality on our outcome variables. Panel B of Table 3.1 shows that about half of the teachers switched between the buildings in a single day, and for period 2, over 90% of teachers had their tutorial meetings in both buildings each day.

Furthermore, the distribution and switching of students as shown in Panel C and Panel D of Table 3.1 further affirms the successful randomization. There was a nearly equal split between treatment and control groups for most courses, as shown in Panel C.

Panel D shows that in period 1, 65% of students were exposed to both buildings during the period, while for period 2, the treatment-control design was strictly maintained, with 99% of students having both their courses in the same building during this period. Between periods, 63% switched buildings while 37% experienced the same building in both periods for all courses.

Table 3.1: Distribution of teachers and students between buildings

	Control		Treatment	
Panel A: Distribution of tutors	Total	Percentage	Total	Percentage
Courses in period 1	#	%	#	%
Management of Organisation & Marketing	15	54	13	46
Quantitative Methods 1	16	53	14	47
Courses in period 2				
Macroeconomics	2	20	8	80
Quantitative Methods 2	15	50	15	50
Strategy	10	63	6	38
	No switch		**Switch**	
Panel B: Tutors that switched buildings	Total	Percentage	Total	Percentage
Courses in period 1	#	%	#	%
Management of Organisation & Marketing	17	61	11	39
Quantitative Methods 1	16	53	14	47
Courses in period 2				
Macroeconomics	1	10	9	90
Quantitative Methods 2	1	3	29	97
Strategy	1	6	15	94
	Control		**Treatment**	
Panel C: Distribution of students	Total	Percentage	Total	Percentage
Courses in period 1	#	%	#	%
Management of Organisation & Marketing	589	53	528	47
Quantitative Methods 1	604	53	530	47
Courses in period 2				
Macroeconomics	191	47	219	53
Quantitative Methods 2	521	50	517	50
Strategy	325	52	305	48
	No switch		**Switch**	
Panel D: Students that switched buildings	Total	Percentage	Total	Percentage
Within period 1	407	35	745	65
Within period 2	1,137	99	3	0
Between periods	464	37	792	63

Lastly, in order to check for internal validity, Appendix Table A3 investigates if sex and age of a student, day time of the tutorial classes, and the achieved grades of a student in period 1 significantly predict the building to which a student is assigned to in period 1 and 2, respectively. The regression analysis shown in Appendix Table A3 regresses a binary variable equals 1 for having classes in the treatment building, and zero for the control building, on the mentioned factors.

No significant association of sex, age, tutorial time or achieved grade in period 1 can be found on the likelihood to be assigned for classes in the treatment building. Therefore, the analysis statistically confirms that students were assigned to either the treatment or control building independent of these factors, confirming a successful randomization procedure.

3.3 Results

3.3.1 Indoor environmental quality in buildings

Before showing the results of the effect of the treatment on the study outcomes, this section illustrates if the indoor environmental quality in the treatment building was indeed different in terms of air quality and thermal conditions, as compared to the control building. Table 3.2 provides descriptive statistics of the indoor environmental parameters for each building per period. It can be observed that the average carbon dioxide (CO_2) concentration in the control building was significantly higher compared to the treatment building with a mean difference of 443 ppm (parts per million) in period 1 and 503 ppm in period 2. Additionally, the CO_2 concentration varied more between classrooms and over time in the control building, with 693 ppm in period 1 and 657 ppm in period 2, compared to 191 ppm standard deviation (period 1) and 141 ppm (period 2) in the treatment building. The total volatile organic compounds (TVOC) concentration indicates a similar picture, recording a mean TVOC concentration difference between both buildings of 425 ppb (parts per billion) in period 1 and 773 ppb in period 2.

Table 3.2: Summary statistics for environmental conditions

	Control				Treatment				
	Mean	St. Dev.	Min	Max	Mean	St. Dev.	Min	Max	t-test signf.
Panel A: IEQ in period 1									
CO_2 (in ppm)	1,212	693	383	4,952	769	191	387	1,731	$p < 0.01$
TVOC (in ppb)	1,090	783	6	5,490	665	342	9	2,984	$p < 0.01$
$PM_{2.5}$ (in counts/L)	9.6	10	0	111	1.8	1.5	0	18	$p < 0.01$
Temperature (in °Celsius)	20	2	14	30	21	1.2	18	25	$p < 0.01$
Relative humidity (in %)	62	8.4	40	86	57	7.2	39	74	$p < 0.01$
Panel B: IEQ in period 2									
CO_2 (in ppm)	1,207	657	397	4,992	704	141	386	1,499	$p < 0.01$
TVOC (in ppb)	1,565	1,090	8	8,798	792	486	7	7,500	$p < 0.01$
$PM_{2.5}$ (in counts/L)	11	12	0	108	4.2	4.3	0	47	$p < 0.01$
Temperature (in °Celsius)	18	1.4	10	22	20	1.1	16	24	$p < 0.01$
Relative humidity (in %)	53	9	27	77	45	7	28	63	$p < 0.01$
Panel C: Outdoor temperature	Period 1				Period 2				
	Mean	Sd	Min	Max	Mean	Sd	Min	Max	Test
Peak outdoor temperature (in °Celsius)	18	3.8	11	30	11	4.2	3.7	18	$p < 0.01$
Average outdoor temperature (in °Celsius)	13	3.4	8.6	22	6.6	4.5	-0.1	13	$p < 0.01$

Note: The table shows the descriptive statistics for the classroom indoor environmental quality (IEQ) aggregated per building for period 1 in Panel A and period 2 in Panel B. Additionally, the daily peak and daily average outdoor temperature are shown in Panel C. Column St. Dev. indicates the standard deviation. CO_2 indicates the concentration of carbon dioxide. TVOC indicates the total volatile organic compounds concentration. $PM_{2.5}$ indicates the concentration of fine particular matter. The last column indicates the significance of the difference in mean based on an independent t-test.

It is important to consider that freshly renovated buildings often emit high concentrations of volatile organic compounds from new materials. The concentration decreases over time given the ventilation of these indoor spaces with fresh outside air [166]. However, the treatment buildings' renovation was finalized in 2020 and due to the COVID-19 pandemic, no classes took place until Autumn 2022. During this time, ventilation rates were set at maximum rate due to COVID regulations. Thus, volatile organic compound concentrations, which is usually elevated after renovation and refurbishment, was already reduced when the study started.

Air pollution in terms of fine particular matter ($PM_{2.5}$) was also significantly higher in the control building and showed a higher maximum concentration as compared to the treatment building, as seen in Table 3.2. As for CO_2, only the treatment building meets the threshold of maximum indoor CO_2 concentration of 1,100 ppm set by the ASHRAE 62.1 building guidelines for indoor air quality and the threshold of 1,000 ppm indoor CO_2 set by the EU-based German Environmental Agency guideline in DIN EN 13779 [23, 95][4]. Overall, these measures show that the indoor air quality in the control building was worse than in the treatment building, due to higher concentrations of air pollutants.

Comparing thermal conditions between the two buildings, the average temperature slightly differed, but the control building showed a higher variation in temperature during use. The temperature range in the control building was 16° Celsius (29° Fahrenheit difference) in period 1, and 12° Celsius (22° Fahrenheit difference) in period 2, while the temperature range for the treatment building was only 7° Celsius (13° Fahrenheit difference) in period 1 and 8° Celsius (14° Fahrenheit difference) in period 2.

Relative humidity ranged substantially between both buildings

[4]ASHRAE standards 55 and 62.1 are commonly used building guideline issued by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

as well, however, less in the treatment building. None of the two buildings fulfilled the indoor temperature range of 19.4° to 27.8° Celsius (67° to 82° Fahrenheit), as recommended by the ASHRAE 55 standard [22].

Considering the difference between periods, the control building recorded similar CO_2 concentrations in both periods, and colder temperature conditions in period 2. However, total volatile organic compounds concentrations peaked at 8,798 ppb, much higher than in period 2, compared to 5,490 ppb in period 1, while the maximum CO_2 concentration between both periods in the control building differed only by 40 ppm. The difference in total volatile organic compounds concentrations between the two periods is even higher for the treatment building, with 7,500 ppb in period 2, compared to 2,984 ppb in period 1.

However, the indoor temperature in the treatment building remained relatively stable between both periods. The maximum and minimum temperature between the two periods differed by 1° Celsius (2° Fahrenheit difference) and 2° Celsius (3° Fahrenheit difference), respectively. In comparison, in the control building, the maximum temperature difference between the two periods was 8° Celsius (14° Fahrenheit difference) and minimum temperature difference was 4° Celsius (7° Fahrenheit difference).

Considering daily peak outdoor temperature in Panel C of Table 3.2, period 1 was much warmer compared to period 2, as it is expected for early Autumn and late Winter weather. During period 1, daily average peak temperature recorded 18° Celsius (64° Fahrenheit) and for period 2 11° Celsius (52° Fahrenheit). Moreover, the daily average peak temperature in period 1 reached a maximum of 30° Celsius (86° Fahrenheit) for one day, while in period 2, it only reached a maximum of 18° Celsius (64° Fahrenheit).

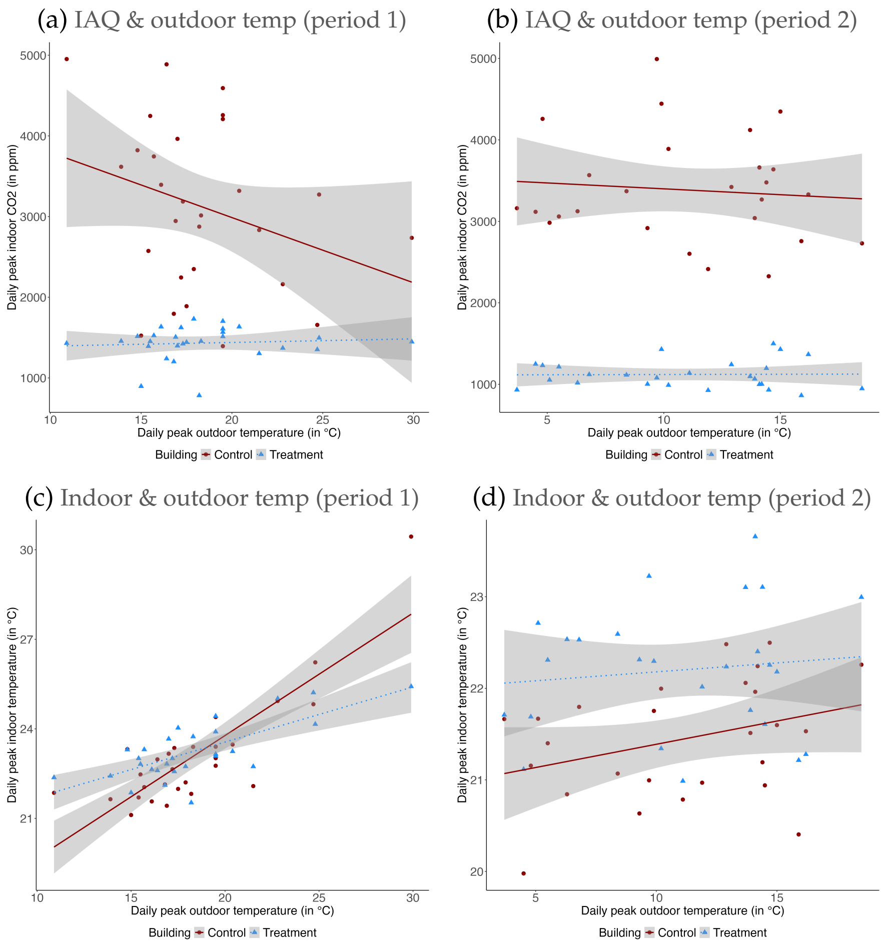
Figure 3.3 relates the daily peak indoor CO_2 concentration and daily peak indoor temperature with the daily peak outdoor temperature for each period separately. Given that period 1 takes place in September and October and period 2 in February and March, different seasons of the year can affect the relationship of indoor environmental quality and outside weather conditions. Occupants tend to open the windows more frequently during warmer days to stay thermally comfortable.

Figure 3.3a illustrates a strong negative relationship of indoor CO_2 concentration and outdoor temperature in the control building in period 1, indicating that occupants presumably opened the windows during warm days to let fresh air enter the room. Figure 3.3c shows also that during this period, indoor temperature increases with outdoor temperature, supporting the assumption of increased window opening.

The treatment building shows more stable indoor CO_2 concentrations, independent of the outdoor temperature in period 1, while indoor temperature in this building also increased with outdoor temperature, but to a weaker extent than in the control building, indicated by a smaller slope of the dotted line in Figure 3.3c. Notably, the lines of indoor and outdoor temperature in Figure 3.3c intersect at 20° Celsius (68° Fahrenheit), showing that for higher outdoor temperature conditions, indoor temperature in the control building exceeded the temperature in the treatment building and vice versa.

Appendix Table A5 shows the correlation coefficients of the three parameters per building and period, confirming that indoor CO_2 was negatively and strongly correlated with outdoor temperature in the control building (correlation coefficient of -0.30, $p > 0.05$), than in the treatment building (correlation coefficient of 0.08, $p > 0.05$), although the coefficients are statistically insignificant. However, the correlation of indoor temperature and outdoor temperature in both buildings are statistically significant and much higher for the control building (0.84, $p < 0.001$) than for the treatment building (0.73, $p < 0.001$), confirming the pattern seen in Figure 3.3c.

Figure 3.3: Air quality, indoor and outdoor temperature



Note: The figure shows the linear relationship of daily peak indoor CO_2 concentration with daily peak outdoor temperature (temp), and daily peak indoor temperature with daily peak outdoor temperature, for each period. The dots and solid line indicate the control building, and the triangles and dotted line indicate the treatment building. The line shows a simple linear regression model fitted to the observations, with the gray shading indicating the confidence intervals.

For period 2, the strong negative relationship of indoor CO_2 and outdoor temperature is less pronounced in the control building, with a nearly flat solid line in Figure 3.3b. Additionally indoor temperature increased much less with outdoor temperature compared to period 1, as shown in Figure 3.3d. Moreover, the relationship of indoor CO_2 and indoor temperature with outdoor temperature in the treatment building is much less pronounced in period 2 than in period 1. Notably, indoor temperature in the treatment building was on average higher than in the control building in period 2, shown by the dotted line in Figure 3.3d being above the solid line and seen in Table 3.2.

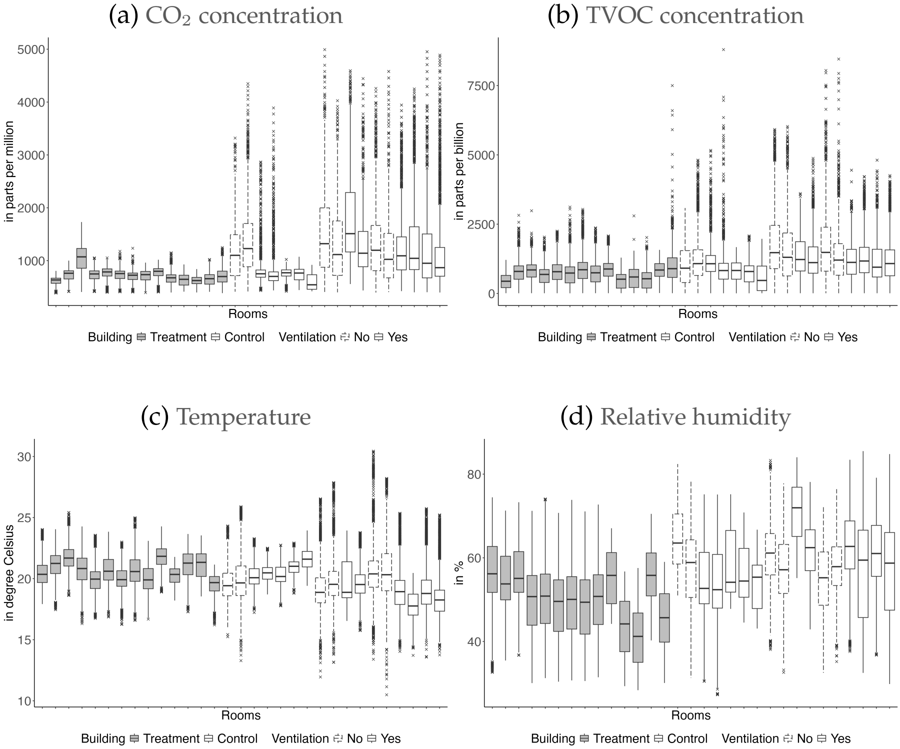
Overall, Figure 3.3 illustrates how important it is to consider both periods separately in our analysis, given the influence of outdoor weather conditions on indoor environmental quality. The patterns seen in Figure 3.3b and 3.3d are also confirmed in the correlation analysis, shown in Appendix Table A5, recording statistically insignificant and much lower correlation coefficients for all given relationships.

Figure 3.4 shows boxplot diagrams per classroom for the indoor environmental quality conditions in the two buildings. Figure 3.4a and Figure 3.4b show a larger variation in the CO_2 and TVOC concentrations within classrooms in the control building. The median CO_2 concentration in the treatment building is also lower than in most classrooms in the control building, exceeding 1,000 ppm for only one classroom in the treatment building. However, the TVOC concentration in some classrooms in the treatment building reached similar levels as in the control building, although the variation in TVOC concentration is much higher in the control building.

Regarding the thermal conditions, Figure 3.4c and Figure 3.4d illustrate a large variation in temperature and relative humidity within classrooms over time, in both buildings. However, the temperature variation is lower in the treatment building compared to the control building, with some classrooms in the control building recording a much lower median temperature. Looking at Figure 3.4d, median relative humidity in the control building is exceeding the median levels in the treatment building's classroom in most cases.

Figure 3.4 also shows the difference in indoor environmental quality between classrooms with and without mechanical ventilation, indicated with solid and dashed boxplot lines, respectively. The boxplot illustrates that in the control building, despite some rooms having mechanical ventilation, the CO_2 and TVOC concentrations (Figures 3.4a and 3.4b) varied substantially. Only three rooms reached CO_2 concentrations below 1,000 ppm, similar to the classrooms in the treatment building.

Figure 3.4: Indoor environmental quality conditions



Note: The figure shows the CO_2 concentration, total volatile organic compounds (TVOC) concentration, temperature and relative humidity in the treatment and control building. In the boxplot diagrams, the thick line in the middle is the median. The upper and lower edges of the box are the upper and lower quartiles. The whiskers that extend from the box show the minimum and maximum of the non-outlier values. Values that are more than 1.5 times the interquartile range away from the box are considered to be outliers and shown as crosses (x). The dashed boxplots indicate classrooms with no mechanical ventilation. The grey boxplots identify the treatment building and the unfilled boxplots the control building.

It shows that the static mechanical ventilation in the control building is insufficient to maintain low concentration levels of air pollutants. In comparison, the treatment building has a balanced, demand-controlled ventilation system which automatically adapts ventilation rates based on peak occupancy hours and real-time CO_2 concentration monitoring to maintain low levels of air pollutants when the room is occupied.

3.3.2 Impact of the treatment building on satisfaction and course grades

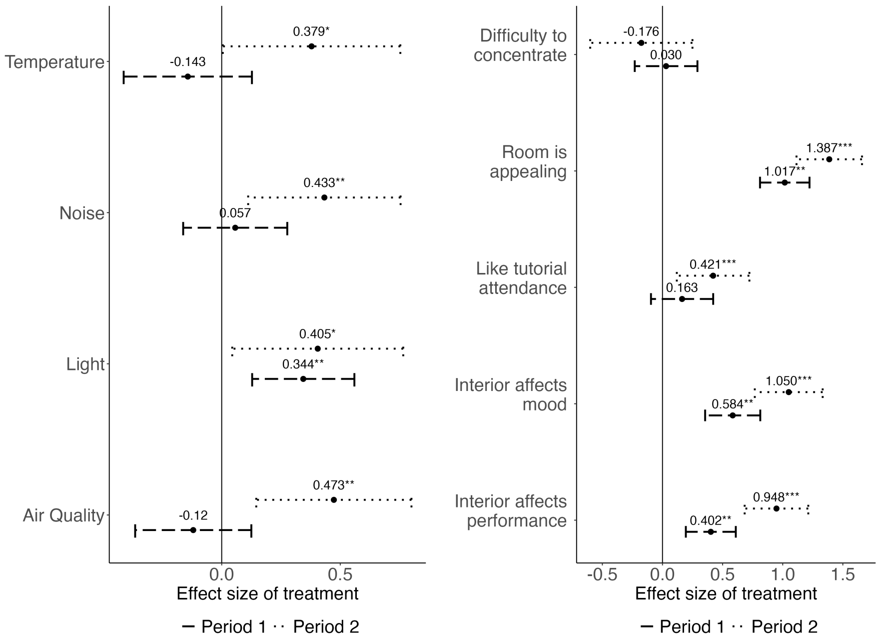
In this section, we present the estimation results for the model described in Equation 3.1 to examine the effect of exposure to the treatment building on student satisfaction with the indoor environmental quality and with the interior design of the classrooms (Figure 3.5 and Figure 3.6). Considering the different effects of the weather in Autumn and Spring, we estimated the two periods separately, controlling for seasonal effects.

Figure 3.5a shows the impact of the treatment building on students' satisfaction with the indoor environmental quality. Students were asked in both buildings on the perceived impact of the indoor environmental quality parameters on their self-assessed performance in class. For period 1, shown as the dashed bar plots, only the satisfaction with light was significantly affected by the treatment ($p < 0.01$).

Students in the treatment building reported a supporting effect of the indoor lighting on their perceived ability to perform well in class. However, despite the objectively measured better indoor air quality and thermal conditions, no significant difference in satisfaction with these factors for period 1 was found. For period 2, shown as dotted bar plots in Figure 3.5a, the effects are more pronounced. For all parameters (air quality, light, noise and temperature) students in the treatment building reported that these factors supported them to perform well in class, compared to students who had their classes in the control building ($p < 0.05$).

Figure 3.5: Satisfaction with the indoor environment

(a) Indoor environmental quality (b) Interior design



Note: The figures show the regression results for the satisfaction of students with the indoor environmental quality (IEQ) in Panel 3.5a and with the interior design in Panel 3.5b. The beta coefficients are indicated as dots • and the confidence interval as bars. Because the regression coefficient is standardized, the beta coefficient on the x-axis corresponds to the effect size of being exposed to the treatment building. For Panel 3.5a, students were asked to which degree the four environmental factors support their ability to perform well in class. Higher values indicate more perceived support reported by students in the treatment building, compared to the control building. For Panel 3.5b, students were asked about the perceived effect of the interior design on their performance and mood, if they like attending class, if the room is appealing, and if they had difficulties to concentration during class. In the first four questions, higher values indicate a more favourable perception when they had their classes in the treatment building. In the fifth question, higher values indicate a higher degree of perceived difficulty to concentrate when situated in the treatment building. The regression results are shown in detail in Appendix Tables A6 and A7. Significance levels are indicated as $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

The coefficient values are based on the standardized z-scores, therefore, the coefficients show the effect size of having classes in the treatment building. All indoor environmental quality parameters record a moderate effect size close to 0.5, indicating a substantial difference in perception among students in the treatment building. In other words, students in the treatment building had a 6.8% higher satisfaction with the indoor air quality, 5.8% higher satisfaction with light, 6.2% higher satisfaction with noise, and 5.4% higher satisfaction with temperature in period 2 [5].

Figure 3.5b shows the estimation results for both periods, for students' satisfaction with the interior design. In period 1, students who had their tutorial meetings in the treatment building believed that the interior design had a more positive effect on their perceived performance and mood during class ($p < 0.01$), indicated by the dashed bar plots.

A moderate effect size has been recorded wit a beta coefficient of 0.402 and 0.584 for the effect on perceived performance and mood, respectively. This effect size corresponds to a 5.7% and 8.3% increase in perceived impact of the treatment building on their performance and mood, respectively.

There was no significant difference in students liking to attend the tutorial meeting between the two cohorts in period 1. Additionally, Figure 3.5b shows that students perceived the room in the treatment building as significantly more appealing as compared to students who had their classes in the control building ($p < 0.01$).

Being in the treatment building had the largest impact on room attractiveness, among all parameters, with an effect size of 1.017, corresponding to a 14.5% change between the control and treatment group. However, there was no difference in reported difficulty to concentrate during class between the two study cohorts.

Period 2 confirms the results from period 1, shown as dotted bar plots in Figure 3.5b. Students in the treatment building had a positive verdict on the effect of the interior design on their self-rated performance and mood ($p < 0.001$). The effect size is substantially large than on

[5] Students indicated their answer on a 7-point Likert scale, with the coefficient in the regression being defined as a dummy variable equals 1 if a student had his or her class in the treatment building. Therefore, for example for air quality, a recorded beta coefficient of 0.473 equates to a $0.473/7 = 0.068$ or 6.8% change on the Likert scale.

period 1, with beta coefficients of 0.948 and 1.05 for the effect on perceived performance and mood, respectively. This effect size corresponds to a 13.5% and 15% increase in perceived impact of the treatment building on their performance and mood, respectively.

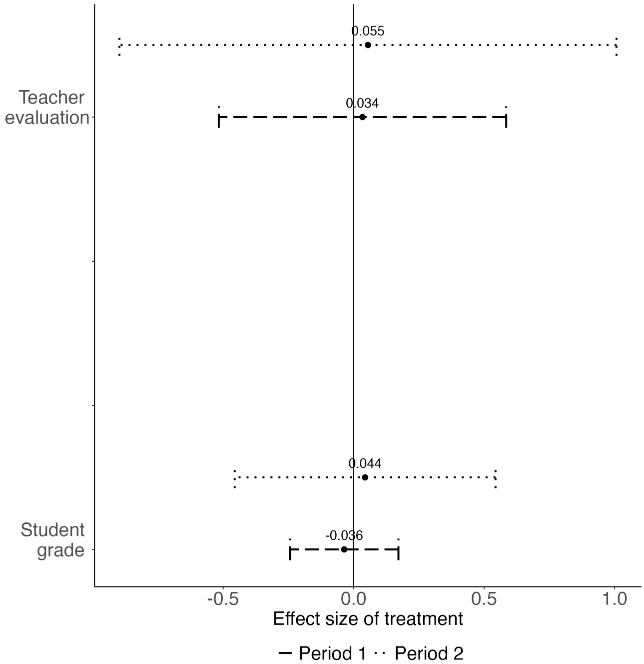
Students also found the rooms in the treatment building to be more appealing ($p < 0.001$), recording the highest effect size of 1.387, corresponding to a 19.8% change compared to the control group. However, different from the results of period 1, for period 2 the treatment building significantly affected students evaluation of the tutorial. Students who had their tutorial meetings in the treatment building in period 2 liked to attend the tutorials more, compared to students in the control building ($p < 0.001$).

Compared to the other factors, the effect size for attendance is moderately high with a beta coefficient of 0.421, or a 6% increase among the treatment group compared to the control group. Similar to period 1, we can not confirm any significant influence of the treatment building on students' reported difficulty to concentrate during class.

Lastly, Figure 3.6 shows the effect of the treatment building on students' course grades and teacher evaluation. The results show that the treatment building had no significant effect on the course grades of students. Therefore, independent of where students had their tutorial meetings, in the treatment or control building, the achieved grade did not differ.

This result includes controls for the time of the day students had their tutorial meetings (schedule fixed effect), the course the students followed, and the teacher. Additionally, student evaluation of teacher performance did not significantly differ between the buildings. Teacher evaluations can be a proxy for teaching quality, and the indoor environment did not seem to have a significant impact on student-rated teaching quality.

Figure 3.6: Student course grades and teacher evaluation



Note: The figures show the regression results for the impact of the treatment building on student grades and teacher evaluation. The beta coefficients are indicated as dots ● and the confidence interval as bars. Because the regression coefficient is standardized, the beta coefficient on the x-axis corresponds to the effect size of being exposed to the treatment building. Higher values for the coefficient indicate a better course grade for students who had their classes in the treatment building, and a better teacher evaluation given by students to teachers who hosted classes in the treatment building. The regression results are shown in detail in Appendix Tables A8. Significance levels are indicated as $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

Overall, these results indicate that students believed that the indoor environmental quality and interior design of the treatment building positively affected their performance during class, as well as their mood. Students in the treatment building were generally more satisfied with the indoor environment, compared to students in the control building. Despite the belief that the indoor environment positively influenced their self-assessed performance, no significant effect of the treatment building on student grades could be observed.

Moreover, teaching quality in the form of teacher evaluation was not significantly affected. These results support the initial hypothesis that the indoor environmental quality in the treatment building leads to higher satisfaction, however a self-reported performance-enhancing effect occurs in the absence of a significant effect of the treatment building on actual performance in terms of course grades.

3.4 Discussion

The importance of indoor environmental quality for health, cognitive performance and general well-being of building occupants is increasingly relevant in the context of global efforts to address climate change and enhance energy efficiency through building renovations. This study addresses building renovation and indoor environmental quality improvements by investigating the effects of a newly renovated, refurbished, and WELL-certified university building, with improved indoor environmental quality, on satisfaction and student performance.

Our findings reveal a contradicting relationship between the perception of the indoor environment, and students' learning outcomes. On one hand, the treatment building has significantly better air quality and thermal conditions, and students in the treatment building showed higher levels of satisfaction and reported a positive impact on their mood and performance in class. Nevertheless, we find no significant effect from enhanced indoor environmental quality on course grades.

This finding indicates that, under real world settings, objectively better indoor environmental quality does not necessarily translate into better student learning outcomes in higher education. This is contrary to what laboratory experiments indicate [98] and what previous studies in primary and secondary education have found [51, 50]. Several factors can influence this process and lead to different results.

Satisfaction with indoor environment: We found a higher satisfaction level of students in the treatment building with the indoor environmental quality and the interior design. Previous studies show discrepancies in the actual indoor environmental quality and the satisfaction with it, and how changes in one indoor environmental parameter can influence the satisfaction with another indoor environmental parameter [141, 391, 360]. Therefore, an objectively better indoor environmental quality might not necessarily lead to higher satisfaction levels.

Previous studies on WELL-certified office buildings give an ambiguous picture if the indoor environmental quality in such a building is perceived as more satisfactory, although recent evidence provides confirmation for a higher satisfaction level in such buildings [189, 212]. However, our study confirms that a WELL-certified university building not only leads to better indoor air quality and a more stable thermal environment, but also that students recognize this improvement and attribute it a positive impact on their performance. Our study therefore extends the current literature by examining the perception and satisfaction with the indoor environment in an educational setting, rather than in office buildings [212, 11, 189].

Regarding the general interior design, students in the treatment group perceived the classrooms in the treatment building as more appealing. The novelty of a newly renovated, refurbished building can lead to a 'halo effect', for which occupants have a more positive judgment of the building simply because everything is newer [165]. Thus, not only does the indoor environmental quality play a role in occupants' satisfaction of the broader indoor environment, non-indoor environmental quality factors can influence occupant satisfaction as well, independent of the actual indoor environmental quality [323, 128].

The results shows that these factors matter, because when specifically asked for the interior design, students in the treatment building rated the classroom as more appealing and assigned the interior design a positive impact on their mood and performance. The treatment building has been fully refurbished, which seems to play a crucial role in student satisfaction with the building. A previous study investigated the impact of a WELL-certified office building on occupants' satisfaction. This study confirms that improvements in satisfaction after relocation were mainly associated with such non-indoor environmental quality factors [212].

Expectations could also change over time through increasing familiarity with the building. Studies on LEED and BREEAM certification suggest that the time occupants spend in a certified building influences their satisfaction level over time [212, 323, 11]. We included the same cohort of students in two periods three months apart from each other and in different seasons. Since we included a first-year cohort, these students were not familiar with the buildings and classrooms in period 1, because it was their first university course. However, in period 2, they became more familiar with the buildings.

Additionally, between our two sample periods, all students had their tutorial meetings in the control building. Thus, students who were assigned to the treatment building for period 2 were able to assess the treatment buildings' indoor environment under the impressions they had from having classes in the control building. During period 1, however, students in the treatment building did not know the control building.

This switch between buildings could explain why the rating of the indoor environmental quality was statistically significant and the effect size was much higher in period 2 compared to period 1. Also for the satisfaction with the interior design, period 2 recorded substantially higher effect sizes than period 1. According to the psychological adaption framework, students might have changed their expectations and extended their frame of reference in period 2, because they were familiar with how classes in the control building felt [87]. Simply speaking, students in period 2 rated the treatment building based on their previous experiences with the control building. However, the satisfaction results for period 1 can be seen in isolation, because the treatment building was the first building these students had experienced at the start of their studies.

Seasonal influences: Another aspect which might mediate the difference in statistical significance between period 1 and period 2 are seasonable variations. We accounted for seasonable effects by considering period 1 (September to October 2022) and period 2 (February to March 2023) separately. Outdoor temperature conditions substantially influence occupant behaviour in opening windows and ventilating the room with fresh air [101, 107]. This is particularly true for rooms with insufficient or no mechanical ventilation, as it is the case for the control building. Our analysis shows a clear seasonal effect, with a strong negative relationship between indoor CO_2 and outdoor temperature for the period of September and October, while for period 2 of February and March with much colder days, CO_2 remained high in the control building.

This illustrates that occupants have to face a trade-off during colder days in period 2: Either opening the window for fresh air or keeping windows closed to maintain thermally comfortable conditions indoors. Our analysis also shows that in period 1, outdoor temperature was more similar to indoor temperature in the control building, than for period 2. Opening windows allows warmer air to enter the room, which can explain the observed nearly full harmonization of indoor and outdoor temperature during hotter days in the control building.

Notably, this relationship cannot be observed in the treatment building, where window opening is limited and the HVAC system determines ventilation rates and temperature indoors. Indoor CO_2 and indoor temperature were less strongly correlated with outdoor temperature in both periods for the treatment building, while there are two clear and distinguishable patterns for the control building for each period. Therefore, it seems that the treatment building with its modern ventilation and air-conditioning system can reduce the trade-off occupants have to face during colder seasons, although opportunities to open windows were anyway limited in the treatment building.

The seasonal differences in outdoor conditions could explain why the impact on satisfaction with the indoor environmental quality between both buildings shows a higher statistical significance level in period 2 than in period 1. Period 2, with its colder days, aggravated the trade-off for occupants in the control building between opening windows and keeping a thermally comfortable indoor temperature. While we cannot clearly relate the variation in statistical significance of our results to particular seasonable effects, our findings nevertheless show the importance of considering seasonal differences when investigating occupant satisfaction with the indoor environmental quality.

Impact on learning: A striking finding from this study is that there was no significant difference in course grades between the two building cohorts, despite students in the treatment building reporting stronger beliefs that the individual indoor environmental quality factors support their ability to perform well in class. This finding illustrates the discrepancy between actual changes in performance and perceived performance changes. A similar contradiction between perception and actual performance change has already been found in another study on heat and decision-making quality [351].

One possible explanation for our results is that the effect of indoor air quality and temperature on cognition strongly depends on exposure duration and frequency of exposure to the actual conditions [98, 376, 153]. Limited exposure duration could explain the non-significance of the treatment impact on course grades in our analysis, since students spent 4 hours per week per course in the corresponding building. Most of their learning time occurred outside of the tutorial meetings, though these meetings play a crucial role in discussing, revising and reinforcing newly learned material. Therefore, the exposure time is much shorter than in primary and secondary education, where children spend several hours each day in the same classroom, with most learning occurring in the same classroom. Higher exposure time might therefore drive the significant impact of indoor environmental quality on learning outcomes of school children [50].

Notably, the absence of a difference in course grades might be due to students in the control building being aware of their slower learning progress than students in the treatment building, which motivates them to study longer for the same grade. Over all, communication between students cannot be avoided and students can easily compare their learning progress relative to their peers. If this would be the case, then the indoor environment could influence learning abilities of students, however, they would be able to equal out this disadvantage with more effort, explaining the insignificant effect on course grades in our analysis. Previous research has suggested that individuals may compensate for the adverse impact of poor indoor air quality on cognitive performance by exerting greater mental effort [98].

However, a secondary analysis, presented in Appendix Table A9, did not confirm any significant difference in self-reported study hours between the two treatment groups. Students in the control building did not report studying significantly more than their peers in the treatment building, suggesting that they did not employ additional study time to maintain grade levels comparable to those of their peers in the treatment building.

The lack of significant results could also be due to the fact that the difference in air quality between the two buildings may not be substantial enough to show a measurable effect on course grades. For example, the average difference in CO_2 concentration between the two buildings is around 460 ppm, with the control building showing only a slight elevation of 210 ppm above the guideline threshold of 1,000 ppm [23, 95]. Findings from various studies suggest a 2% decrease in performance with a CO_2 concentration increase from 900 to 1,200 ppm [385]. Over an extended learning period, this 2% decrease could accumulate into a substantial impact on grades. However, given the limited exposure duration and frequency of exposure to the building conditions, along with the relatively short duration of 7 weeks per course, the magnitude may simply be too small to affect course grades.

Another factor that might play a role in understanding no significant changes on students' grades is the grading policy of the courses. As explained in Section 3.2.1, the final course grade is a weighted average of partial grades, including the exam, presentations and course assignments. The exam grades are usually weighted the most and students have last years' editions of the exam for preparation. This raises the question of how much tutorial attendance contributes to students' exam performance.

In this context, a previous study using the same teaching environment as ours shows, for instance, that the seniority of the teacher does not affect students' course grades [111]. Taken together with the evidence in this study, this suggests a generally low impact of the tutorial setting (environment, seniority of teaching staff) on students course grades. It can be hypothesized that this is due to the relatively large weight of standardized exams, which students may prepare through self-study. Therefore, unlike in primary and secondary education, it may be concluded that the influence of in-class tutorial meetings on course grades tends to be smaller in a university setting.

Teaching quality: Teaching quality could play a critical role as a mediator in the relationship between indoor environmental quality and student performance. Previous studies have demonstrated a negative impact of poor indoor air quality on work performance and cognitive function in office workers [98]. This suggests that the indoor environment may influence learning outcomes by impairing teachers' cognitive performance, leading to a decline in teaching quality. Prior research done in primary and secondary schools has not explicitly accounted for teaching quality when reporting a negative effect of indoor air quality on students' academic achievement [385].

By using a teacher fixed effect, we control for variation in teaching quality between teachers, which could affect students' learning experience and course grades. Our analysis also indicates that teacher evaluations do not differ between the treatment and control buildings. While student perceptions of teaching quality is only a proxy for actual teaching quality, the lack of significance does not support the hypothesis that teaching quality is affected by the indoor environment.

A notable similarity between students and teachers in our study is, that the found discrepancy between perception of performance and actual performance is not only found in student grades, but also in teacher evaluation. In a questionnaire distributed at the end of each study period, teachers were asked to rate the impact of the classroom interior on their ability to perform effectively in class, similar to the question asked to students in the main analysis. While teacher evaluations showed no significant differences, teachers in the treatment building reported that the interior design had a more positive impact on their performance compared to those in the control building. An independent t-test confirms the significant difference in perceived impact on performance, as shown in Appendix Table A10.

This finding aligns with the recorded discrepancy of students' belief in a positive effect of the indoor environment on their performance, despite no observable change in actual grades. Similarly, teachers appear to perceive a positive impact of the indoor environment on their teaching performance, even though no significant change was observed in teacher evaluations. However, this result should be interpreted with caution. The limited number of responses (73) provides an insufficient sample size to apply a fixed-effect regression model, which would control for potential confounders. Future research should aim to collect more comprehensive data on both perceived and actual teaching quality to better investigate the extent to which the indoor environment in classrooms affects teaching performance.

Policy implications: The results of our study raise the question of where investments in the indoor environment are most effective for improving learning outcomes. The educational sector, like the private sector, is required to invest in renovating buildings and educational facilities to reduce carbon emissions and improve energy efficiency. Therefore, investments in renovating educational buildings offer an opportunity to improve not only energy efficiency and sustainability, but also the indoor environmental quality of classrooms, thereby enhancing learning outcomes.

Previous work in primary and secondary education provide strong evidence that improving the indoor environmental quality in school classrooms has a substantial effect on learning outcomes of school children [51, 385, 379]. However, our study cannot confirm the same positive effect of an improved indoor environment on student performance in higher education. Investments in improving the indoor environment of university classrooms may not be as effective in enhancing learning outcomes, as they are in primary and secondary education.

Moreover, our results are important for university boards making decisions about investing in the indoor environmental quality of their facilities. These findings suggest that improving the indoor environment in places where students spend most of their time learning, such as libraries or dedicated learning spaces, may have a stronger impact on learning outcomes than improving the classroom environment. Exposure time and frequency within specific indoor environments should be major factors in deciding where to invest capital for indoor environmental quality improvements which aim to enhance learning outcomes. Our study cannot confirm that spending the extra money to certify a university building with the WELL certificate necessarily leads to better learning outcomes.

That being said, our findings confirm a positive impact of WELL certification and indoor environmental improvements on students' learning experience, self-assessed performance, and well-being, independent of an effect on actual academic performance. University boards and decision-makers aiming to improve well-being and satisfaction of students (and potentially also teaching staff) can consider our results as confirmation to invest in the optimization of the built environment. Therefore, decision-makers should consider whether they aim to improve learning outcomes or well-being and satisfaction, when deciding where to invest in building improvements.

3.5 Conclusion

This paper describes a large-scale, single-blind field experiment to investigate the impact of a newly refurbished, renovated, and WELL-certified university building on satisfaction with the indoor environmental quality and course grades. Objective measures of the indoor environmental quality in each classroom revealed that the certified treatment building had better indoor air quality, in terms of lower concentrations of air pollutants, and a more stable indoor temperature level. Students were more satisfied with the indoor environmental quality and the interior design of the renovated building. Furthermore, they also believed that the indoor environment had a positive impact on their performance in class.

Despite the more favourable perception, we did not find a statistically significant difference in course grades between the student cohorts. This study shows that, under experimental settings, an objectively better indoor environmental quality does not necessarily translate into better learning outcomes in higher education and that individual learning perception can differ from actual performance effects. Moreover, besides environmental quality factors, other aspects are important to consider when investigating the satisfaction of occupants within the built environment.

4
Cognition, economic decision-making, and physiological response to carbon dioxide

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Abstract

This study examines the isolated effect of carbon dioxide on cognition, economic decision-making, and the physiological response in healthy adults. The experiment took place in an air-tight respiration chamber controlling the environmental conditions. In a single-blind, within-subject study design, 20 healthy participants were exposed to artificially induced carbon dioxide concentrations of 3,000 ppm and 900 ppm in randomized order, with each exposure lasting for 8 hours. A high ventilation rate and an air pollutant filter were used to keep concentrations of volatile organic compounds and fine particles equally low in both conditions. Cognition tests were conducted twice during the 8 hours and physiological parameters were measured continuously over the 8 hours. No evidence on a robust statistically significant effect of carbon dioxide on either cognitive or physiological outcome variables were found. These findings imply that the human body is able to deal with exposure to indoor carbon dioxide concentration of 3,000 ppm for a limited time without suffering significant cognitive decline, changes in decision-making or showing any physiological response.

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4.1 Introduction

The indoor environmental quality in buildings plays an important role in influencing the cognitive performance and health of occupants [375, 260]. Indoor air quality is an important aspect of the indoor environment, because it is influenced by the supply of fresh outside air via mechanical ventilation and natural ventilation [65]. Mounting evidence has shown that insufficient ventilation removing carbon dioxide and other air pollutants are associated with impaired cognitive performance and work performance in office workers [98, 380]. Exposure to poor indoor air quality in classrooms has also negative effects on learning and academic achievement in school children [120, 385]. A recent article by 43 experts emphasizes the importance of good indoor air quality for human health, productivity and learning [255].

However, buildings majorly contribute to greenhouse gas emissions, thus there is a need to provide energy efficient buildings [100]. On average, approximately half of a building's energy consumption is dedicated to heating, cooling, and ventilation [221]. This proportion varies depending on the climate and the building type. Increasing ventilation rates directly affects energy consumption, but also indirectly leads to higher energy demand for cooling and heating to maintain a stable indoor temperature during cold or hot weather [321, 85, 310]. Thus, building owners face a profound trade-off between providing healthy indoor air quality and improving the energy efficiency of buildings.

Modern demand-controlled ventilation systems use real-time measurements of carbon dioxide (CO_2) concentration levels to adjust the ventilation rate, providing good indoor air quality during high occupancy and reducing energy consumption during low occupancy [104, 150]. CO_2 is a useful metric for estimating ventilation rates and modelling indoor air quality, because its concentration strongly correlates with human-emitted air pollutants (bioeffluents) and volatile organic compounds [292, 71, 355]. The negative effects of poor indoor air quality on cognition and health are often linked to bioeffluents and volatile organic compounds [98, 403]. Thus, it has long been believed that, while CO_2 is a useful proxy for indoor air quality, its association with adverse cognitive and health outcomes is not of causal nature, but rather mediated by other air pollutants that increase in concentration with CO_2 indoors.

However, a number of papers have examined the isolated effect of CO_2 on cognitive parameters, showing mixed results [345, 7, 322, 331, 313, 404, 402]. These studies are quite heterogeneous in terms of participant population, exposure time, outcome measurement, and size of groups measured at the same time (see Appendix Table A14 for an overview of previous literature on CO_2.). Additionally, only two studies have measured the effect of CO_2 exposure on cognitive and physiological responses simultaneously, reaching contradicting results about its influence on these outcomes [345, 404]. The studies which found a strong negative effect of CO_2 did not measure any physiological parameters which could explain their results [7, 322, 331]. Although, there is evidence that elevated CO_2 concentrations can trigger adverse physiological reactions. It is assumed that elevated CO_2 levels lead to a change in breathing pattern, which could affect blood homeostasis and trigger heightened states of arousal or sleepiness [98, 403, 370]. However, it is unclear if changes in respiration are triggered by other air pollutants co-occurring with CO_2 [343]. Thus, measuring cognitive performance and physiological parameters provides valuable insights into the pathways of a possible impact of CO_2 on cognitive performance.

While current ASHRAE guidelines (American Society of Heating, Refrigerating and Air-Conditioning Engineers) see CO_2 solely as a proxy for indoor air quality, but not as an air pollutant itself, a position paper by ASHRAE recommends further research on the role of CO_2 itself on human health and cognition due to the mentioned inconsistency in previous studies [23, 15]. The position paper emphasises the need to examine the role of CO_2 on cognition and health with a focus on the physiological mechanism and its impact on blood chemistry and respiration. Such studies become particularly relevant considering that peak CO_2 concentrations commonly reach levels above 2,500 ppm, exceeding recommended threshold levels, sometimes despite the presence of mechanical ventilation [23, 120].

Understanding the role of CO_2 in human cognitive performance and health also helps determine the importance of air cleaning devices. Since demand-controlled ventilation systems use CO_2 levels to adjust ventilation rates, removing CO_2 from the air should be done carefully and only when necessary, to avoid unintended effects such as increased concentrations of other air pollutants [15]. Air filtration and purification systems remove airborne pathogens and particles, however gaseous substances are not removed by this process. Therefore, in such a case, CO_2 might not be an accurate measure of air quality anymore [255]. Using filtration systems can reduce energy consumption from ventilation systems [32]. However, identifying CO_2 as an air pollutant would have consequences for determining the optimal combination of filtration and ventilation systems to provide healthy indoor air while maximizing energy efficiency.

To address this urgent gap in the understanding of CO_2 on human cognition and health, this study examines the isolated effect of CO_2 on a broad set of outcomes in a tightly controlled environment. Using an interdisciplinary approach, we investigated the effect of an 8-hour exposure to a CO_2 level of 3,000 ppm induced from a liquid CO_2 bottle, as compared to a CO_2 level of 900 ppm, on the cognitive performance, economic decision-making, and physiological response of healthy adults. Ventilation rates were maintained at a high level ($> 500l/min$) and an air cleaner was used to ensure low levels of volatile organic compounds, bioeffluents and other air pollutants in both conditions, attributing any observed effects to CO_2. Various physiological parameters were continuously measured during exposure to associate any effects with potential physiological reactions, including changes in blood CO_2 concentration and respiration. The experiment was conducted in an airtight respiration chamber, commonly used in metabolic research [326].

We hypothesize that an elevated ambient CO_2 level leads to lower cognitive performance. Cognition is measured using a neuropsychological test battery to test the domains of attention, psychomotor control, executive function, and memory. We also investigated the impact on individuals' risk and time preferences by applying multiple price lists, a tool commonly used in economics literature, to analyse the effect of CO_2 on economic decision-making [78, 167]. It is assumed that elevated CO_2 levels lead to changes in risk-taking and time preferences. Risk and time preferences have been found to predict economic decision-making in a wide variety of settings and are often found to correlate with cognition [239, 19]. Moreover, any effect on cognitive performance or economic decision-making is assumed to be mediated by a physiological reaction, such as a higher heart rate, higher blood pressure, higher physical activity level, or elevated oxygen consumption. It is further hypothesized that the respiration rate will decrease as a response to the higher CO_2 concentration and this is associated with a higher blood CO_2 concentration, as suggested by earlier research [370, 343]. This finding would indicate that elevated levels of CO_2 lead to a respiratory acidosis due to altered breathing patterns. Given the large number of hypotheses tested in the empirical analysis, we draw inferences based on *p*-values corrected for multiple hypothesis testing.

4.2 Methods

4.2.1 Experimental setup

This study was conducted on a cohort of 20 healthy individuals between November 2021 and July 2022. A sample size of 20 participants was chosen based on a power calculation using an effect size of 1, as suggested by previous studies on the impact of CO_2 on cognitive performance [98]. Participants were exposed to CO_2 levels of 3,000 ppm (High-CO_2) and 900 ppm (Low-CO_2) during an 8-hour stay in a respiration chamber at the Metabolic Research Laboratories at Maastricht University. A CO_2 concentration of 3,000 ppm is commonly found in indoor spaces despite mechanical ventilation and has also been used in previous laboratory studies [120, 403, 404, 345]. A level of 900 ppm is below the threshold for good indoor air quality, as suggested by common building guidelines [23, 95].

The chamber (14 m^3) is equipped with a desk, sink, and deep-freeze toilet. It is airtight, creating negative pressure to allow precise measurements of CO_2 and oxygen levels, suitable for indirect calorimetry to determine metabolic rate. Fresh air is drawn from the building roof and circulated through the chamber. The concentrations of CO_2 and oxygen of the inflow and outflow air are measured minute-by-minute using paramagnetic oxygen analysers and infrared CO_2 analysers. Each gas sample is measured with two separate analysers to improve reliability. A detailed description of the chamber setup can be found in previous work [326].

Only one participant at a time was measured in the chamber, as behaviour and perception can be influenced when occupants are measured in groups [327]. We used a cross-over design where participants were exposed to both CO_2 conditions, with a break of four to six weeks between the two test days. The order of the test conditions was randomized. Among the 20 participants in this within-subject design, 10 were first exposed to the High-CO2 condition on their initial testing day and then to the Low-CO2 condition on their second testing day. The remaining 10 participants experienced the conditions in the reverse order, starting with the Low-CO2 condition on their first day, followed by the High-CO2 condition on their second day. Upon study inclusion, each participant was randomly assigned to one of the two starting conditions to ensure that the order of exposure was randomized throughout the participant inclusion process. Participants were unaware of the condition.

The ventilation rate was set in both conditions at a high level ($> 500l/min$) to minimize the concentrations of volatile organic compounds and fine particulate matter in the chamber. Thereby, the concentration of total volatile organic compounds was kept constant across both conditions. Previous work shows that increasing ventilation rate successfully reduces total volatile organic compounds concentration [7]. Additionally, a particle and volatile organic compounds filter (Molekule Air Mini+, Molekule, Florida, USA) was installed. Remaining fine particular matter ($PM_{2.5}$) and total volatile organic compounds were measured every 5 minutes using a commercially available monitor (Foobot SAT, Airboxlab SA, Luxembourg) to confirm low and stable volatile organic compounds concentrations across the exposure conditions. The used monitor has been validated and compared to other low-cost sensors [405]. No standardized hygiene practices for participants were enforced.

In the Low-CO_2 condition, the ventilation rate of $> 500l/min$ led to a steady-state CO_2 concentration of 900 ppm. The same ventilation rate was kept in the High-CO_2 condition. For this condition, after participants entered the chamber, CO_2 was induced via a gas bottle until it reached a stable level of 3,000 ppm, which took an average of 11 minutes. After the 3,000 ppm concentration was reached, the infusion of additional CO_2 was reduced to a level sufficient to maintain the steady-state concentration of 3,000 ppm for the remainder of the test day. Inducing the CO_2 before participants entered the chamber would have resulted in an outflow of CO_2 when the door was opened due to the under-pressure condition inside the chamber. Therefore, in the Low-CO_2 condition, the 900 ppm CO_2 concentration represents participant-induced CO_2, while the High-CO_2 condition consisted of 3,000 ppm CO_2 from a mixture of exhaled and artificially added CO_2. Indoor temperature and relative humidity were maintained at 21° Celsius and 32%, respectively.

4.2.2 Recruitment of participants

Inclusion criteria were 1) having an office job that includes mentally demanding tasks, 2) being between 25 and 50 years old, 3) being generally healthy with no intake of any medication (except for contraceptives), and 4) not smoking. Individuals with any of the following characteristics were excluded: 1) being unemployed at the time of testing, 2) having a disorder or disease, including Parkinson's diseases, Attention Deficit Hyperactivity Disorder, Alzheimer's diseases, diabetes, cardiovascular disorders, respiratory impairments, or hypertension; 3) participating into professional sports or exercising more than five times a week for more than two hours; 4) working in shift work; 5) being colour-blind, or 6) being pregnant. Participants received a lump-sum compensation of €170.

The final sample included eleven female and nine male participants, with an average age of 31 years, ranging from 25 to 46. The average Body Mass Index (BMI) was 23, with the lowest at 20 and the highest at 27. The average height was 174 cm (minimum of 156 cm and maximum of 191 cm) and the average weight was 69 kg (minimum of 51 kg and maximum of 92 kg). From a socioeconomic perspective, participants were quite similar: All had a university degree, and the majority (N = 17) had a monthly gross income between €1,000 and €5,000, while two participants earned between €5,000 and €7,500, and one participant earning more than €10,000 in gross monthly salary.

This study received Medical Ethical Approval from the Clinical Trial Center Maastricht (CTCM) of the Academic Hospital Maastricht before any data collection began, adhering to the Declaration of Helsinki. Participants signed an informed consent form before starting the study and were informed of their rights, including their right to withdraw from the study at any point without the obligation to provide reasons. The approval is registered under the nation-wide Dutch number *NL77015.068.21*, internal CTCM number *METC21-033*.

4.2.3 Outcome variables

Cognitive tests: The Cambridge Neuropsychological Test Automated Battery (CANTAB) was used to assess participants cognitive functioning. Participants completed the test on a tablet computer with a touch screen. The CANTAB tests have been validated against other neuropsychological test batteries [344]. Four domains were measured: Attention, psychomotor control, memory, and executive function.

For attention and psychomotor control, the Reaction Time Task and Motor Screening Task were used. The Reaction Time Task measures the speed of movement and mental response in milliseconds when a stimulus is presented. The Motor Screening Task assesses movement latency in milliseconds when a stimulus is presented.

The Delayed Matching to Sample and Paired Associate Learning tests were used to measure memory. Delayed Matching to Sample measures visual matching ability and short-term visual recognition memory as a percentage of correct choices. Paired Associate Learning assesses visual memory and learning as the number of correct responses.

To measure executive function, the Multitasking Test, One Touch Stocking of Cambridge, Stop Signal Task, and Spatial Working Memory were used. The Multitasking Test measures the ability to manage conflicting information as the time (in milliseconds) that a participant needs to give the correct response when two contradicting stimuli are presented. One Touch Stocking of Cambridge assesses spatial planning and working memory as the number of problems solved on the first attempt. Stop Signal Task measures impulse control as the time (in milliseconds) it takes for participants to inhibit a reaction when the test initially asks for a reaction. Last, Spatial Working Memory measures strategy and working memory errors as the number of incorrect revisions from finding a specific figure among several covered fields.

A detailed description of the CANTAB tests can be found on its website [219]. To ensure a balanced loading of the different cognitive domains, the same order of testing was applied during the test days: Start with the Reaction Time Task, then Paired Associate Learning, Stop Signal Task, and Spatial Working Memory , followed by a 10-minute break. After the break, the testing continued with Motor Screening Task, One

Touch Stocking of Cambridge, Delayed Matching to Sample, and Multitasking Test. The eight tests, including, the 10-minute break, took approximately 60 minutes. The CANTAB tests were conducted twice during a test day, first in the morning after 30 minutes of exposure and then in the afternoon after 330 minutes of exposure.

Economic decision-making: In addition to general cognition, we tested how varying CO_2 levels affect economic risk and time preferences, specifically risk aversion (hereafter called ”risk preferences”) and the level of impatience when delaying a financial payment (hereafter called ”time preferences”). To elicit these preferences, we employed multiple price lists (MPLs), following the methods by Holt and Laury [167] for risk preferences and by Coller and Williams [78] for time preferences. We used six multiple price lists in total, each comprising ten choices between two neutrally labelled options, A and B. These choices were involving either lotteries for risk preferences or intertemporal prospects for time preferences, defined over monetary payoffs. Appendix Tables A11 and A12 provide summaries of all MPLs used in this experiment.

To elicit risk preferences, participants repeatedly chose between lotteries with differing levels of risk in MPL1.1, MPL1.2, MPL2.1 and MPL2.2. To assess time preferences, participants repeatedly chose between varying monetary payoffs at different points in time in MPL3.1 and MPL3.2. The order of displayed choices within each multiple price lists were randomized, while the sequence between the six multiple price lists remained fixed. To incentivise participants to reveal their true preferences, they were informed beforehand that at the end of each test day, one of the 60 presented choices would be randomly drawn, and they would receive the corresponding payments in cash at the end of the test day. If the randomly selected decision involved a choice between lotteries (risk preferences), a coin was flipped to determine the outcome of the chosen lottery. For an intertemporal choice (time preferences), participants would either receive payment immediately, or one month later, depending on their choice.

Physiological outcomes: To assess the physiological responses and thus the potential mechanism by which exposure to elevated CO_2 may impair cognitive performance, several outcome parameters were measured on a minute-by-minute basis throughout each 8-hour test day. Blood CO_2 concentration was measured continuously with a transcutaneous monitor (SenTec, Therwil, Switzerland), which was also used in a previous study [370]. For this reason, a non-invasive sensor was attached to the forehead. The software V-STATS was used to derive the data (version 5.01, SenTec AG, Switzerland). Due to occasionally, brief measurement errors, the blood CO_2 concentration data was cleaned in two steps.

First, the monitor also measured the saturation level of oxygen, which, given the respiration chamber's condition (sea level atmospheric pressure and no exercising), were expec should stay above 95 percent [69]. Thus, minute-by-minute values of the partial pressure of CO_2 were excluded if the saturation level of oxygen during the particular minute fell below 95 percent, indicating a likely measurement error. Second, remaining blood CO_2 concentration values below 30 mmHg or above 50 mmHg were removed as outliers, as partial pressure values for blood CO_2 are expected to fall within this range [243]. This resulted in removing 10.4% of the minute values for blood CO_2. Additionally, heart rate and respiration rate were measured using the Polar H10 belt (H10, polar, USA, RR interval accuracy 99.6 % [144]), which was attached around the thorax. The mobile application Polar SDK developer kit for Android was used to extract raw ECG data, while the Kubios software (Biosignal Analysis and Medical Image Group, Department of Physics, University of Kuopio, Kuopio, Finland, [357]) was used to calculate heart rate and respiration rate.

Physical activity levels were measured using the three-axis activity monitor ActiGraph (ActiGraph GT3X) with a sampling frequency of 30 Hz. The ActiGraph was placed on the right side of the hip. The Vector Magnitude counts per minute were derived from the raw data. Oxygen consumption was continuously measured in the respiration chamber using indirect calorimetry equipment (Omnical, Maastricht

Instruments, Maastricht, NL), which measures oxygen consumption over time [326]. Lastly, blood pressure was automatically measured every 15 minutes starting at each full hour, using the Mobil-O-Graph device (I.E.M. GmbH, Stolberg, Germany).

4.2.4 Experimental protocol

The detailed test protocol is shown in Figure 4.1. Participants were continuously exposed to the testing conditions for 8 hours, from 09:00 h until 17:00 h. The chamber is equipped with a desk, sink and toilet, allowing participants to remain in the chamber throughout the 8 hours, ensuring consistent environmental conditions. They were allowed to eat their own breakfast while in the room.

Additionally, participants were either provided with lunch or brought their own. The breakfast and lunch they ate during the first test day was documented to ensured that participants ate the same breakfast and lunch during the second test day. Food intake time was not standardized. Participants were provided with decaffeinated coffee if they requested coffee (they were not informed that coffee was caffeine-free).

Between the cognition tests, participants were free to spend their time with either reading or desk-based work, but they were not allowed to watch TV or sleep. They were instructed to behave as they would during a normal workday. To reduce any interference from a learning effect, participants practised the cognition test once during the screening session prior to the first test day.

Additionally, the statistical analysis described in section 4.2.5 includes a test day fixed effect and morning fixed effect to control for any variation in test score due to initial exposure to the testing condition and any possible learning effect during the testing day. To further reduce a possible bias from a learning effect, the exposure of CO_2-condition has been equally randomized among the 20 participants, as described in section 4.2.1.

Figure 4.1: Experimental protocol

Time in testing condition (min)	Time of day (hh:mm)	Testing steps and cognition tests	Physiological continuous measurements	
0	09:00	Chamber door closed	Blood CO2 level, heart rate, respiration rate, physical activity level, oxygen consumption	Systolic and diastolic blood pressure (measured every 15 minutes starting with the full hour)
30	09:30	CANTAB test (60 Min)		
60	10:00			
90	10:30			
120	11:00	Multiple price lists (15 Min)		
150	11:30			
180	12:00			
210	12:30			
240	13:00			
270	13:30			
300	14:00			
330	14:30	CANTAB test (60 Min)		
360	15:00			
390	15:30			
420	16:00	Multiple price lists (15 Min)		
450	16:30			
480	17:00	Leaving the chamber		

4.2.5 Statistical analysis

Cognitive and physiological responses: We started the analysis by estimating the linear fixed-effect regression model described in Equation 4.1 to evaluate the impact of elevated CO_2 level on the cognitive and physiological responses of participants:

$$Y_{itd} = \eta + \delta HighCO2_{id} + \lambda_t + \theta_i + \gamma_d + \epsilon_{itd} \tag{4.1}$$

Where Y_{itd} is the outcome variable measured for participant i at the time of the day t at test day d. $HighCO2_{id}$ is a binary variable that takes the value of *one* if participant *i* is exposed to the High-CO_2 condition (3,000 ppm) on test day *d* and *zero* otherwise. λ_t represents a set of binary variables capturing the exact time of the day at which certain outcome variables are measured. The cognitive tests (CANTAB) were measured twice a day, in the morning and afternoon, while the physiological parameters were continuously measured during the test day.

We aggregated the physiological parameters to hourly averages. Therefore, we defined two different sets of dummy variables included in λ_t: For the cognitive outcome variables, we included one binary variable $Morning_t$, taking the value of *one* if the test was taken in the morning session and *zero* otherwise. For the physiological parameters, we included eight binary variables $Hour_t$ each representing one hour of the test day.

In addition, we included an individual fixed effect θ_i to restrict the analysis to within-participant comparisons, and test day fixed effect γ_d to account for potential learning effects and familiarization with the testing environment when measuring cognitive performance on the second test day for each participant *i*. Lastly, Equation 4.1 includes the constant η and error term ϵ_{itd}.

With this model, the parameter of interest δ measures the impact of each participant's exposure to 3,000 ppm CO_2 concentration on test day *d* for the outcome variable Y_{itd}, in comparison to the same participant being exposed to 900 ppm CO_2 concentration on the other test day. Given the random assignment of participants for both conditions and test days, δ allows for a causal interpretation.

Finally, given the low number of clusters in our study (N = 20), which potentially violates the large-sample assumptions of analytical standard errors, we base our inference of standard errors on wild bootstrap clusters, as recommended in previous literature [62]. We applied 1,000 bootstrap replications clustered at the participant level to estimate the variance-covariance matrix. Using bootstrapped standard errors to derive significance does not require normal distribution of the outcome variable [162].

Given the relatively large number of hypotheses tested (8 tests for CANTAB and 7 tests for the physiological outcomes), we added adjusted p-values based on the method by Hommel to take the multiplicity of tests into account [169]. We provide the bootstrapped standard errors as well as the p-values based on multiple hypothesis testing with the estimated coefficients in the results table below.

Furthermore, we enhanced the baseline model from Equation 4.1 to allow the treatment effect δ_t to vary over the day. We estimated the following regression model, adding an interaction term to Equation 4.1 by interacting the treatment parameter $HighCO2_{id}$ with the time-of-the-day dummy variables λ_t.

$$Y_{itd} = \alpha + \delta_1 HighCO2_{id} + \delta_2(HighCO2_{id} \times \lambda_t) + \\ \lambda_t + \gamma_d + \theta_i + \epsilon_{itd} \tag{4.2}$$

In Equation 4.2, δ_1 represents the difference in outcome variables between High- and Low-CO_2 conditions at reference time t_0 (afternoon testing for CANTAB, and first test day hour for physiological parameters), and δ_2 represents the same difference, but measured during other times of the day in relation to t_0. Therefore, the analysis allows to draw conclusions on whether the effect of CO_2 exposure on outcome variables is time-variant, such as testing a dose-response gradient and how it influences the outcome variables.

Economic decision-making: To analyse the impact of increased CO_2 on economic risk and time preferences, we used a maximum likelihood model [239, 18, 156] to estimate preference parameters of a discounted expected utility model, similar to a previous study [18]. Utility over monetary gains is modelled assuming constant relative risk aversion (CRRA):

$$u(x) = \frac{x^{1-\alpha}}{1-\alpha} \tag{4.3}$$

where x denotes monetary gains, and α is the parameter of relative risk aversion, describing the curvature of the utility function; $\alpha = 0$

implies risk neutrality, $\alpha > 0$ risk aversion, and $\alpha < 0$ implies risk-seeking behavior. For $\alpha > 0$, the larger α, the larger risk aversion. Secondly, intertemporal choices as a measure of time preferences are modelled using a simple expected discounted utility model:

$$U(x_t, ..., x_t) = E_t[u(x_t) + \sum_{k=1}^{T-t} \frac{1}{(1+\rho)_k} u(x_{t+k})] \tag{4.4}$$

Here, ρ is the discount factor. The larger the value of ρ, the more the future is discounted, leading to a lower willingness to wait for the future payment. As a result, individuals become more impatient.

Participants repeatedly choose between two options, labelled A and B. We denote the expected discounted utility of options A and B as U^A and U^B, respectively. Our model allows for two types of decision errors to be as flexible as possible regarding the parametric assumptions. Specifically, decision noise is accounted for by a tremble error (κ) and a Fechner error (μ) [239, 20]. The tremble error measures decision errors due to choice randomization, that is individuals may randomly choose between A and B with some probability κ. The Fechner error term accounts for errors in evaluating the expected utility of lotteries: options A and B are assessed based on their expected utility plus a random element ϵ, such that an individual chooses option B if $U^B + \epsilon^B > U^A + \epsilon^A$. Overall, the probability of choosing option B is given by:

$$P(B) = (1-\kappa)F(\frac{U^B - U^A}{\mu}) + \frac{\kappa}{2} \tag{4.5}$$

where *F* is the cumulative distribution function of ($\epsilon^A - \epsilon^B$), which follows a standard logistic distribution. For $\kappa \to 0$, the tremble error has no effect on choice, and for $\kappa \to 1$, the choice approaches uniform randomization. For $\mu \to 0$, the decision becomes deterministic (conditional on not choosing at random due to the tremble error), and for $\mu \to \infty$, choice approaches uniform randomization. We estimate the preference parameters (α, ρ) and error parameters (κ, μ) of the model with maximum likelihood, using binary choice data from the multiple price lists.

Parameters are estimated jointly for all participants as linear functions of the treatment dummy $HighCO_2$ and the interaction of $HighCO_2$ with a *Morning* dummy. Given that multiple price lists are asked two times per test day, once after 120 minutes of exposure and once after 420 minutes of exposure, we added a $Morning$ fixed effect, equals one if the multiple price lists were answered after 120 minutes of exposure time. Binary controls such as sex and whether it is the first test day were added. The estimated coefficient of the treatment dummy thus indicates how much the estimated parameters differ across treatments.

4.3 Results

The results are presented in two parts. In the first part, we provide evidence supporting the validity of our experimental setting by showing that CO_2 concentration differed across the two test days, while other parameters remained constant. In addition to objective measures of indoor environmental quality, we also considered participants' subjective perceptions of the indoor environment between the two test days. We then proceed to the main part of the results, where we present the findings regarding the impact of increased CO_2 concentration on participant's cognitive performance, economic decision-making, and physiological responses.

4.3.1 Descriptive statistics of environmental conditions

Table 4.1 shows a comparison of environmental conditions between both testing conditions. In panel A, we show objective measures on the environmental conditions inside the respiration chamber for the two different CO_2 levels. The last column shows the resulting *p*-values, based on a simple *t*-test of equal means with the null hypothesis of no difference between 900 ppm CO_2 (Low-CO_2) and 3,000 ppm CO_2 (High-CO_2).

Table 4.1: Comparison of environmental conditions

	Low-CO_2		High-CO_2		
	Mean	SD	Mean	SD	P-value
Panel A: Indoor environmental quality					
Carbon dioxide (CO_2) (ppm)	918	122	3011	139	0.000
Ventilation rate (l/min)	543	28	525	12	0.000
Total volatile organic compounds (ppb)	519	365	574	317	0.156
Temperature (°C)	21	0.15	21	0.16	0.144
Relative humidity (%)	32	6	32	6	0.525
Fine particles $PM_{2.5}$ (in counts/L)	0.000	0.000	0.001	0.045	0.317
Panel B: Perception of environment					
Air quality	2.7	1.4	2.4	1.2	0.457
Temperature	3.0	1.4	3.6	1.5	0.213
Light	2.8	1.4	2.8	1.3	0.867
Noise	4.6	1.2	4.3	1.5	0.522

Note: The table shows the mean and standard deviation (SD) of objectively measured and perceived indoor environmental quality during the test day with low (900 ppm) and high (3,000 ppm) CO_2 levels. Panel A contains environmental conditions continuously measured inside the respiration chamber. Panel B shows measures reflecting participants' perceived indoor conditions collected via a questionnaire for which participants reported their satisfaction with the air quality, temperature, lighting and noise based on a scale ranging from "1 - Extremely Satisfied" to "7 - Extremely Dissatisfied". Column 1 and 3 show the average value, and column 2 and 4 the standard deviation. The last column shows the resulting p-value from a simple t-test of equal means (H_0 = no difference between High- and Low-CO_2 condition).

The targeted average CO_2 concentration was achieved for both conditions, with an average CO_2 concentration of 918 ppm for the Low-CO_2 condition (122 ppm standard deviation) and 3011 ppm for the High-CO_2 condition (139 ppm standard deviation). In the Low-CO_2 condition, the ventilation rate was slightly higher (543 l/min) as compared to the High-CO_2 condition (525 l/min). However, the average concentrations of total volatile organic compounds did not differ significantly between the Low- and High-CO_2 conditions. Additionally, temperature, relative humidity and fine particular matter ($PM_{2.5}$) concentrations were not significantly different between the two conditions.

In addition to the comparison of the objective measures of indoor environmental conditions, we also collected information on participants' subjective perception of indoor environmental quality, based on a survey that participants had to complete shortly before leaving the respiration chamber (at the end of each test day). We used an adapted version of the Center for the Built Environment (CBE) survey [175], asking participants how satisfied they were with the temperature, air quality, lighting conditions, and noise level. The satisfaction level with each item was reported based on a 7-point Likert scale ranging from "1 - Extremely satisfied" to "7 - Extremely dissatisfied".

Panel B in Table 4.1 shows the mean comparisons for these variables. There were no statistically significant differences ($p > 0.05$), which indicates that participants did not perceive indoor environmental quality differently in the Low-CO_2 or High-CO_2 condition. This confirms that participants were unaware of the testing condition. The analysis reveals no differences in objective or subjective measures of indoor environmental quality, except for the concentration of CO_2. This validates the experimental setting, thereby allowing us to attribute the outcome measures causally to CO_2 exposure.

4.3.2 Cognitive responses

Our main findings focus on the impact of exposure to 3,000 ppm CO_2 on cognitive performance and economic decision-making, starting with the effect on general cognitive abilities, as assessed by the Cambridge Neuropsychological Automated Test Battery (CANTAB). We provide the estimated treatment effects based on the fixed effects regression described in equation 4.1 in Table 4.2. The treatment coefficient $HighCO_2$ is defined as a dummy variable which is either 1 if the corresponding cognition test was done under the 3,000 ppm CO_2 exposure, or zero if it was conducted in the 900 ppm CO_2 condition. The regression results allow for direct inferences regarding the average difference in outcome variables between both testing conditions. In addition, the results of the interacted regression described in equation 4.2 in Table 4.2 assess the heterogeneity over the course of the day, describing a possible dose-response relationship of the effect of CO_2 on cognitive performance.

Focusing on the first model specification (without interaction terms), we did not find any statistically significant effect of elevated CO_2 concentrations on the cognitive domains of psychomotor control and attention, executive function, and the Paired Associate Learning task among the memory tasks. We document a statistically significant effect (at the 5%-level) for the Delayed Matching to Sample task, suggesting that exposure to 3,000 ppm improves participants' share of correct choices by 3.55%-points. However, based on the corrected p-values for multiple hypotheses testing, the effect becomes insignificant ($p = 0.2$).

For the second model specification, which includes an interaction term with the time of the day (*Morning* dummy), we observe a similar effect pattern. Only the Paired Associate Learning task, which measures memory, is affected at the 1% significance level in the High-CO_2 condition. This indicates that participants made, on average, one and a half more correct choices when asked to memorize the presented figure. Additionally, there is also a significant time effect at a 5% level, which offsets the positive effect of exposure to a 3,000 ppm CO_2 concentration. The results suggest that participants exposed for 30 minutes to the higher CO_2 concentration made, on average, two times fewer correct choices compared to when they were exposed to 3,000 ppm CO_2 for 330 minutes. However, these coefficients are also statistically insignificant once corrected for multiple hypothesis testing ($p = 0.056$ and $p = 0.184$, respectively). Overall, we document that statistically significant effects disappear once we correct for multiple hypotheses testing. The results in Table 4.2 do not provide robust evidence that exposure to a CO_2 concentration of 3,000 ppm (compared to 900 ppm) influences cognitive performance, at least as measured by the CANTAB tests.

Table 4.2: Elevated indoor CO_2 and CANTAB test scores

	Panel A: Attention & psychomotor control				Panel B: Memory			
	Reaction Time Task		Motor Screening Task		Delayed Matching to Sample		Paired Associate Learning	
High CO_2	3.587	2.025	0.493	4.445	3.550*	4.050	0.500	1.550**
	(4.622)	(6.064)	(12.651)	(16.93)	(1.518)	(2.432)	(0.288)	(0.552)
	[0.871]	[0.798]	[0.968]	[0.798]	[0.200]	[0.501]	[0.483]	[0.056]
High CO_2 x Morning		3.125		-7.905		-1.000		-2.100*
		(8.910)		(7.905)		(3.405)		(0.915)
		[0.960]		[0.960]		[0.960]		[0.184]
Fixed effects								
First test day	Y	Y	Y	Y	Y	Y	Y	Y
Morning	Y	Y	Y	Y	Y	Y	Y	Y
Participant	Y	Y	Y	Y	Y	Y	Y	Y
Observations	80	80	80	80	80	80	80	80
R^2	0.897	0.897	0.625	0.625	0.483	0.484	0.705	0.737
Adj. R^2	0.858	0.855	0.480	0.471	0.284	0.272	0.591	0.628
	Panel C: Executive function							
	Multitasking Test		One-Touch Stocking of Cambridge		Stop Signaling Task		Spatial Working Memory	
High CO_2	-11.037	-9.650	0.450	0.350	6.239	6.437	-0.400	-1,000
	(8.516)	(13.517)	(0.233)	(0.239)	(4.140)	(4.073)	(0.677)	(0.845)
	[0.715]	[0.798]	[0.311]	[0.593]	[0.570]	[0.488]	[0.968]	[0.798]
High CO_2 x Morning		-2.775		0.200		-0.396		1.200
		(14.408)		(0.358)		(8.019)		(1.035)
		[0.960]		[0.960]		[0.960]		[0.960]
Fixed effects								
First test day	Y	Y	Y	Y	Y	Y	Y	Y
Morning	Y	Y	Y	Y	Y	Y	Y	Y
Participant	Y	Y	Y	Y	Y	Y	Y	Y
Observations	80	80	80	80	80	80	80	80
R^2	0.842	0.842	0.712	0.713	0.564	0.564	0.820	0.823
Adj. R^2	0.781	0.778	0.601	0.596	0.396	0.385	0.750	0.751

Note: The table shows the results of the regression analysis as presented in section 4.2.5 with regards to the cognitive performance of participants in the Cambridge Neuropsychological Test Automated Battery (CANTAB) tests. For each outcome variable, we show two columns, with the first column containing the estimated treatment parameter δ based on Equation 4.1, and column 2 showing δ_1 and δ_2 based on Equation 4.2. Fixed effects on whether participants conduct the tests on their first test day independent of the CO_2 condition, if they conduct the test in the morning after 30 minutes of exposure, and participant fixed effect has been added. See section 4.2.3 for a detailed description of the outcome variables. Bootstrapped standard errors based on wild bootstrap clusters with 1,000 replications are shown in (parentheses). Significance levels before multiple hypothesis testing are indicated as $***p < 0.001$; $**p < 0.01$; $*p < 0.05$. In addition, p-values resulting from multiple hypotheses testing, based on the method by Hommel [169] are in [brackets].

4.3.3 Economic decision-making

We estimated the effects of CO_2 on risk and time preferences, using structural maximum likelihood estimations, similar to previous studies [239, 18, 156]. The estimated results for economic decision-making are shown in Table **??**. Both parameters of relative risk aversion α and the monthly discount rate ρ are jointly estimated as linear functions of the treatment dummy while controlling for sex, time of day, and test day. Larger levels of α and ρ indicate higher levels of risk aversion and time discounting, respectively. The results show that neither risk nor time preferences are significantly affected by the higher CO_2 concentrations. To control for decision noise, we included a Fechner error and tremble error in the structural estimations. The tremble error captures random decision-making among individuals answering the multiple price lists, and the Fechner error captures errors in evaluating the expected utility of lotteries. Both errors are not significantly affected by the levels of CO_2 exposure. In summary, we conclude that exposure to CO_2 levels of 3,000 ppm does not have a detectable effect on individuals' risk and time preferences and decision errors.

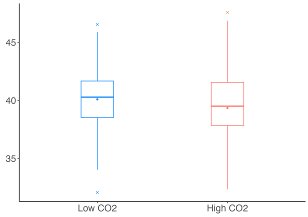
4.3.4 Physiological responses

As a next step, we evaluated the physiological responses to exposure to CO_2 concentration of 3,000 ppm versus 900 ppm. The boxplots in Figure 4.2 provide the unconditional distribution of the physiological parameters in each testing condition, and the results of the regression analysis in Table 4.3.

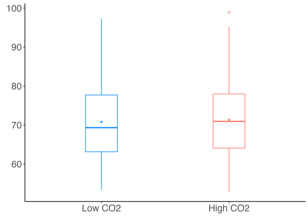
Similar to the regression analysis conducted for the CANTAB tests, we first examined the effect of elevated CO_2 concentration on the hourly average level of the corresponding physiological parameter. In this analysis, we controlled for the hour of the test day, fixed effects for each participant, and included a dummy variable for the first test day. Next, we conducted a second analysis based on Equation 4.2, where we interacted the CO_2 dummy coefficient with the dummy variables

Figure 4.2: Physiological response between CO_2 conditions

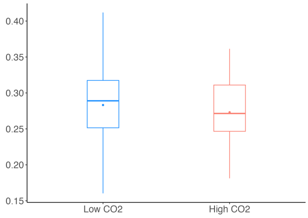
(a) Blood CO_2 concentration (in mmHg)



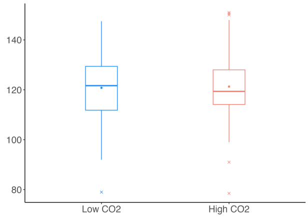
(b) Heart rate (in bpm)



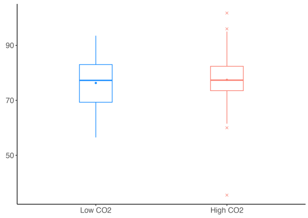
(c) Respiration rate (in Hz)



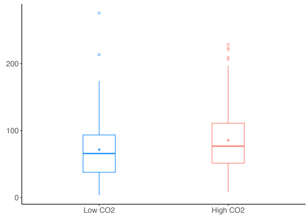
(d) Systolic blood pressure (in mmHg)



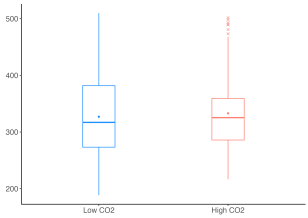
(e) Diastolic blood pressure (in mmHg)



(f) Physical activity (in counts per min)



(g) Oxygen consumption (in L/min)



Note: In the boxplot diagrams, the thick line in the middle is the median and the point is the average value of each corresponding outcome. The upper and lower edges of the box are the upper and lower quartiles. Values that are more than 1.5 times the interquartile range away from the box are considered to be outliers and shown as crosses (x). The whiskers that extend from the box show the minimum and maximum of the remaining, non-outlier values.

for each hour that participants were in the testing condition to examine a dose-response relationship.

The boxplots in Figure 4.2 indicate similar distributions between the two testing conditions. This is confirmed by the regression analysis in Table 4.3. We do not find any significant difference in participants' physiological responses to Low-CO_2 versus High-CO_2 conditions for most of the outcomes, in both model specifications. Solely for physical activity level, the regression reveals a statistically significant increase in physical activity after two hours of exposure to 3,000 ppm CO_2 concentration ($p < 0.05$). However, after conducting multiple hypothesis testing, this effect becomes insignificant ($p = 0.287$).

4.3.5 Physiological response during cognition tests

Furthermore, we examined the physiological response during the time that the individual CANTAB Cognition tests were conducted. We used a similar regression model, as described in Equation 4.1 and Equation 4.2, which includes an interaction effect between the $HighCO2$ dummy and the $Morning$ dummy variable. The dummy is equals *one* if the CANTAB test was answered in the morning, 30 minutes into exposure, and **zero** if it was answered after 330 minutes of exposure. The dependent variables in these regressions are the average blood CO_2 concentration, average heart rate and average respiration rate during the time of the individual CANTAB tests.

These physiological parameters were chosen because the human body is able to rapidly change its heart rate and respiration rate, which also impacts the blood CO_2 concentration. The individual CANTAB tests took between 1 minute for the Motor Screening Task and 12 minutes for the One-Touch Stockings of Cambridge Task.

Thus, changes in these outcomes could be expected within the short time the individual CANTAB tests were taken. In addition to a fixed effect for the first test day of the participant and a fixed effect for the

Table 4.3: Elevated indoor CO_2 and physiological response

	Blood CO_2		Heart rate		Respiration rate		Systole blood pressure		Diastole blood pressure		Physical activity		Oxygen consumption	
High CO_2	-0.628	-0.379	0.637	1.151	-0.007	0.002	1.071	1.382	1.482	0.498	12.379	3.284	6.087	9.935
	(0.586)	(0.719)	(2.226)	(2.548)	(0.011)	(0.012)	(1.552)	(2.519)	(1.017)	(1.306)	(7.925)	(9.805)	(7.167)	(8.700)
	[0.647]	[0.817]	[0.677]	[0.817]	[0.677]	[0.817]	[0.677]	[0.817]	[0.530]	[0.817]	[0.424]	[0.817]	[0.677]	[0.817]
High CO_2 x Hour 2		-0.189		-0.486		-0.013		-2.653		0.299		21.363*		3.404
		(0.288)		(1.117)		(0.008)		(3.143)		(1.672)		(9.151)		(6.272)
		[0.864]		[0.864]		[0.752]		[0.864]		[0.864]		[0.287]		[0.864]
High CO_2 x Hour 3		-0.442		-1.898		-0.007		3.486		-0.187		8.884		-0.6814
		(0.374)		(1.958)		(0.010)		(2.953)		(1.621)		(11.058)		(9.395)
		[0.824]		[0.824]		[0.824]		[0.733]		[0.895]		[0.895]		[0.895]
High CO_2 x Hour 4		-0.466		-1.062		-0.003		-1.947		0.473		-4.414		-5.584
		(0.395)		(2.248)		(0.009)		(2.903)		(1.841)		(9.473)		(7.622)
		[0.839]		[0.839]		[0.839]		[0.839]		[0.839]		[0.839]		[0.839]
High CO_2 x Hour 5		-0.365		0.523		-0.008		-0.255		1.130		18.072		-5.404
		(0.436)		(2.019)		(0.006)		(3.239)		(1.671)		(15.324)		(8.468)
		[0.925]		[0.925]		[0.856]		[0.925]		[0.925]		[0.925]		[0.925]
High CO_2 x Hour 6		-0.469		0.611		-0.008		-1.511		2.317		21.034		-3.222
		(0.371)		(2.423)		(0.006)		(2.766)		(2.616)		(11.179)		(8.947)
		[0.750]		[0.750]		[0.619]		[0.750]		[0.750]		[0.426]		[0.750]
High CO_2 x Hour 7		-0.105		-1.464		-0.017		4.632		3.759		17.817		-10.479
		(0.423)		(2.263)		(0.009)		(3.294)		(2.086)		(14.248)		(11.642)
		[0.845]		[0.845]		[0.262]		[0.621]		[0.419]		[0.713]		[0.844]
High CO_2 x Hour 8		0.052		-0.331		-0.016		-4.491		-0.012		-9.999		-2.684
		(0.592)		(2.260)		(0.009)		(3.740)		(3.282)		(14.788)		(10.398)
		[0.997]		[0.997]		[0.425]		[0.997]		[0.997]		[0.997]		[0.997]
Fixed effects														
First test day	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Hour into test day	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Participant	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Observations	311	311	288	288	288	288	295	295	295	295	312	312	288	288
R^2	0.745	0.746	0.816	0.817	0.759	0.762	0.657	0.670	0.603	0.609	0.456	0.471	0.844	0.845
Adj. R^2	0.720	0.714	0.796	0.792	0.732	0.729	0.620	0.626	0.561	0.556	0.402	0.404	0.828	0.825

Note: The table shows the results of the regression analysis as presented in section 4.2.5 with regards to the physiological response. For each outcome variable, we show two columns, with the first column containing the estimated treatment parameter δ based on Equation 4.1, and column 2 showing δ^1 and δ^2 based on Equation 4.2. The dependent variable for each physiological parameter is aggregated on an hourly average. Fixed effects on whether participants were in their first test day, the hour into exposure, and participant fixed effect has been added. See section 4.2.3 for a detailed description of the outcome variables. Bootstrapped standard errors based on wild bootstrap clusters with 1,000 replications are shown in (parentheses). Significance levels before multiple hypothesis testing are indicated as $***p < 0.001$; $**p < 0.01$; $*p < 0.05$. In addition, p-values resulting from multiple hypotheses testing based on the method by Hommel [169] are in [brackets].

participant, a fixed effect for the specific CANTAB test was also included. This approach controls for variation between testing time, participant, and individual CANTAB tests. Table 4.4 shows the results of this analysis.

Table 4.4: Physiological response during cognition tests

	Blood CO_2		Heart rate		Respiration rate	
	(1)	(2)	(3)	(4)	(5)	(6)
High CO_2	-0.468	-0.596	0.056	-0.398	-0.010	-0.019
	(0.533)	(0.515)	(2.225)	(2.662)	(0.012)	(0.011)
	[0.980]	[0.860]	[0.980]	[0.980]	[0.980]	[0.652]
High CO_2 x Morning		0.256		0.909		0.017*
		(0.414)		(2.337)		(0.007)
		[0.697]		[0.697]		[0.038]
Fixed effects						
First test day	Y	Y	Y	Y	Y	Y
Morning	Y	Y	Y	Y	Y	Y
Participant	Y	Y	Y	Y	Y	Y
CANTAB test	Y	Y	Y	Y	Y	Y
Observations	619	619	571	571	571	571
R^2	0.744	0.766	0.758	0.809	0.579	0.632
Adj. R^2	0.731	0.752	0.745	0.797	0.556	0.609

Note: The table shows the results of the regression analysis with the dependent variable as the average level of blood CO_2 concentration, heart rate, and respiration rate during the time each individual CANTAB cognition test has been conducted. Fixed effects on whether participants conduct the tests on their first test day, morning fixed effect, participant fixed effect, and individual CANTAB test fixed effect have been added. Bootstrapped standard errors based on wild bootstrap clusters with 1,000 replications are shown in (parentheses). Significance levels before multiple hypothesis testing are indicated as $***p < 0.001$; $**p < 0.01$; $*p < 0.05$. In addition, p-values resulting from multiple hypotheses testing based on the method by Hommel [169] are in [brackets].

We observe that, similar to the previous analysis, elevated CO_2 levels do not trigger any physiological response, even if cognitive load is imposed through the cognition tests. However, for the model including the interaction effect, an elevated CO_2 concentration of 3,000 ppm during the morning session of the CANTAB test (after 30 minutes of exposure) is significantly associated with a higher respiration rate ($p < 0.05$), compared to the afternoon session (after 330 minutes of exposure).

This statistical significance remains after conducting multiple hypothesis testing ($p = 0.038$ for the adjusted p-value). However, the magnitude of the effect is small: The coefficient indicates an increase in the respiration rate of 0.017 Hz, which is approximately one additional breath per minute.

4.4 Discussion

Magnitude and significance: Overall, the results show that there is no effect of CO_2 concentrations of 3,000 ppm (compared to 900 ppm) on cognitive performance and physiological outcomes. Although this study uses a similar sample size compared to previous studies (see Appendix Table A14 for an overview), the question remains about whether the estimated effects are indeed zero or if the sample size of 20 participants is simply too small to estimate the effects precisely enough to reject the null hypothesis. We addressed this question from two angles: First, we calculated relative effects, where we express the effects as changes in standard deviations of the underlying distribution of the outcome variable. This approach provides insights into the magnitude of the effects, that is whether the estimated effects are meaningful, independently of statistical significance. For instance, if the relative effects are very small, i.e., the High-CO_2 condition hardly changes the outcome variable, statistical significance is less relevant because the magnitude of the effect would be negligible. Second, we ran a post-hoc power analysis to calculate the required sample size to examine how many participants we actually would need in order to be able to estimate statistically significant effects in case the CO_2 concentration truly affects the outcome variable. Appendix Table A13 provides the results of both analyses.

For the vast majority of outcome variables, the relative effect of elevated CO_2 levels is weak to very weak, with a change of 0.2 standard deviation or less. This suggests that the magnitude of most parameters is negligible, even if they were statistical significance. Only two parameters appear to be meaningful, showing relative effect sizes of 0.41 and 0.79 standard deviations for the CANTAB's Delayed Matching to Sample task and tremble error for time preferences, respectively. However, a power calculation based on the calculated effect sizes suggests a sample size of 22 participants for the CANTAB test and 13 participants for the economic decision-making test, which is very close to and below our actual sample of 20 participants. This indicates that our inference tests are reliable and sufficient to draw conclusions about the statistical significance of this meaningful effect. Given that we find only a few significant effects based on the bootstrapped (analytical) standard errors and no statistical significance based on the multiple hypotheses tests, we conclude that the effects are statistically insignificant and, therefore, zero.

Link to previous literature: To our knowledge, this study is the first to exposed adults individually and uninterrupted to elevated CO_2 concentrations in an air tight respiration chamber for as long as 8 hours. Most previous studies used exposure times of up to 255 minutes in either climate chambers or office rooms [98]. Previous work suggests that the exposure time plays an important role in moderating the effect of CO_2, assuming that humans can withstand high concentrations of CO_2 for a certain time period [185, 40]. Only one previous study exposed adults for 8 hours in groups to different air quality conditions in an office room [7]. However, behaviour and perception can be influenced if occupants are measured in groups [327].

Our results contrast with three studies that measured complex decision-making using the Strategic Management Simulator, documenting a negative effect of CO_2 concentration on cognitive decision making [7, 322, 331]. However, one such study, which included "astronaut-like" subjects, found that the negative effect was either mitigated or even reversed at higher CO_2 concentrations [331]. This study did not conduct multiple hypotheses testing to account for the multitude of hypotheses tested. A fourth study did not find any effect of CO_2 on complex decision-making using the Strategic Management Simulator test [313].

Among previous work, the study by Allen et. al. (2016) [7] is the most similar to our setup, focusing on office workers who were exposed to elevated CO_2 concentrations for 8 hours, while measuring the concentration of volatile organic compounds to ensure low levels of these air pollutants. However, this study was conducted in an ordinary office room and no physiological parameters were measured - factors that may explain the decline in complex decision-making abilities. Nevertheless, time pressure and task complexity can be important moderators of the effect of CO_2 and indoor air quality in general on cognitive performance [201, 6, 185]. It is reasonable to assume that the CANTAB tests used in our study do not provide a high level of complexity. Furthermore no tasks uses limited time to increase mental load, except for CANTAB's tests on attention and psychomotor control. Thus, our results should be compared carefully to previous studies using the Strategic Management Simulator or tests which induce time pressure.

Nevertheless, our finding that CO_2 has no significantly negative effect on human cognition is in agreement with a series of other previous studies [404, 402]. These two studies used climate chambers and exposed their population for a short period of time (255 and 150 minutes, respectively). Although, volatile organic compound concentration was not measured during the testing to validate whether the concentrations of air pollutants have been successfully reduced. Our study extends this previous work by prolonging the exposure time to 8 hours and measuring basic cognitive domains twice during this time. While these tests are only of diagnostic nature for cognitive performance and are thus not fully comparable with office work, they show that basic cognitive functions such as attention, psychomotor control, memory and executive functions are not negatively impacted by an elevated level of 3,000 ppm CO_2.

Unique to this study, we broadened the cognition analysis, including multiple price lists from the economic literature to examine the potential effect of CO_2 on economic decision-making in terms of risk-taking and time discounting for monetary payouts. We found no effect on risk and time preferences. Previous literature suggested a potentially negative effect as lower cognitive abilities lead to more random decision-making when answering multiple price lists [20]. The multiple price lists used in our study do not induce time pressure to respond, or require complex thinking - both of which could influence the impact of CO_2. However, the simplicity and transparency of multiple price lists are strengths, as they help to truthfully reveal individual preferences [17].

Additionally, while we used common reward amounts, most studies using multiple price lists included a student population, for whom the offered rewards can be much more substantial, compared to our participants. In contrast, the maximum reward and spread offered was less than 2% of their salary [1]. Therefore, it remains uncertain whether higher rewards can induce enough stress to trigger an effect of CO_2 on economic decision-making. Nonetheless, our results are consistent, showing no effect on neither cognitive performance measured with the CANTAB test, nor for economic decision-making.

Regarding the physiological response to CO_2 exposure, heart rate and blood pressure did not show any elevated levels, which would hint towards a physiological stress response. Previous studies that measured a variety of physiological parameters found a significantly higher heart rate at 2,700 ppm and 3,000 ppm CO_2, but no difference in heart rate at 5,000 ppm CO_2 compared to a concentration of 500 ppm CO_2 [345, 403, 402]. However, while various parameters were measured to record the physiological response to elevated CO_2 concentrations, no multiple hypotheses testing was conducted in these studies to adjust the *p*-values.

[1] The highest amount offered in our multiple price lists was €44 and the largest spread €42.60. Considering that 17 of the 20 participants earned on average €3,000, this amount would account for 1.5 % and 1.4 % of their salary, respectively.

This study is the first study that specifically examined the physiological stress response during the time the cognition test was administered, to derive a possible performance-induced effect of CO_2. Past studies suggest that the cognitive load might play a mediating role in the effect of CO_2, and more generally, indoor air quality on cognition [**Du2020**, 380, 201]. However, we did not find any significant change in heart rate or blood CO_2 levels during the time of testing, which would indicate a moderating role of cognitive load. Nevertheless, we found a robust and significant increase in respiration rate if the CANTAB tests were conducted in the morning during the elevated CO_2 condition. Such an increase could reveal a compensatory mechanism against the elevated CO_2 concentration during cognitive load, although its magnitude was rather small with an increase of just one breath per minute, and it ocurred independent of any significant change in heart rate.

Furthermore, our findings do not support the hypothesis that an indoor CO_2 concentration of 3,000 ppm induces a respiratory acidosis. Neither the respiration rate nor the blood CO_2 partial pressure were significantly affected throughout the test day. Only one prior study found higher blood CO_2 concentrations after four hours of exposure to up to 5,000 ppm CO_2 [370]. However, the CO_2 concentration in that study was achieved by reducing the ventilation rate, leading to a 2.2-fold increase in volatile organic compounds concentration in the room. The authors attribute the elevation in blood CO_2 to the increased CO_2 level in the room, but did not elaborate on whether such a relationship could be mediated by the other air pollutants in the room which might had an impairing effect on the lungs [84, 343].

Previous literature assumes that air pollutants could cause changes in the breathing pattern, which in turn leads to a build-up of CO_2 in the blood due to an insufficient removal through exhalation [26, 343]. Moreover, Snow and co-authors [345] argue that the higher heart rate for an exposure level of 2,700 ppm could be indicative of an increase in circulation to maintain CO_2 levels in the blood. However, they documented no effect on respiration rate and emphasized that no blood-gas analysis was conducted to examine this hypothesis. Since we isolated the effect of CO_2 in our study setup, we cannot confirm that a respiratory acidosis is related to a CO_2 concentration of 3,000 ppm and associated with a change in respiration rate. However, we did not measure tidal volume which could be affected independently of the respiration rate. Importantly, our study does not aim to examine the claim stated in previous literature that air pollutants beyond CO_2 affect the breathing pattern of individuals [343, 26].

Furthermore, two studies found an increase in end-tidal CO_2 in exhaled air but were not able to examine the physiological reasoning for this observation [403, 402]. Increased exhalation of CO_2 can be a sign of increased cellular CO_2 production or CO_2 build-up in the blood due to increased metabolic rate. To maintain a stable pH-level, the body increases the respiration rate or tidal volume to remove excess CO_2 from the lungs [265]. However, we could not find any significant effect on oxygen consumption as a measure of metabolic rate and also no significantly higher physical activity level in the High-CO_2 condition, which would increase the energy expenditure and metabolic rate. Therefore, while we did not measure end-tidal CO_2 or tidal volume, our analysis cannot confirm that elevated CO_2 levels affect human metabolic rate, as suggested by a previous study [26].

Limitations and future recommendations: We used a validated respiration chamber and measured total volatile organic compounds continuously to ensure that our method of isolating the effect of CO_2 was successful. However, we simulated only two conditions: High- and Low-CO_2 with 3,000 ppm and 900 ppm concentration levels. In reality, CO_2 levels might be much higher. It has been shown that peak CO_2 levels in primary schools can easily exceed 3,000 ppm even in the presence of mechanical ventilation and effects of exposure to CO_2 might be non-linear [101, 120]. In addition, the study population was an average age of 25 to 46 years and had no health-related complaints. Thus, our study does not answer how CO_2 concentrations might affect individuals with respiratory restrictions, such as chronic obstructive pulmonary disease and asthma, metabolic syndrome, or mental disorders such as depression and anxiety disorder. Future studies should investigate the effects of CO_2 on health and cognition of children and elderly people. Furthermore, we used diagnostic cognitive tasks, while our study provides input on the effect of CO_2 on general cognitive performance, thus it does not provide evidence on the effect of office work. However, it is reasonable to assume that office-related tasks rarely require maximum effort or time pressure to conduct, which is similar to the cognitive tests used in this study.

4.5 Conclusion

This study used a validated respiration chamber in a cross-over, single-blind experimental design to assess the impact of chemically pure CO_2 levels on cognitive performance and physiological response in 20 healthy adults. The analysis revealed that a CO_2 concentration of 3,000 ppm compared to 900 ppm does not trigger any significant cognitive decline or any physiological response. Only respiration rate was marginally elevated during time the cognition tests were conducted, which could hint towards an adaptive mechanism to resist elevated CO_2 levels. However, respiration rate and blood CO_2 concentration (among other physiological parameters), which would indicate an impact on bodily homeostasis, were unaffected by CO_2 during the course of the day. As such, these results suggest that for healthy individuals, no negative effect of a CO_2 concentration of 3,000 ppm compared to 900 ppm on cognition and health can be expected - at least for a relatively short exposure duration of one day. These results extend the findings of existing studies, which provide equivocal findings on the influence of short-term exposure to elevated CO_2 concentrations on cognition and health.

The results are of practical relevance, because CO_2 is used as a metric for indoor air quality. Modern control-demand ventilation systems use CO_2 to adjust ventilation rates based on occupancy rate and thereby reducing a building's energy consumption. Air filtering systems cannot remove CO_2, therefore, it is important to determine if CO_2 itself should be considered an air pollutant to optimize cognitive performance of groups such as office workers and school children. However, the results presented in this paper suggest that this may not be the case. Finding no physiological reaction supports the assumption that CO_2 at the examined level of 3,000 ppm does not affect humans during an uninterrupted exposure time of eight hours. Therefore, this study provides important implications for designing indoor spaces with good air quality and developing effective ventilation strategies to optimize occupants' cognitive performance.

5

Ten questions concerning the economics of indoor environmental quality in buildings

Abstract

Indoor environmental quality in buildings encompasses various factors such as air quality, thermal environment, acoustics, and lighting. While engineering and health sciences have studied the impact of these attributes on occupants' work performance, health, and well-being, a limited number of economic studies have investigated their financial implications. However, the profitability of optimizing the indoor environmental quality for real estate developers, investors, and tenants remains unclear. This ten-question paper summarises existing literature on the economic value and costs of improvements in indoor environmental quality. The first four questions summarize existing evidence which shows that these factors influence human performance, health, and well-being through different pathways, not all of which are sufficiently understood. The second part explores the economic value of optimized indoor environments and how economic research on energy-efficient (green) buildings can serve as a suitable blueprint. The economic literature on energy-efficient buildings confirms that these buildings provide a higher value for tenants and owners, and offer a profitable case for investments in such buildings. However, to our knowledge, no research so far could effectively quantify the financial benefits of improved occupant productivity, health, and well-being due to an optimized indoor environmental quality, and how it could be used in a cost-benefit analysis to compare it with the rent and price premium tenants and owners need to pay for health-certified buildings. Existing studies estimating the economic value of indoor environmental quality improvements often rely on indirect measures and lack direct evidence linking these improvements to objectively measured productivity or health outcomes. Therefore, this paper concludes with suggestions for future research to facilitate studies on the economic value of indoor environmental quality improvements and related healthy building attributes.

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CRediT authorship contribution statement: Stefan Flagner: Writing – review & editing, Writing – original draft (introduction, conclusion, question 1, 6, 8, 9) Conceptualization, Project administration, Supervision. Stefano Schiavon: Writing – review & editing, Writing – original draft (question 5), Conceptualization. Nils Kok: Writing – review & editing, Writing – original draft, Conceptualization. Franz Fuerst: Writing – review & editing, Writing – original draft (question 7, 10). Dusan Licina: Writing – review & editing, Writing – original draft (question 1). Angela Loder: Writing – review & editing, Writing – original draft (question 10). Shadab Rahman: Writing – original draft (question 4). Frank Scheer: Writing – original draft (question 4). Lily Wang: Writing – original draft (question 3). Gabriel Weeldreyer: Writing – original draft (question 3). Hannah Pallubinsky: Writing – review & editing, Writing – original draft (question 2).

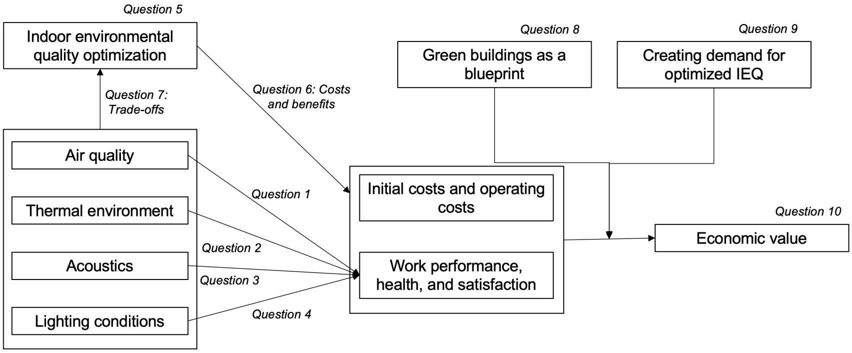
5.1 Introduction

In the early 1970s, built environment scientist Povl Ole Fanger emphasized that modern humans spend the vast majority of their time indoors [109]. Over time, this statement has been reinforced by multiple studies in North America and Europe [200, 328, 235], underscoring the significant influence of indoor environments on human performance, health, and overall well-being and related satisfaction. Key factors such as indoor air quality, thermal environment, acoustics, and lighting play pivotal roles in shaping occupants' experiences [375, 260, 12, 13]. Studies have not only demonstrated the individual effects of these factors on occupants, but also highlighted their complex interactions [360].

Despite growing evidence on the importance of indoor environmental quality (IEQ) for building occupants, much less is known about the economic value and costs of investments in IEQ optimization. For real estate developers, investors, tenants, and building managers, understanding the cost-effectiveness of improving specific IEQ elements is essential. The adoption of healthy building attributes, such as advanced ventilation and filtration systems, dynamic indoor temperature control, improved acoustical conditions, and adaptive lighting require a well-defined business case to justify adoption. Better insights into the economics of IEQ could unlock significant opportunities for the capital market to incorporate health-promoting and performance-enhancing attributes into commercial and residential buildings. Lessons from the adoption of green-certified building features, such as energy-efficient systems and water management strategies, showcase that a clear business case can accelerate investments, driving a transition toward a more sustainable built environment [100, 131].

This ten-question paper addresses the gap by reviewing existing literature on the economic value and costs of optimizing IEQ in buildings. It explores the relationships between IEQ and occupants, and synthesizes studies on the benefits and costs of IEQ-improvements. The paper aims to encourage new research on the business case of optimized

Figure 5.1: Examined relations per question



IEQ and serves as an effective guideline for stakeholders in the real estate sector designing healthy buildings and seeking to make profitable investments in the built environment.

The paper is structured around ten key questions designed to explore the economics of IEQ in buildings. As illustrated in Figure 5.1, the first four questions give an overview of current evidence on the impact of each IEQ factor on building occupants' performance, health and satisfaction. Question 5 addresses aspects of design and operation strategies for optimizing IEQ.

Questions 6 and 7 evaluate studies on the costs, benefits and trade-offs associated with IEQ investments. Question 8 explores business case parallels with green-certified buildings that can serve as a blueprint for healthy buildings. Question 9 suggests strategies to stimulate demand for improvements of IEQ and healthy buildings. Finally, question 10 focuses on monetizing the impact of IEQ improvements. Lastly, the paper concludes with suggestions for future research, aimed at accelerating the adoption of IEQ investments and fostering a deeper understanding of their economic potential in real estate development.

5.2 Question 1: How does indoor air quality affect building occupants?

Indoor air quality (IAQ) refers to the condition of the air inside buildings and its influence on the performance, health, and well-being of occupants. Indoor air pollutants comprise a broad spectrum of physical, chemical, and biological pollutants that can originate from outdoor sources, indoor activities, materials, and processes [291, 355, 320]. Many pollutants are not primary emissions, but are formed through chemical reactions, such as those involving reactive species like ozone or hydroxyl radicals [394]. Indoor pollutants are best controlled by eliminating or reducing sources and mitigating risks of chemical transformations. Additional strategies include ventilation with outdoor air (assuming outdoor air is free of significant pollutants) [7, 164], local exhaust systems, filtration, air cleaning, isolation, or other capture techniques [215].

Public interest in IAQ surged in the early 1980s following widespread reports of Sick Building Syndrome (SBS) - symptoms like headaches, fatigue, and eye or throat irritation associated with poor indoor environments and acute incidents such as carbon monoxide poisoning [393] and Legionnaires' disease [127]. These issues were often attributed to energy conservation measures adopted in buildings after the 1970s energy crisis, such as tightening building envelopes to reduce uncontrolled outdoor air infiltration without using mechanical outdoor air ventilation, which reduced the amount of outdoor air supplied indoors. Modern buildings, typically more air-tight than older structures [264], further exacerbate IAQ concerns. Advances in construction technology and the proliferation of synthetic materials have introduced a greater variety of chemicals into indoor environments [387]. Notably, for approximately 95% of these chemicals, health effects remain poorly understood [276]. Consequently, modern buildings are more likely than ever to generate and accumulate pollutants.

The mechanisms through which IAQ impacts human health differ substantially, as "indoor air" encompasses a wide range of pollutants. Numerous studies link increased air pollution levels to acute and chronic health effects, including asthma, allergies, cardiovascular diseases, and infectious diseases [97, 205, 333, 25]. Attention has predominantly been focused on respirable particulate matter because of its strong association with mortality [261]. However, other pollutants, such as radon, formaldehyde, volatile organic compounds, semi-volatile organic compounds, house dust mites, mold, and bacteria, also pose concerns. Relative humidity levels outside the 30% to 60% range have been linked with elevated stress response in occupants [305]. Carbon dioxide (CO_2), a by-product of human metabolism [291], is a widely used proxy for IAQ, though this approach has significant limitations [15, 66]. However, no systematic evidence suggests that CO_2 at concentrations typical of non-industrial buildings should be classified as a pollutant [117]. Overall, while indoor air pollution is undeniably critical for human health, the physiological responses it triggers, whether individually or in combination, are complex. Different pollutants provoke varied reactions, leading to a range of health effects that remain incompletely understood. Evidence linking indoor air pollution to chronic health outcomes remains particularly limited [218].

Beyond health, IAQ influences overall well-being, work and cognitive performance, and learning [380, 353]. Exposure to elevated pollutant levels are assumed to lead to attention impairments, physiological stress, reduced sleep quantity and quality, or higher rates of sickness-related absenteeism [380, 385, 246, 403]. These factors may directly impact occupant performance in the short term. Alternatively, sleep disturbances and increased sickness-related absences could lead to a gradual decline in work performance over the long term. Insufficient ventilation in offices has been associated with reduced work performance including cognitive performance in neuropsychological tests and decision-making abilities [98, 380], and increased sick leave [246, 46, 279]. Reduced ventilation rates in schools have been associated with poorer learning outcomes and higher rates of sickness-related absences among children [385]. Conversely, studies suggest that improved IAQ may enhance sleep quality, cognitive performance the following day [349], and reduce the intensity and prevalence of acute health symptoms reported by occupants [336, 119]. However, the mechanisms underlying the impact of IAQ on human performance remain largely hypothetical. Currently, no empirically robust evidence confirms a causal or statistically significant mediating role for the proposed mechanisms.

Understanding the distinction between physical IAQ and perceived IAQ is also critical. Perception involves the interpretation of sensory information and plays a key role in occupant behaviour, including interactions with environmental controls that influence IAQ and human performance [13]. Laboratory studies suggest that volatile organic compounds and related bioeffluents significantly contribute to perception of poor IAQ, while CO_2 appears to play a lesser role [404, 222]. Environmental factors such as temperature, humidity, and air movement also influence perceived air quality, independent of actual pollutant levels [360]. For instance, perceived air quality can improve when air temperature and humidity are lowered [108], and air movement is increased [325, 240]. However, despite advancements in ventilation standards, occupant satisfaction surveys conducted across hundreds of buildings worldwide reveal that the percentage of individuals satisfied with and positively perceiving IAQ falls significantly short of the levels prescribed by building guidelines [147].

In conclusion, evidence consistently demonstrates that IAQ affects human health, performance, perception, and satisfaction. However, the mechanisms underlying these relationships are not yet fully understood. Existing research primarily focuses on mitigating negative impacts, with limited attention given to promoting positive outcomes such as satisfaction or pleasure [12]. Thereby, most findings stem from laboratory studies, while robust field studies remain relatively scarce. Additionally, many studies rely on single dose-response and static models, overlooking the complex interactions among various indoor air pollutants and with other IEQ factors [12, 42]. Addressing these gaps requires greater emphasis on real-world research and holistic approaches, as well as consideration of the economic implications, including absenteeism, productivity, and healthcare costs.

5.3 Question 2: How does the thermal environment affect building occupants?

The thermal environment of indoor spaces is a crucial aspect of architectural design and engineering, and can influence cognition, health, well-being and satisfaction [380, 275, 306]. Four physical parameters, air temperature, relative humidity, air velocity and mean radiant temperature, partially define the thermal indoor environment [286]. To maintain a stable body core temperature of approximately 37 $\pm$ 0.5°C (98.6 $\pm$ 0.9°F), the human body is constantly working to balance out these external influences as well as internal influences (e.g. physical activity or the thermal effect of food) through three major physiological mechanisms: i) the regulation of blood flow to the skin for heat dissipation (peripheral vasodilation and vasoconstriction), ii) evaporative heat loss via sweating, and iii) metabolic heat production, with or without shivering [356]. Thermoregulatory behaviour, for example seeking sunlight or shade, finding shelter from wind, or adjusting clothing complements physiological processes and helps to prevent and reduce thermal discomfort and stress [125]. Through the combined effort of physiological and behavioural thermoregulation, humans can safely withstand a wide range of thermal environments [356, 228, 282].

Humans, just as many organisms, are natural comfort seekers. Over time, humans have shaped our (indoor) environments to meet their desires, rather than adjusting to the natural thermal environment [68]. From an evolutionary point of view, being in a state of thermal comfort provides major advantages: It saves precious resources such as water for sweating and calories for metabolic heat production, and helps maintain optimal body temperature [282]. The biological urge to seek comfort ensures physiological functioning, and thus, survival. Despite advancements in resource availability in developed nations, the urge for thermal comfort remains strong.

Providing thermal comfort is one of the main goals of international indoor environment standards such as ASHRAE 55 or ISO 7730 [22, 179]. Assuming thermal neutrality would translate into comfort for the majority of building occupants, and thus represent the optimal indoor environment. Research by P.O. Fanger in the 1970s established the indices of "*predicted mean vote*" (PMV) and "*predicted percentage of dissatisfied*" (PPD) [110, 109]. The PMV and PPD models present a straightforward method for building engineers to predict thermal comfort of building occupants, taking into account physical parameters of the thermal environment, and aspects of clothing and physical activity and metabolic rate of the building occupant [369]. Most standards adopted these indices, recommending thermally neutral indoor conditions, to minimize discomfort and ensure optimal performance [22, 179]. As a consequence, the majority of mechanically conditioned buildings are operated to provide uniform indoor environments, usually accepting only minor fluctuations around the targeted set point [282, 88]. However, the PMV has a low prediction accuracy ($\sim$34%) while the PPD is an unreliable metric [75] and has been removed from ASHRAE 55-2023 [22].

Interestingly, uniform indoor conditions and standard thermal set-points have been recommended and applied in different geographical areas, despite vast differences in outdoor climatic and cultural conditions [369]. Initially, it was assumed that universal thermal set-points should be applicable in all climatic zones, overlooking the role of acclimatization, inter-individual and population differences. However, it is now well-established and widely accepted in the field of human thermophysiology that the human body adapts to its thermal environment [358, 290, 67, 83]. Acclimatization, a natural form of functional physiological adaptation to heat and cold [79], involves beneficial changes that enhance thermal resilience. An adjustment of the core temperature balance, blood flow and skin temperature redistribution, more efficient sweating and adapted fluid balance, or increased metabolic heat production and less shivering, represent examples of physiological changes due to thermal acclimatization [358, 290, 67, 83, 281]. These physiological adaptations typically develop over a few days of exposure, stabilize over time to a new "*optimal*" situation, and thereby ensure improved thermal tolerance to the experienced thermal environment. Adaptation capabilities of the human body are, however, limited, and a slow approach to acclimatisation over an extended period of time, can aid in avoiding major discomfort [282]. Importantly, prolonged exposure to uniform and strictly controlled, thermally neutral environments, independent of outdoor conditions, attenuates opportunities for adaptation to the natural climate [228, 229].

Studies have shown that next to physiological changes, also the preferred temperature of people differs, or changes, based on the habitual thermal exposure [270, 271]. Occupants of naturally ventilated buildings in the United Kingdom reported different preferred temperatures in winter versus summer. Additionally, thermal preferences in warmer regions such as Singapore or Baghdad (up to approx. 30°C, 86°F) rise with increasing outdoor temperatures [270, 271, 269]. This concept of "*adaptive thermal comfort*" was introduced to the ASHRAE 55 standard in 2002, suggesting that in naturally conditioned buildings, thermal set-points should be linked to the mean running outdoor temperature [22, 88]. However, even though it has been more than 20 years after the adaptive comfort model was first adopted by indoor environment standards, the implementation in practice has been slow and rather limited. So far, it has only been applied as an evaluation tool, rather than in the design phase [282]. Having been limited to naturally ventilated buildings only, recently, the revised ASHRAE 55-2023 standard [21] is now also recommending the adaptive comfort model for mixed-mode buildings.

One of the critical drivers for comfort-based operation of buildings has been the question of optimal productivity. One study suggests that work performance peaks at 21.8°C (71.24°F), and a decrease of productivity by approximately 2% could be expected with every ±1°C (±1.8°F) deviation [334]. This finding shaped building standards, strengthening the argument for strict climate control [22, 179]. However, a recent meta-analysis shows a weaker relationship between productivity and the ambient temperature, in a range between $18 - 34$°C ($64.4 - 93.2$°F) [298, 214, 90]. Inconsistent findings on cognitive performance further challenge the notion of an optimal indoor temperature [380, 375, 297]. Given that multiple factors determine thermal comfort, establishing a thermal environment that is optimal for cognitive performance becomes even more complex.

In conclusion, the thermal indoor environment has major implications for building occupants and should provide a safe, healthy, salutogenic and performance-enhancing indoor environment. To this end, a re-thinking and shift in how we design and operate thermal indoor conditions is inevitable and urgent, particularly in the context of climate change.

5.4 Question 3: How do acoustics affect building occupants?

Acoustic conditions significantly influence occupant experience, performance, well-being, and satisfaction, depending on the intended use of a space. For example, classrooms require high speech intelligibility to support effective learning [377]; hospitals demand tranquil environments conducive to patient recover [173, 176]; restaurants benefit from acoustics that enhance social interactions within close proximity [311]; while storage closets typically require minimal acoustic consideration.

To achieve acceptable acoustics, one must account for (1) geometric factors that impact the distribution of reverberation in rooms, such as the room's dimensions, form, surface materials and type of construction, and (2) noise sources internal and external to the space that may influence the sound environment unduly, such as mechanical systems, alarms, occupant activity, and traffic [12]. Eliminating all ambient noise, though, is not entirely the solution to achieving optimal acoustic environments, as very low background noise levels can also create issues. Across the dynamic nature of soundscapes in occupied buildings, sudden sounds or the lack of speech privacy can become more noticeable and distracting when the background noise is too low; in these cases, some level of constant ambient noise can help to 'mask' other acoustic distractions [181, 256].

Metrics commonly used to evaluate acoustics typically include ones that categorize the overall level of ambient sound in the space, such as the A-weighted equivalent sound pressure level (LAeq), and ones that describes how long sound persists in a space after the source stops, such as reverberation time (RT). Higher reverberation times (above 1.0 sec) typically result in impaired speech intelligibility but may enhance music quality. An added complication is that acoustic performance can vary across the range of audible acoustic frequencies, 20 Hz to 20 kHz, with the speech frequency octave bands of 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz being considered most important.

Acoustic conditions in buildings significantly impact occupant task performance, their health, well-being, and satisfaction. Higher sound levels have been linked to reduced task performance [204] and student achievement scores [49]. Besides high sound levels, higher reverberation times could also impact speech perception by non-native English speaking listeners compared to native English speakers [289]. Higher sound levels (above 85 dBA) have been shown to affect both auditory health via noise-induced hearing loss, and non-auditory health such as through stress, sleep disturbance, and heart disease [28, 238].

While optimal or acceptable acoustic environments are achievable, many buildings do not address acoustics adequately, resulting in distractions, annoyance, and difficulty in communication between occupants [129]. Recent studies have found that 81% of respondents in 600 office buildings were dissatisfied with at least one aspect of their workplace, with 54% listing acoustics as a source of discomfort [285]. Elevated sound levels result in significant decreases in overall comfort and increased annoyance [386]. Additionally, acoustic discomfort becomes more pronounced when other indoor environmental factors, such as thermal comfort and air quality, are ideal [47].

To conclude, the optimal acoustical environment depends on the building use and characteristics, type of work, and occupant characteristics. Past studies provide evidence how the acoustical environment affect human performance, health, and well-being, making it an important factor to consider when optimizing the indoor environment.

5.5 Question 4: How does indoor lighting affect building occupants?

Just as our ears have two distinct functions (i.e., hearing and balance), our eyes also have two critical roles. Light enables vision, which begins at the level of the visual photoreceptors in the eye. However, light also acts through a non-visual photoreceptor in the eye to influence a wide range of non-visual (also called non-image-forming) functions. These non-visual effects can be broadly categorized into circadian resetting and acute effects, such as, pupil constriction, melatonin suppression, and increasing alertness.

Both the circadian resetting and acute non-visual effects of light are mediated by light exposure of the eye and projections from its retina to the central circadian pacemaker. This pacemaker is located in the suprachiasmatic nucleus (SCN) of the hypothalamus, for inducing circadian resetting and to many other central and peripheral targets to induce acute neurobehavioral and physiologic changes [82, 80, 389]. On the one hand, the acute effects of light on outcome measures are restricted to during (or shortly) after light exposure. The effects of light on the phase (timing) of the circadian pacemaker, and thereby its influence on physiology, alertness, and well-being, outlast the light exposure, affecting circadian rhythms across subsequent days [82].

It is thus important to think not only about the acute effects of light, but also about the circadian resetting effects of light, especially when occurring in the evening, night, or early morning, as experienced by shift workers [371, 63]. Key factors affecting non-visual effects of light include timing, intensity, duration, wavelength, and an individual's prior light exposure history [82, 63]. Typically, high-intensity and short-wavelength (blue-enriched) light is more effective in inducing physiological responses than dim and blue-depleted light [59, 399, 216, 61, 60, 217, 70, 302].

In the context of the built environment, non-visual effects of light have recently started to garner attention based on the realization that understanding and leveraging these effects may optimize work performance, health, and well-being. Research consistently demonstrates that lighting impacts neurobehavioural performance and several, but not all, cognitive domains [375]. There are differences in magnitude and in which physiological endpoints are affected by light exposure, based on whether the exposure occurs during the day or night. Nighttime exposure typically suppresses melatonin, heightening alertness and potentially disrupting sleep, which can impair alertness the following day [301].

Field studies confirm that natural light exposure has a measurable positive impact, including improving alertness, mood, and cognitive performance and reducing errors [245, 373, 45, 73]. Exposure to natural daylight in office spaces improves self-reported sleep, health, and well-being [274, 203, 396, 378, 44, 277]. In many office spaces, however, there may be limited exposure to daylight for most occupants due to design constraints and occupancy needs, necessitating electric lighting [138, 44, 114, 45, 392]. The standards for indoor lighting, however, are based primarily on optimizing visual needs (e.g., acuity), without consideration of the other physiological responses to light exposure, which can lead to suboptimal lighting for non-visual responses including worker performance [114, 45, 33].

Evidence from intervention studies underscore the benefits of optimized lighting. In an 8-week cross-over study, short-wavelength enriched white light (17,000K, with high melanopic strength) improved subjective alertness, mood, cognitive performance, concentration, and reduced fatigue, irritability, and eye discomfort compared to standard white light (4,000K) with low melanopic strength [373]. Similar interventions in schools, hospitals, and care-homes facilities have demonstrated enhanced alertness, mood, and health outcomes [257, 187, 145, 171, 148].

Emerging evidence has led to expert consensus statements and recommendations supporting the incorporation of lighting technologies engineered to support work performance and health of knowledge workers [372, 53, 112]. The only international standard for quantifying the biological non-visual strength of lighting, adopted by the International Commission on Illumination (CIE), is based on photopigment excitation, including that of melanopsin.

Importantly, melanopic strength modelled as melanopic Equivalent Daylight Illuminance (mel-EDI) correlates well with the magnitude of non-visual responses [300, 52]. The current consensus recommendation is to set daytime and nighttime (beginning three hours before bedtime) lighting intensity at ≥ 250 mel-EDI and ≤ 10 mel-EDI, respectively, in the vertical plane (i.e., plane of an observer's eye). Recommendations depend on users' sleep/wake schedules rather than clock time. For instance, shift workers require higher nighttime light levels to maintain productivity, while most other users benefit from reduced levels to support healthy sleep patterns.

In conclusion, the lighting environment has a profound effect on human physiology and therefore also cognitive performance and well-being. When optimizing the lighting conditions indoors, it is important to consider the type of tasks which needs to be performed, as well at which time of the day it needs to be performed.

5.6 Question 5: How can we optimize the design and operation of indoor environments to improve indoor environmental quality?

The design and operation of indoor environments typically approach each factor of IEQ - indoor air quality, temperature, acoustics and lighting - independently. For example, one firm may be responsible for indoor air quality and thermal comfort, another firm for lighting, and yet another for acoustics, each likely using a set of related but independent standards and building code rules. As discussed in *Questions 1 and 2*, these requirements have usually been developed based on field or laboratory experiments that focus on one dimension at a time, often targeting the "*average occupant*" [43]. However, people experience these environmental factors simultaneously, and their combined effect can influence both perception and outcomes. Research efforts have aimed to capture the interactions between these different dimensions, often referred to as "*multi-domain*" exposure and quality criteria. A critical review of multi-domain studies found that even if there are many studies on this topic, existing research lacks qualitative requirements to be included in meta-analysis. To compensate for that, they tried to develop guidelines and recommendations for designing, deploying and reporting multi-domain studies [76].

The lack of accepted and implementable knowledge that can be incorporated into standards and building codes leaves designers and engineers without a reliable foundation for making informed decisions. Currently there is a lack of a model that simultaneously accounts for the various environmental factors and their interactions. These factors often influence each other in complex ways. For instance, increasing daylight and window view might involve using open spaces and transparent vertical elements, which can create acoustical, air quality and thermal comfort issues. Similarly, improving IAQ by increasing ventilation rates and filtration levels can lead to higher noise levels. This raises the question: How do we prioritize among IEQ factors to maximize benefits?

One approach is to rely on green and healthy building certifications, such as LEED and WELL, to guide design and operational decisions. However, only a handful of field studies exist on their effectiveness, with contradicting findings, primarily relying on self-reported measures of productivity and health [10, 177, 212, 211, 189]. Additionally, these certifications typically address environmental factors separately, neglecting the interactive relationships among IEQ parameters [237]. Although, such certification schemes often include survey results asking occupants for their overall satisfaction with IEQ, which can be considered as a way to cover interactive effects. Another approach is to select a specific outcome to optimize productivity, health or well-being. Given the constraints, which are usually the minimum building code regulations, one can explore possible solutions for different types of combinations of environmental parameters. A major challenge is that there is a lack of standardized or objective measures of variables like work performance, health, and well-being. While objective measures of health can include monitoring physiological parameters, work performance and well-being are multifaceted concepts, which should be measured using a combination of objective and subjective, self-reported measures.

One proxy for well-being that has been explored is occupant satisfaction [13]. We know that occupant satisfaction is generally low in buildings. The Center for the Built Environment at the University of California, Berkeley, has the largest dataset on this topic ($\sim$90,000 answers from $\sim$900 buildings over 20 years) showing that a total of 68% of the respondents are satisfied with their workspace. Satisfaction is highest with spaces' ease of interaction (75% satisfied), amount of light (74%), and cleanliness (71%). Dissatisfaction is highest with sound privacy (54% dissatisfied), temperature (39%), and noise level (34%) [147]. One way to use this data is to address the aspects with the highest dissatisfaction, by reducing noise, providing personal control, and offering more space to occupants. Additionally, enhancing the environmental characteristics associated with high satisfaction, such as proximity to a window and having a private office, can also improve overall satisfaction [285].

Another approach involves applying a weighting scheme to the four main factors. An early attempt to do this assigned 39% of the total credits in the certification scheme to acoustics, 29% to lighting, 20% to IAQ, and 12% to thermal comfort [161]. This was obtained by quantifying the individual contribution of each factor on determining the overall satisfaction. Researchers have been using panels of experts or surveys of a large group of professionals to develop these weightings [224, 314, 202]. While certifications might simplify the complex interactions between different IEQ factors, such schemes nevertheless help to derive practical solutions for decision-makers in the real estate sector [224, 259].

Overall, there is not a deterministic solution to optimize the indoor environment and, for the time being, we will continue to rely on the ability of professionals to make the trade-off based on project objectives and constraints. The situation could be different in building operations, where occupant feedback could be collected and IEQ can be measured continuously. In that case, evidence-based improvements can be obtained. There are certification programs like WELL and RESET that guide operators towards the continuous collection of data during operation and there are products like *ComfyApp*, helping to close the feedback loop. However, evidence on their effectiveness remains scant. Future research should consider objective and subjective measures of performance, health, and well-being, in order to capture a holistic picture to assess the effectiveness of the certification schemes [126].

5.7 Question 6: What evidence exists on the cost and benefits of optimizing indoor environmental quality?

The previous questions have explored how IEQ affects cognitive performance, health, and well-being of building occupants. However, to support practical decisions, it is equally important to consider the financial costs associated with improving IEQ against the potential benefits. This question reviews existing studies on the costs and benefits of improving IEQ.

Focusing on indoor air quality, studies propose that the additional costs of increasing ventilation rates are outweighed by economic benefits in work performance, although, productivity gains were solely quantified using salary estimations [116, 221]. Additionally, adequate selection of air filtration systems can reduce the energy consumption associated with ventilation [32, 30, 252]. For example, recirculating filters within the heating, ventilation, and air conditioning (HVAC) systems have been identified as a cost-effective solution for reducing infection risks, often outperforming equivalent increases in outdoor air ventilation [25]. The efficacy and economic benefits of air filtration vary based on factors such as city-specific climate conditions, building use (residential or commercial), and health-related cost assumptions derived from epidemiological models. Furthermore, some filters may increase HVAC energy use due to added airflow resistance, underscoring the need for careful system design [252, 31, 5].

Focusing on the thermal environment, a recent review summarizes existing literature on the energy performance and economic value of using personal comfort systems [304]. A personal comfort system allows occupants to adapt their microclimate around the workplace according to their preferences. Studies estimate energy savings of 17% to 48% for cooling in spaces where localized air movement is used to reduce thermal discomfort [324]. Personal comfort systems can also lead to substantial energy savings in hot and humid climates [190]. However, the energy-saving potential of personal comfort systems depends on factors such as building type and usage, and outdoor climate. Improperly designed or operated personal comfort systems can even increase energy usage compared to conventional HVAC systems [304, 160, 332]. Introducing more seasonal and daily thermal dynamics, in consideration of the natural thermal environments, can also be considered to reduce energy demand and enhance occupant resilience at the same time [282, 192].

However, a major shortcoming of most studies on the costs and benefits is that the economic value and associated costs are solely estimated based on energy consumption simulations, labour costs (e.g. salary data) to quantify productivity, or healthcare costs [116, 121, 221, 32, 30, 252, 25, 324]. Changes in productivity were often quantified based on previous work in laboratory studies and translated into equation models to estimate changes in performance [121, 221, 193]. An unique approach among the literature is to use insurance costs for employers related to occupational disease to estimate the economic costs of negative health symptoms [193], although that implies that costs are created for insurances and employers, rather than the owner of the building who decides on IEQ investments. Therefore, these studies lack actual measures of productivity and objective health outcomes on whether financial revenues are causally linked to changes in the operation of HVAC systems, including higher ventilation rates, installation of filtration systems, or the induction of a dynamic indoor temperature.

Considering the costs and benefits of improving the indoor acoustical environment, to our knowledge, no study has so far effectively measured the related costs of improving indoor acoustics and how these costs compare to the economic benefits of improved performance, health, and well-being. This is surprising given the evidence on the negative effects of high noise levels on human performance, health, and well-being, as discussed in *Question 3* [260, 12]. Some literature focuses on the effects of outdoor noise pollution, showing its impact on health outcomes [262] and real estate valuation [254, 266, 29]. One study investigated the impact of noise on productivity in a manufacturing setting, showing that noise can significantly decrease the output rate of workers. The author estimated a productivity reduction of 3% for a 7 dB increase in noise level. Notably, the study also shows that there is only a very low willingness to pay among workers to move to a quieter workplace.

The author concludes that workers do not seem to be aware of the negative effects of noise on their work performance [89].

When it comes to lighting, its improvements present some of the most conclusive evidence of cost-benefit advantages. For instance, replacing traditional lighting with LED systems in a garment factory significantly increased production output while reducing thermal discomfort among workers [3]. Using daylight access can improve energy efficiency due to lower energy usage from electrical lighting [208], while increased daylight exposure is also related to important benefits for performance, health and well-being, as discussed in *Question 4*. These papers provide empirically robust evidence of the beneficial effects of solid-state lighting technology, which is being incorporated into workplaces to improve energy efficiency, while also providing greater control over intensity regulation and spectral modulation compared to incandescent or fluorescent lighting. These upgrades can provide a favourable return on investment from energy savings [194, 208] while providing productivity gains in a manufacturing setting [3] and improving occupants' perception of indoor lighting [194].

To conclude, although the monetary benefits of improving IEQ are often estimated to exceed their costs, there is a lack of evidence based on actual performance and health measures, as well as a lack of robust methods, such as natural experiments, instrumental variable estimations, or the use of exogenous shocks to measure actual changes in energy consumption alongside objectively assessed productivity and health outcomes. Additionally, quantifying the economic value of improved well-being relies on both objective and subjective measures. Certification schemes like WELL incorporate surveys to quantify overall satisfaction with IEQ among occupants. Some past studies on the economic value of lighting and noise reduction provide useful examples of empirical work to quantify costs and benefits. One notable example is a study that employs a quasi-experimental design, linking an increase in breast cancer mortality to the introduction of outdoor LED street lights in Los Angeles [184]. Similarly, the aforementioned study on noise and productivity levels among manufacturing workers uses an experimental setting with a randomization procedure to quantify the change in output per worker from noise reduction [89].

This study illustrates an important point: In order to monetize the potential economic value of optimized IEQ, awareness of its negative impact on performance and the associated foregone revenues must first be created. The study recorded a low willingness to pay among workers for a quieter workplace, despite the negative effect on their productivity. Without stronger evidence, it remains challenging to definitively determine whether optimizing IEQ is universally cost-beneficial. Despite previous evidence on the impact of IEQ on human performance, health, and well-being, a low level of awareness among decision-makers regarding the related costs and benefits results in a low willingness to pay for IEQ improvements. This, in turn, influences the expected return on investment for such improvements. Future research must address these gaps to more clearly quantify the economic value of IEQ improvements.

5.8 Question 7: Which trade-offs need to be considered when optimizing indoor environmental quality?

Designing and operating indoor spaces that prioritize work performance, health, and well-being involves balancing competing priorities, a process of constrained optimization. If indoor spaces were exclusively optimized for one factor, such as IAQ, while ignoring others like natural daylight, energy efficiency, or access to greenery, they would fall short to meet broader definitions of healthy buildings. From a theoretical point of view, the more constraints in an optimization process, the less likely any single factor, such as IAQ, will reach its maximum possible value. Hence, building designers and engineers must carefully evaluate and prioritize relevant parameters, deciding which aspects to emphasize and which can be de-emphasized to achieve an optimal balance, as it has already been discussed in *Questions 5* above.

Establishing a hierarchy of goals early is crucial to avoiding dilution of efforts and maintaining focus on key factors and outcomes.

IEQ aligns with broader goals of real estate management, particularly in the context of a larger sustainability strategy. For instance, maximizing natural light through large windows and skylights reduces the need for artificial lighting, thereby potentially shrinking energy consumption and carbon footprints. Energy savings of up to 60% can be achieved this way, while also maintaining visual comfort for occupants [338]. Using LED lighting is estimated to lead to a 6.7 times reduction in energy consumption [170]. However, an important caveat is that large windows may simultaneously increase energy requirements for heating and cooling due to their thermal and insulation properties.

Exposure to natural light is also linked to improved mood, enhanced sleep quality, and increased productivity, as it has extensively been discussed in *Questions 4*, which creates advantageous synergies. Similarly, non-toxic, materials, low in volatile organic compounds emissions, improve IAQ and promote overall health while reducing environmental impacts, as summarized in *Questions 1* above. Access to green spaces, such as rooftop gardens or indoor plants, can improve air quality, reduce urban heat island effect and reduce stress. These features align environmental sustainability with mental and physical health benefits [365]. Water efficiency measures such as rainwater harvesting or greywater recycling conserve resources and ensure a sustainable supply of clean water, thereby preventing waterborne diseases [341].

However, highly energy-efficient, green-certified buildings often prioritize airtightness, which can reduce ventilation and lead to issues such as mold, dampness, and elevated CO_2 or volatile organic compounds levels [258]. Poorly designed airtight systems can negatively impact respiratory health [346]. These challenges, however, can be addressed through advanced ventilation solutions like mechanical systems with heat recovery, ensuring efficiency without compromising air quality.

Furthermore, maintaining indoor temperatures within a narrow range, as dictated by standards like ASHRAE and ISO, may adversely affect physiological energy metabolism, glucose and lipid metabolism [227, 230, 226]. Research suggests that persistent thermal comfort could contribute to global obesity and diabetes epidemic [228, 236, 183, 249]. In contrast, periodic exposure to temperatures slightly outside comfort zones, both higher and lower, can improve cardiovascular and metabolic health, even for vulnerable groups such as older, overweight, and metabolically compromised individuals [228, 154, 283]. Hence, exposure to thermal conditions at the fringes of the comfort zone can not only aid in building thermal tolerance and resilience, but also enhance important health parameters. Another potential trade-off looms when thermal comfort and energy conservation are at odds with each other. Higher temperatures in winter and lower temperatures in summer require increased energy use, even with passive heating and cooling systems. While these systems reduce energy demands overall, they may not guarantee precise temperature control, potentially resulting in thermal discomfort for sensitive occupants [118]. Nevertheless, *Question 2* pointed out that allowing for a dynamic temperature shift can combine energy savings with positive health benefits.

Perhaps one of the most intractable trade-offs revolves around building and urban density versus human well-being. Higher urban density is associated with lower greenhouse gas emissions due to reduced energy use from transport and buildings [146]. However, dense environments often lack green spaces, which are critical for physical and mental health [248, 278]. This constitutes an important trade-off between what is effective for lowering carbon emissions and what is desirable from a human health and well-being point of view. Similarly, efforts to integrate greenery and recreational areas often require additional space, posing energy and design challenges.

A number of technical, organizational and urban planning solutions have been proposed to address these trade-offs. For example, advanced ventilation systems like energy recovery ventilators or demand-controlled ventilation can balance IAQ and energy efficiency [335, 207]. Biophilic design integrates natural elements, such as indoor green spaces, *"living walls"*, natural light and water features, thereby improving mental well-being and IAQ while enhancing energy efficiency by reducing the need for artificial lighting and cooling [188]. Flexible spaces, thermal zoning, and hot-desking optimize space usage and energy demands while catering to individual occupant needs [186, 195]. As mentioned in *Question 6*, a personal comfort system allows for an individualized thermal micro-climate around the workplace while reducing energy demand [304].

At the urban level, creating accessible green spaces, even if they are relatively compact, can help balance the benefits of high-density living with access to nature. For example, this can be achieved by integrating small parks or rooftop gardens into the design [157]. Finally, it is important not to overstate the magnitude of these trade-off effects in practice. For instance, a study by the U.S. Environmental Protection Agency contrasted energy cost-reducing measures with two different scenarios. The findings showed savings between 22% and 41% when no adjustments were made to improve IAQ, and between 19% and 37% when such adjustments were included [364]. This illustrates that optimizing for both health and sustainability is possible, and any residual gaps can be narrowed effectively through the measures outlined above.

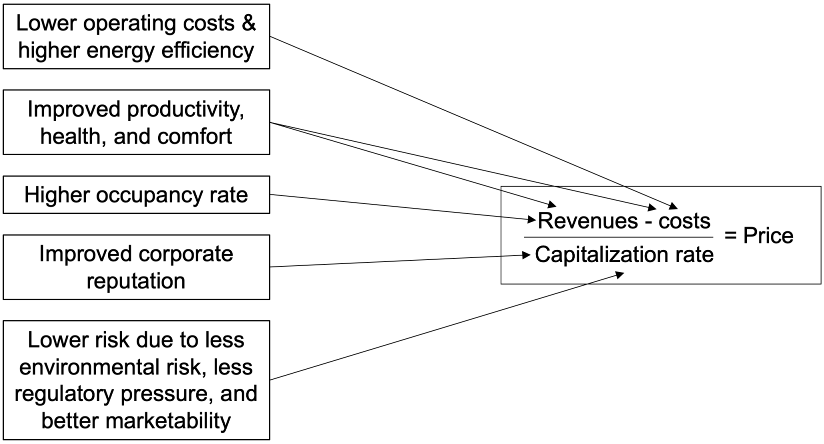
Overall, evidence shows that optimizing IEQ goes beyond just improving IAQ, thermal conditions, lighting and noise levels. More than just these four factors affect the impact of IEQ on occupants, including the access to nature, natural elements and the ability to individualize ones micro-climate. Additionally, subjective criteria such as psychological safety and mental health are only poorly researched with regards to their relation with different IEQ conditions, however these factors are equally important as objective measures of health and satisfaction to improve occupant well-being [12]. Understanding the trade-offs between these different factors is crucial to define the optimal solution for maximizing outcomes such as performance, health and well-being without neglecting aspects of energy-efficiency and sustainability criteria. Several papers have pointed out the need for a more holistic view on IEQ and its impact on occupants [126, 76].

5.9 Question 8: What can we learn from the economics of green buildings?

To define a business case for healthy buildings, it is useful to examine the development of green buildings. Green buildings focus primarily on minimizing energy, material and water use, site disturbance, and waste generation. They can be identified through certifications, with numerous schemes available worldwide [299, 237]. Investments in green-certified buildings have experienced a strong growth in recent years, driven by substantial evidence supporting their profitable business case [400]. Healthy buildings, along with their associated certification schemes like WELL and Fitwel, can be regarded as a spin-off of green buildings, emphasizing IEQ, health and well-being of occupants [237]. Understanding the economics of optimized IEQ and healthy buildings can thus benefit from insights gained from green-certified buildings.

Evidence from the last decade consistently shows better financial performance for green buildings, certified by programs such as LEED, Energy Star or BREEAM. The financial premium of green-certified buildings is attributed to several advantages, some of which are also relevant for healthy buildings. These include higher rents, higher occupancy rates, lower operating expenses, lower risk, and improved productivity, comfort and health of occupants [206, 401]. Numerous studies have confirmed that green-certified buildings command higher rents and selling prices [100, 134], although the extent of these benefits is influenced by local climate conditions and energy prices [168]. A review on green-certified buildings reported a rental premium of 6.3%, a 6% higher occupancy rate, 0.4% lower operating costs, and a 14.8% higher sales price, albeit with substantial variability in these metrics [206].

Figure 5.2: Benefits of green-certified buildings



Studies also confirm higher occupancy rates of green-certified buildings [133, 206] and better corporate reputation for investors [103], which can reduce equity cost of capital [308] and debt cost of capital [102]. Lower operating costs, while significant, only partially explain the rental premium [307], and they are not entirely driven by energy savings [206, 354]. Notably, green-certified buildings do not always achieve lower energy consumption [268, 330, 329, 16, 140]. However, variation in the market premium is linked to the actual energy performance. This illustrates that energy savings play a role in determining the value premium although the value of green-certified buildings goes beyond lower operating costs and higher energy saving potential [100].

Figure 5.2 illustrates how factors such as lower operating costs, improved productivity, health and comfort, and higher occupancy rates contribute to higher revenues and lower costs. These factors constitute the net operating income of a building. Divided by the capitalization rate, which improves due to better corporate reputation and reduced risk, this determines the price and thus value of a building.

In addition to tangible advantages, green-certified buildings offer several intangible benefits, such as higher tenant satisfaction, higher probability of renewing leases, and decreased rent concessions, all of which contribute to lower risk and increased cash flows [94]. Such intangible benefits may also include improved productivity, comfort and health of occupants, which are strongly influenced by IEQ. Nevertheless, there is mixed evidence as to whether green-certified buildings consistently lead to better IEQ and its associated benefits, such as higher productivity, better health, or higher satisfaction [10, 8, 9].

Despite these advantages, constructing green buildings often incurs higher upfront design and construction costs, leading to higher marginal costs [72, 400]. The observed cost premium ranges from a small decrease of 0.4% to substantially higher upfront costs around 11% [400]. Thus, rational investors would only invest in green buildings if the present value of future income flows and reduced risk compensates for the higher initial costs [131].

Overall, the business case for green-certified buildings illustrates that attracting investments into healthy buildings requires demonstrating positive financial returns from developing, investing in, and renting healthy buildings with improved IEQ. While green-certified buildings show the difficulty of pinpointing the exact sources of financial benefits, they also emphasize the importance of understanding not only if, but also why, healthy buildings could provide financial returns, potentially even superior to those of green-certified buildings.

5.10 Question 9: How can demand for investments in optimized indoor environmental quality be stimulated?

To examine the demand for buildings with optimized IEQ, it is important to consider the diverse stakeholders involved throughout the life cycle of a healthy building. While there are multiple incentives for investing, developing or renting a healthy building, the benefits are not evenly distributed among stakeholders. Developers primarily benefit from increased market value, especially if they plan to sell the building after construction. The new owner would benefit from a higher resale value, but also from lower operational costs, higher occupancy rates, and lower risk. Tenants, on the other hand, benefit from higher productivity, improved comfort and satisfaction, and, under certain conditions, from lower operating costs and energy savings.

Developers bear the initial costs and higher risks associated with investing in new technology to construct a healthy building. If developers sell the building shortly after construction, they must rely on higher selling prices to recoup these costs. There is indeed emerging empirical evidence that health-certified office buildings command a rental premium over otherwise comparable non-certified buildings [247, 317]. Despite this evidence from econometric studies, the principal-agency problem, characterised by information asymmetry, may impose a barrier for developers, because the true value of provided benefits might reveal itself only gradually over time [267, 339]. For example, one study shows that the resale price of green-certified residential buildings is much higher than during the pre-sale phase, indicating that developers bear most of the costs but may not be adequately compensated [92]. To address this issue, developers must signal the value of healthy buildings with an improved IEQ to potential buyers in advance to reduce this information asymmetry and receive a selling price which compensates them for additional upfront costs. Certifications from independent institutions can serve as an effective indicator of superior building quality and help bridge the information gap [132].

Owners of healthy buildings may benefit from lower holding costs due to lower vacancy rates, longer tenant retention, and reduced regulatory risk, because the building already fulfils stricter standards on IEQ conditions that might be implemented in the future [134]. Also, healthy building certifications such as WELL and Fitwel are complementary with green certification programs like LEED [213].

Thus, owners can also benefit from lower operating costs due to energy and utility savings if the leasing structure is an all-inclusive contract in which the tenant pays a fixed amount for utility costs, independent of the actual consumption. Such a full-gross leasing contract would shift the benefit of energy savings to the owner, however it provides the tenant no more incentive to save energy [401]. Owners might also benefit from improved productivity, comfort, and health, if it can lead to higher tenant retention rate.

However, most leasing contracts require tenants to pay the utility bill separately from the rent, which leads to the classical split-incentive problem [58]. While developers or owners are investing into the energy efficiency and IEQ conditions of a building, it is mostly the tenant, as building occupant, who benefits from the lower energy bill and positive effects of optimized IEQ on performance and health, given that the leasing structure excludes utility costs. So, the owner would have no incentive to invest in the energy efficiency and IEQ optimization of the building [132, 206].

The split-incentive problem regarding investments into the utility costs can be solved using an adapted leasing contract [132, 400]. However, the benefits of improved productivity, comfort and health are less easy to divide between the owner and tenant. Tenants primarily benefit from the higher productivity, better health and improved well-being, because the IEQ has a direct impact on occupants in the building. These benefits can justify the rent premium they pay to lease a healthy or green building [132, 400]. However, tenants are only willing to pay a premium rent if the improved IEQ leads to higher revenues for the tenant's firm, which exceed the additional rent the tenant would pay. To our knowledge, no research so far could effectively quantify the financial benefits of improved occupant productivity, well-being, and health, which could be used in a cost-benefit analysis to compare it with the rent premium tenants need to pay.

Furthermore, the slow adoption of green-certified buildings is often attributed to higher marginal costs and higher design fees [72], potentially also affecting the adoption rate of healthy buildings with an optimized IEQ. For example, research indicates that BREEAM-certified buildings are approximately 6.5% more expensive to construct, and these cost increases primarily come from higher design fees and building finishing and fitting costs. Although design fees are 150% higher for those buildings, they constitute only 3% of the overall costs. The challenge is that design fees often need to be paid upfront by the developer and are primarily equity financed, thus they imply a higher financial risk. A fact that aggravates this problem is that the study records an 11% longer duration for green buildings to be constructed, delaying positive cash flow for developers.

To reduce this barrier, financial institutions are increasingly offering green loans to construct or refurbish a building to make it green. These loans have lower rates and a higher loan-to-value ratio than conventional loans, making them attractive for developers to finance the upfront higher design fees [72]. Similar incentives, such as *"healthy loans"*, could incentivise developers to invest in optimized IEQ. However, banks require a clear cash flow forecast to determine favourable loan terms. Demonstrating stable returns, such as premium rents, higher selling prices, and reduced vacancy rates/higher occupancy rate, can make healthy buildings attractive additions to mortgage and loan portfolios, as they would reduce the overall risk.

In conclusion, it is important to carefully consider who bears the initial costs and who benefits from the financial gains. Obstacles to the adoption of healthy buildings, such as the split-incentive problem and higher upfront costs should be considered. Leasing structures and investment models should be created to eliminate these barriers and ensure that the financial benefits of healthy buildings are distributed among the stakeholders who bear the extra costs and make the investment decision.

5.11 Question 10: How can tenants and investors monetize indoor environmental quality?

Studies point to potential benefits for corporations of leasing or developing office spaces that provide, at a minimum, indoor environmental conditions that reduce risks to occupant health and performance, as discussed in *Question 6*. In the post-COVID era, however, corporate tenants need to know if providing good IEQ is enough to justify paying a premium rent, particularly with hybrid work being a reality in many parts of the world. This can be challenging since real workplaces have multiple interrelating factors that impact the experience of a space, and studies on the cumulative benefits of all possible IEQ conditions in the workplace are difficult given their interdisciplinary nature. Further complicating any analysis are the well-known, and often interrelated, psychosocial and organizational management factors, such as social capital, psychological safety, and perceived organizational support [288, 57, 309] and even environmental perception [73]. Thus, to understand if a healthy building is profitable for tenants and investors, three key aspects need to be addressed: i) clarification and broadening the definition of a healthy building; ii) exploring holistic approaches to workplace health and well-being; and iii) and analysing current drivers for real estate and associated risks of not investing in a healthy building.

While the evidence from a risk-management approach can provide compelling data for corporations on the benefits of better IEQ, given the competition of the home office, corporations may need to go further than the minimum to entice workers back to the office [220, 234]. After all, the working-from-home trend imposes a major challenge for the office real estate market, potentially leading to substantial financial losses [149, 244, 143]. Expanding to a salutogenic, or health-promoting approach, has been linked with positive health and well-being outcomes for built spaces. These can include Active Design [2], Activity Based Working models to increase physical activity [64], and biophilic design [406] to create places of healing, place attachment, and social cohesion, all pivotal in providing resources to employees to balance against the demands and stressors of work [315].

While these approaches are not always included in traditional definitions of IEQ, their growing research base may be a vital component of encouraging people back to the office and fostering a sense of engagement and social cohesion [347, 56]. Recent reviews have examined a range of built environment factors across disciplines that influence outcomes such as mental health [35] and overall health and performance [77], supporting the case for more holistic frameworks in workplace design.

Another approach is to look at building certifications such as LEED or WELL, which capture data across a range of built environment factors and which can indicate potential costs and benefits of investing in higher performing and potentially healthier buildings. While green-certified buildings are not always healthier buildings [10] and can conflate comfort with health, they do overlap with a risk-reduction approach to good IEQ and can be a useful metric, as it has already been discussed in *Question 8*. Multiple studies have shown that environmental certifications like LEED and BREEAM garner sale and rental premiums, indicating support for the owner to invest in healthier buildings. Recent studies on WELL buildings which focus on built environment and some organizational metrics from occupant's perspective are even better indications on the benefits of investing in or leasing healthier buildings, finding that occupants in WELL-certified spaces are more satisfied with the indoor environment, outperforming other high-performing buildings [234, 177, 189]. However, more research on the effect of the WELL certification is needed, because current evidence is scarce and inconclusive on the effectiveness of certifications on improving IAQ and satisfaction of occupants [211, 212, 189, 177].

Considering the question if healthy buildings with an optimized IEQ provide a similar return on investment than green-certified buildings, one working paper analysed office buildings with a WELL or Fitwel certification in ten cities in the US and found that assets with healthy building certifications achieved approximately 4.4% to 7.7% higher effective rent per square foot than comparable non-certified buildings [317]. Another recently published working paper records a 4% to 6% higher rental premium for WELL-certified office buildings [247]. Other empirical evidence focused on the price impact of individual healthy building features. For instance, offices in Manhattan with more natural light indoors achieve 5.0% to 6.1% more effective rent than comparable offices with less natural light [362]. However, evidence on the financial return and economic value of health-certified buildings and IEQ optimization is scarce, thus any conclusions would be premature.

Evidence on health-related characteristics at the neighbourhood level is less sparse than it is for indoor spaces, due to better data availability. For example, there seems to be a 5.6% to 7.8% rent, and 8.9% to 10.5% sales price premium for office buildings in New York in the vicinity of visible green areas compared to office buildings with very low levels of visible green areas [395]. Previous studies also demonstrate a positive relationship between the walkability of an area and real estate related prices [48, 135, 296, 303].

Despite these promising findings, current evidence is rare and does not provide strong statistical methods to examine the economic value of an improved IEQ, as discussed in *Question 6*, and only few studies investigated the economic value of a health certification. More research is needed which quantifies the benefits and costs of improving IEQ, to answer the question how tenants and investors can monetize IEQ improvements. The onset of certification schemes for healthy buildings, such as WELL and Fitwel, allows for such empirical investigations of the investment value of healthy buildings, as it has been already done for green building certification schemes [206, 400]. If more studies on the positive financial return of health certifications such as WELL arise in the future, understanding the individual contributions from various IEQ factors becomes more important in order to estimate the generated cash flows from optimizing IEQ.

5.12 Conclusion

A review of the effects of individual indoor environmental quality (IEQ) parameters reveals significant understanding of their impact on occupants. However, the interactions between these parameters and how changes in one parameter impacts others remain less understood. Certifications often treat aspects of IEQ in isolation, and the ability to trade scores may lead to the neglect of important IEQ parameters. Therefore, future research should focus on understanding the interaction of building environment factors, which also allows to identify which parameters most effectively improve occupants' performance, health, and well-being.

The economics of green buildings offer insights applicable to healthy buildings. More research is needed across the entire building lifecycle, including development, initial sale, operation, and demolition. As this paper highlights, incentives vary between developers, investors, and tenants. A holistic approach is needed, that considers all tangible and intangible costs and benefits, for establishing a profitable business case for healthy buildings and investments in IEQ. Understanding how adoption of healthy buildings shapes the availability and pricing of IEQ technologies is also essential. Increased adoption could boost supply, reduce acquisition risks, and lower uncertainty for developers regarding technologies and materials. Finally, institutional factors, such as the signalling function of certifications, should be considered in future research. Certifications can reduce uncertainty caused by information asymmetry and increase regulatory pressure on the adoption of healthy building designs.

Future research should explore if healthy buildings and IEQ investments can differentiate developers' offerings in an increasingly saturated real estate market. Comparative studies on the price and rent premiums of green and healthy buildings over time are particularly valuable. A declining premium for green buildings due to market saturation might be observed over time. Healthy buildings could emerge as a novel source of price and rent premium, because they include additional investments in IEQ, which green buildings do not cover. In this context, an improved IEQ could become a strategy to maintain a value and rental premium as highly energy-efficient buildings become the standard.

Furthermore, additional research is needed to evaluate the additional costs of health-focused certifications compared to green-focused certifications. Understand how changes in IEQ affect financial returns for investors and owners, as well as occupants' health, productivity and well-being of occupants, is critical. Such insights could demonstrate whether the benefits outweigh any additional costs during both design and operation.

Finally, the efficacy of certification programs in achieving their intended IEQ outcomes requires scrutiny. Objective measures are needed to confirm whether certified buildings meet IEQ targets and how these align with enhanced financial performance. Special attention should be given to the financial return of benefits of improved productivity, health and well-being. Understanding these pathways is important for developing cost-effective schemes to design or renovate buildings that optimize IEQ while ensuring attractive returns on investment.

6
General discussion and conclusion

This thesis discusses the impact of indoor air quality on human cognitive performance and health. The results show that indoor air quality substantially affects learning outcomes in primary school children, independent of any influence of sickness absence in this relationship. Additionally, university students believed that the indoor environment positively affects their performance in class. However, contrary to these beliefs and findings in primary schools, the indoor environment did not significantly affect course grades of students. These two field studies use carbon dioxide (CO_2) as an estimator for indoor air quality. However, a third study in this thesis shows that exposure to elevated CO_2 concentration commonly found in classrooms did not result in lower cognitive performance or adverse health effects. Lastly, the fourth paper in this thesis discusses the economic implications of investing in the indoor environmental quality of buildings, indicating that more work is needed to analyse the costs and benefits of improved indoor environmental quality for tenants and investors. This sections discusses the results of the thesis in line of previous work and proposes recommendations for future research.

6.1 Exposure time to indoor air quality moderates its impact

Distinguishing between the short-term and long-term effects of exposure to poor indoor air quality is essential. Most laboratory studies expose humans for short periods, typically only a few hours [98]. These studies provide evidence that exposure to poor indoor air quality can lead to immediate cognitive impairments in various settings. However, these studies are conducted in a laboratory setting, therefore they might not entirely explain findings from field experiments. For example, evidence confirms that poor indoor air quality and insufficient ventilation in school classrooms negatively affect long-term academic achievement of school children [385]. Several important aspects need to be considered when comparing the results from laboratory studies to the findings in the field.

First of all, school children are consistently and frequently exposed to a certain indoor air quality condition. They spend several hours per day - excluding regular breaks outside of the building - in the same classroom for months. Thus, while laboratory studies provide insights into how short-term exposure to poor indoor air quality affects cognitive performance, field studies illustrate the long-term consequences of accumulated exposure on learning outcomes.

Academic achievement is often measured in these studies in the form of achieved test scores. While the performance on a cognition test depends on the immediate mental state, test scores from exams in school settings strongly depend on learning performance prior to the test. Thus, cognitive tests and test scores from school exams are not entirely comparable. However, laboratory studies on cognitive performance and short-term indoor air quality exposure provide evidence of a possible mechanism related to school performance. Given that short-term exposure to poor indoor air quality immediately impairs cognitive performance [98], repeated exposure could reduce the effectiveness of learning and thereby hindering knowledge accumulation over time. This could ultimately result in lower test scores.

The results in **Chapter 2** empirically support a negative effect of frequent, long-term exposure to poor indoor air quality on academic achievement. The analysis shows that children who were exposed to poor indoor air quality during a 3-month learning period prior to the testing date, recorded lower exam scores. This reveals an ex-post negative impact on learning outcomes, from an ex-ante frequent exposure. Comparing these findings with the results in **Chapter 3** further highlights the importance of exposure time. Students in **Chapter 3** were exposed to the indoor environment for a short period of time every week (4 hours per course), while the majority of learning took place somewhere else, either in the library, dedicated learning spaces or at home. In contrast, primary school children spend a substantial amount of time in the same classroom every day. Thus, the exposure time to the specific classroom environment is much shorter for the case of **Chapter 3**, which may explain why university students' course grades are not significantly affected by the indoor environmental quality. This highlights the importance of exposure time on the impact of indoor air quality, as previously suggested in laboratory studies [98].

6.2 Sickness absence as mediator of indoor air quality and learning outcomes?

Learning outcomes may be impacted by indoor air quality in the long run, because frequent exposure to poor indoor air quality can reduce cognitive performance during learning, as laboratory studies suggest [98]. Thereby, frequent impairments of cognitive performance, leading to reduced learning abilities, can accumulate to a substantial effect in the long run, which results in lower exam scores. However, the long-term influence of repeated exposure to poor indoor air quality allows for other mechanisms that can explain any long-term consequences on academic achievement, compared to short-term exposure. Sickness absence can be such a mechanism, which can explain the long-term relationship of indoor air quality on academic achievement [380]. Assuming a mediating role of sickness absence seems plausible, given earlier studies that show a strong association between indoor air quality and sickness absence in school children [340, 241, 137]. Moreover, frequently being absent can reduce academic achievement, due to less time in school [199, 191].

However, the study in **Chapter 2** cannot confirm a mediating role of sickness absence on the relationship between indoor air quality and academic achievement. Indoor air quality did not influence the sickness absence rate of children, nor did sickness absence affect test scores. A major difference between this study and earlier studies was that the field study in **Chapter 2** applied a longitudinal design, following the same child over time being exposed to different indoor air quality conditions. Additionally, data on test scores and sickness absence on child level were used. Earlier studies considered only the cross-sectional relationship and have absence data only on classroom level [340, 241, 137]. Therefore, the results in **Chapter 2** provide robust statistical evidence that indoor air quality directly affects learning outcomes of primary school children, regardless of sickness absence as a potential mediator.

6.3 The role of CO_2 for cognitive performance

The field studies in **Chapter 2** and **Chapter 3** both used CO_2 as a proxy for indoor air quality. CO_2 is a useful metric for indoor air quality, as its concentration strongly correlates with that of other air pollutants in the room due to shared emission sources [291, 292]. However, past studies show conflicting findings regarding the direct impact of CO_2 on cognitive performance [98]. To examine the impact of CO_2 on cognitive performance, **Chapter 4** presents results of a laboratory study on healthy adults exposed to 3,000 ppm CO_2 concentration and 900 ppm. The study found no meaningful or statistically robust effects of CO_2

on basic cognitive domains, such as attention, memory and executive functioning, nor on economic decision-making.

These findings suggest that CO_2 does not meaningfully affect the cognitive performance of healthy adults. Past studies that found a negative effect of CO_2 focused on strategic decision-making [7, 322, 331], however, two of these studies show inconsistent results reporting both negative and positive effects of CO_2 [322, 331]. These studies tested numerous outcomes but did not conduct multiple hypothesis testing to examine the statistical robustness of their results. One of the strengths of the study in **Chapter 4** is its use of multiple hypothesis testing as a robustness check. Before adjustments, CO_2 appeared to affect cognitive performance, however, as in previous work, the effects varied in direction depending on the cognitive outcome. However, the results in **Chapter 4** are not robust to multiple hypothesis testing, thus the study cannot empirically confirm the hypothesis of any effect of CO_2 on cognition performance.

Another study using the same test for strategic decision-making also found no effect of CO_2 [313]. However, this study included submariners, whose fitness levels differ from those of the general population, limiting the generalizability of the results. This leaves us with the study by Allen et. al. (2016) [7] which examined office workers and compared the impact of CO_2 alone, and in combination with other air pollutants on cognitive performance. The study found that CO_2 and volatile organic compounds - which are commonly found together indoors [355] - independently affected strategic decision-making.

The results in **Chapter 4** do not necessarily contradict those of Allen et. al. (2016) [7], as strategic decision-making is a complex task that requires greater mental effort. Previous research suggests that task complexity and time pressure may mediate the potential influence of CO_2 on cognitive performance [98, 201]. However, most office and school work do not typically require complex strategic decision-making. Therefore, **Chapter 4** broadens our understanding of CO_2's impact on cognition performance by applying statistical robustness checks, and demonstrating that at commonly occurring indoor concentrations, CO_2 does not meaningfully affect basic cognition functioning or economic decision-making. But, is CO_2 harmful for human health?

6.4 CO_2 and its health effects

One hypothesis is that high levels of air pollutants may restrict lung function, leading to insufficient exhalation of metabolically produced CO_2 [343]. This could result in a build-up of CO_2 in the blood, causing respiratory acidosis. Such an acidosis may impair cognitive performance by disrupting homeostatic balance in the body and brain. One study examined the impact of CO_2 and air pollutants on lung function and found a negative effect on lung performance [343]. Earlier work documented elevated CO_2 levels in the blood after 4 hours of exposure to 5,000 ppm ambient CO_2 concentrations, co-occurring with high levels of volatile organic compounds due to restricted ventilation [370]. The authors associate the elevated blood CO_2 concentration with high ambient indoor CO_2 concentrations, but were unable to isolate the effect of CO_2 due to its co-occurrence with other air pollutants. The results of these two papers lead to the assumption that air pollutants affect respiration, which disturbs homeostatic balance of the body, implying adverse health effects, however the role of CO_2 in this relationship is still unclear.

Chapter 4's findings suggest that higher CO_2 concentrations (3,000 ppm) does not significantly affect key health metrics, such as heart rate, blood pressure, physical activity level, oxygen consumption, or blood CO_2 levels, when compared to a CO_2 level of 900 ppm. This challenges the assumption from earlier work that ambient CO_2 levels result in increased blood CO_2 concentrations, leading to potential homeostatic imbalance [370]. Therefore, the results **Chapter 4** do not support the hypothesis that ambient CO_2 levels directly impact blood CO_2 levels or cause significant adverse health effect.

Assuming that blood homeostasis remains unaffected by ambient CO_2 concentrations commonly found indoors seems to be plausible, considering the sophisticated mechanisms the human body employs to regulate even the slightest changes in blood CO_2, blood oxygen, or pH-level [265]. Peripheral chemosensors in the carotid arteries and central chemosensitive neurons in the ventral parafacial nucleus of the brainstem monitor the partial pressure of CO_2 and oxygen, as well as pH-levels in the blood and cerebral fluid of the brain. These neurons send signals to the pre-Bötzinger Complex in the ventralateral medulla of the brainstem to increase or decrease the breathing rate and thereby regulate blood homeostasis. This system is highly sensitive to changes in the homeostatic balance. For example, a 2.5% increase in partial pressure of CO_2 in the blood from 40 to 41 millimetres of mercury (mmHg) leads to a 40% increase in breathing rate, resulting in a 2 litre increase in breathing volume per minute [265].

Keeping this in mind, **Chapter 4** recorded a significantly higher breathing rate during the cognitive tests when the CO_2 concentration was elevated. The lack of a significant change in blood CO_2 in **Chapter 4** may therefore be explained by the increased breathing rate, as a build up of CO_2 in the blood is avoided due to more air being exhaled. Importantly, these results can neither confirm nor reject findings of restricted lung function, since earlier studies considered the effect of CO_2 in conjunction with other air pollutants on lung functioning [343]. However, the findings in **Chapter 4** contradict the hypothesis from earlier work [370] that ambient CO_2 at commonly occurring indoors concentrations affect blood homeostasis. These results support the assumption that the human body is resilient to elevated indoor CO_2 levels through an adequate physiological response.

Chapter 4 also sheds light on the influence of CO_2 on metabolic health. One study estimated metabolic rate and suggested a lower metabolic rate when individuals were exposed to poor indoor air quality [26].

However, this study measured a group of individuals in a standard room rather than a validated respiration chamber for metabolic research. Therefore, the findings need to be interpreted with caution. **Chapter 4** measured each participant individually in a validated respiration chamber [326], and showed that oxygen consumption, as a measure of metabolic rate, was not affected by a higher CO_2 concentration.

Nevertheless, no research has investigated the effect of CO_2 in combination with other air pollutants on substrate oxidation using indirect calorimetry. Therefore, further research is need on the effects of indoor air quality on respiratory behaviour, blood homeostasis, and metabolic rate, to determine whether higher concentrations of air pollutants lead to respiratory acidosis due to impaired lung function, possibly exaggerated by a higher metabolic rate.

Interestingly, CO_2 might be more than just a proxy for indoor air quality when examining its impact on communicable disease. Recent studies presented findings showing that ambient CO_2 concentration can affect the survival rate of some airborne viruses indoors [152, 151]. There is evidence that shows how insufficient ventilation can increase the risk of airborne infections and trigger respiratory symptoms, which would cause a higher sickness rate [209, 263, 130].

However, **Chapter 2** could not confirm a significant association of indoor air quality, determined by CO_2 concentration, on sickness absence of children, contradicting pervious studies that found a negative association [353, 241, 137, 91]. Furthermore, previous studies examined this relationship cross-sectionally based on proportion of sick children per classroom, whereas the study in **Chapter 2** followed the same child over time under varying indoor air quality conditions. Thus, using a longitudinal study design, **Chapter 2** did not empirically confirm a negative effect of indoor air quality on sickness absence in school classrooms.

6.5 Self-reported vs. actual performance

The findings in **Chapter 3** are particularly interesting because they reveal that perception and beliefs about the impact of the indoor environment on learning performance do not necessarily reflect actual performance. Students in the WELL-certified, newly renovated building did not achieve significantly different course grades than students in the conventional building. However, when specifically asked about the impact of the indoor environmental quality, they believed that the indoor environment had a supportive effect on their learning performance.

A possible explanation could be that students had higher expectations towards the indoor environmental quality of that building due to the signalling effect of the WELL certificate. The context and beliefs shape the expectation of occupants in accordance with the psychological adaption framework, and therefore influence the rating of occupants [87]. Individuals do not rate their satisfaction or perception in isolation, instead they often anchor it to a previously established framework, a heuristic bias referred to as 'anchoring effect' [136].

Chapter 3 provides noteworthy results regarding students' ability to distinguish between indoor environmental and non-environmental quality factors such as interior design, furniture, or general appearance of the indoor space. In this study, students in the renovated building reported a high satisfaction with the non-environmental quality factors, and also believed that the interior design had a positive effect on their mood and performance in class. Such non-environmental factors can influence general satisfaction with the indoor environment independently of the actual indoor environmental quality [323, 128, 211, 212]. Past studies support these assumption, pointing out discrepancies in actual indoor environmental quality and the perception of it [141, 351]. The results in **Chapter 3** reveal that occupant perception and satisfaction with environmental factors beyond indoor environmental quality are important factors to consider. Additionally, self-reported performance appears to be biased, making it a poor estimator of actual performance. Therefore, field studies that rely on self-reported performance measures cannot generalize their findings to actual performance changes.

6.6 A business case for healthy buildings

In order to foster the adoption of healthy and performance-promoting indoor environmental quality in buildings, it is important to consider the economic costs and benefits of it. The development of green, energy-efficient buildings, and their adoption over the last decades, provides a blueprint for successful capitalization of healthy buildings. Investing in the sustainability and energy efficiency of buildings has been shown to be a profitable business case, providing real estate investors with competitive market returns [401]. Such green buildings show a higher property value, lower vacancy rate, and building owners are enabled to ask for a premium rent, which tenants are willing to pay [100, 168]. A higher willingness to pay from the tenant signals an economic value in renting green buildings. However, much less is known about the economic value of improved indoor environmental quality.

Chapter 5 reviews the current literature on the effect of indoor environmental parameters, such as air quality, temperature, acoustics, and lighting on occupants, and if investing in the indoor environmental quality shows a profitable return for real estate investors and tenants. This review illustrates that much is known about the effect of individual environmental factors on humans, emphasizing the importance of indoor environmental quality on occupants' productivity, health and well-being [375, 260, 12].

More importantly, **Chapter 5** shows that there is a lack of evidence that answers the question if investing in improving the indoor environmental quality in buildings is profitable for investors and for tenants.

No thorough analysis has yet been done to examine whether healthy buildings provide a profitable business case.

The review in **Chapter 5** points out that studies were not able to quantify tangible economic benefits of improved health and performance, and higher satisfaction levels of occupants. However, parameters such as higher ventilation speed and the related increase in energy consumption can be easily and directly measured. Thus, there is a mismatch between the feasibility of quantifying economic costs and benefits of investments in improving indoor environmental quality.

Most of the studies that aim to determine the economic benefits of improved indoor air quality apply simplified, "*back-of-the-envelope*" calculations, and use building models to estimate the impact on energy consumption [121, 122, 252]. However, field studies or observational studies that effectively measure and quantify productivity gains and health benefits which are causally linked to improved indoor environmental quality are missing.

Determining these benefits is crucial to foster the adoption of healthy building standards. Initial costs and time required to develop and construct a building with improved indoor environmental quality can be higher and longer, respectively, compared to a conventional building. For example, developing an energy-efficient building often comes with higher marginal costs and higher design fees that need to be paid upfront [72].

Additionally, it is unclear if certification schemes for healthy buildings, like WELL and Fitwel, are also successfully achieving their intended outcomes of a health- and performance-enhancing indoor environmental quality, considering previous examinations of WELL [211] and regarding the results in **Chapter 3**. There is an urgent need to quantify the economic benefits of improving the indoor environmental quality and investing in healthy buildings.

6.7 Recommendations for future research

6.7.1 Population-specific resilience levels

Current evidence on the effect of indoor air quality on humans is mostly done in healthy adults or children. However, considering the effect sizes of past studies, a recent review observed large variation in the magnitude of the effect for different populations [98]. No studies that specifically investigate how different population groups react to the exposure to indoor air quality exist. Therefore, there is no understanding of resilience factors against unfavourable indoor air quality conditions. Given that there is also no sufficient understanding of the physiological mechanisms explaining the observed effects on cognitive performance and health, investigating different population groups can help identify a possible mechanism. It is plausible to assume that different population groups, in terms of age, sex, fitness level, or diseases status, respond differently to indoor air quality exposure.

Physiological factors such as metabolic rate, heart rate, and respiration rate differ between children and adults, which could modulate the volume and rate of inhaled air pollutants and other toxic substances [139, 124, 34]. It is apparent that the effect of indoor air quality and CO_2 on cognitive performance are more profound in pupils and students and no effect on professional divers and submariners, who are generally more physically fit [98]. Being overweight or obesity also plays an important role in the functioning of the respiratory system [312]. Sex differences in the respiratory system could influence the effect of indoor air quality on health as well [250]. Moreover, patient population should be considered, including patients with respiratory syndromes (chronic obstructive pulmonary disease (COPD), asthma, allergies), cardiovascular conditions, (hypertension, heart disease), and mental disorders (depression or anxiety disorders). These groups could show a stronger reaction to exposure to indoor air pollutants than compared to healthy adults.

With regards to indoor air quality and school performance, there is vast literature on the effects of health behaviour on academic achievement. It has been shown that a healthy diet and high levels of physical activity and cardiovascular fitness are positively correlated with academic achievement in school children and adolescence [233, 96, 39, 99]. Additionally, being overweight or obesity is correlated with general cognitive performance and the risk for developing asthma. The latter is especially important, considering that lung functioning may be an important resilience factor for the effect of indoor air quality [74, 210].

6.7.2 Building up health - Examining resilience factors

Further research in these specific populations is important due to the increasing prevalence of these diseases. As an example, the prevalence of asthma is increasing in Western countries, with more than 10% of the population suffering from this condition [93]. Ignoring the influence of asthma on the role of indoor air quality and health would therefore mean excluding a substantial part of the population. Moreover, observed differences in the response to indoor air quality also provides insights in building resilience against poor indoor air quality exposure. Assuming that poor cardiovascular fitness and being overweight or obese play an important mediating role, interventions that improve cardiovascular fitness and having a healthy weight can build up resilience. Much more work is needed on the impact of indoor air quality and indoor environmental quality for different population groups.

6.7.3 Interaction of indoor environmental quality parameters

Another often neglected aspect of indoor air quality is the interplay with other indoor environmental parameters, such as temperature and humidity. Some previous work has shown that indoor temperature and humidity have a profound impact on the satisfaction with indoor air quality [360]. In return, humidity might modulate the perception of indoor air quality on respiratory symptoms [391]. However, there are only a few studies that investigate the interactive effect of several indoor environmental quality parameters, and how indoor air quality interacts with factors such as the thermal environment. Recent reviews have emphasized the need for more studies on the interactive effects [98, 213]. Considering that certain indoor air quality conditions rarely occur in isolation, understanding their interactions is highly relevant.

Chapter 3 aims to contribute to this discussion by examining the holistic effect of a WELL-certified, newly renovated, and refurbished building on students' perceptions and satisfaction. The results highlight the importance of considering indoor environmental quality parameters and non-environmental factors when aiming to understand the overall impact of a building, designed to enhance well-being of its occupants.

6.7.4 Indoor environmental quality and sustainable employability

Indoor environmental quality is also related to occupational health management and sustainable employability. Sustainable employability focuses on how to maintain the health and well-being of employees, and decrease chances of a premature end of employment due to health conditions. A common definition of sustainable employability says that *"sustainable employability means [...] workers [...] enjoy the necessary conditions that allow them to make a valuable contribution through their work [...] while safeguarding their health and welfare"* (p. 74 in [368]). Sustainable employability should target four major components, such as health, productivity, valuable work, and long-term perspective [159].

The health and productivity components are strongly influenced by the physical indoor environment at work. This qualifies improvements in indoor environmental quality of the workplace as an intervention for occupational health and sustainable employability. It makes investing in indoor environmental quality a key component of occupational health management. With this in mind, investing in the physical indoor environment should go beyond removing health hazards towards a human-centred approach of promoting health and well-being of workers [213]. Bringing these two research fields together would extend the scope and highlight the importance of providing a health- and performance-optimized indoor environmental quality for occupants.

6.7.5 Healthy buildings - combining the *E* and *S* in *ESG*

Corporations are increasingly required through regulations and reporting standards to take measurable actions in their corporate activities related to the environmental, social, and governance (ESG) aspects [37]. The environmental part includes reducing greenhouse gas emissions by constructing energy efficient buildings. The social part focuses on employees' well-being and health [361, 374].

A healthy building which achieves a high energy efficiency score and provides a healthy indoor environment can therefore be seen as a tool to promote sustainable employability and complying with regulations with regards to ESG. The new Corporate Sustainability Reporting Directive, initiated by the European Union for corporations operating in member states, require companies to report on their ESG activities and how it impacts the profitability of their business [106].

Investing in indoor environmental quality clearly plays a role in ESG activities, not only due to its influence on occupant health, but also the relation to energy efficiency of buildings. In the best case scenario, an optimized indoor environmental quality would even be essential for the corporations' profitability and competitiveness, as it has been shown for green buildings, which provide a profitable business case [100, 168].

6.8 Conclusion

To conclude, while the findings in this thesis aim to shed light on aspects of indoor air quality, human cognitive performance, and health, much more work is needed to fully understand the impact of indoor air quality, both from a human-related, and an economic perspective. This discussion highlights several aspects to consider for future research, including the importance of understanding the physiological drivers behind the impact of indoor air quality, and, related to this, the underlying mechanisms that explain its effect on cognitive performance and health. Understanding the physiological drivers helps to examine the influence of indoor air quality on health and most importantly respiratory health.

Additionally, investigating the interaction of indoor air quality with other indoor environmental factors is increasingly important. Lastly, in order to make a substantial shift towards a healthy and performance-enhancing building design in the real estate sector, the economic value of improved indoor air quality - and more broadly indoor environmental quality - needs to be made tangible and measurable.

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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.

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.

Samenvatting

Luchtkwaliteit is vaak een agendapunt geweest van beleidsmakers die de volksgezondheid willen verbeteren, met de nadruk op *buitenlucht*vervuiling veroorzaakt door verkeer en economische activiteiten. Echter, sinds de COVID-19-pandemie is het publieke bewustzijn over de luchtkwaliteit binnenshuis in woningen en openbare gebouwen toegenomen. Onderzoek naar de invloed van luchtkwaliteit binnenshuis op de menselijke gezondheid en cognitieve prestaties is veel ouder dan de uitbraak van COVID-19.

Dit onderzoeksgebied koppelt slechte luchtkwaliteit binnenshuis aan lagere cognitieve prestaties bij volwassenen, slechtere schoolresultaten bij schoolkinderen en nadelige gezondheids effecten, wat kan leiden tot hogere ziekteverzuimpercentages. Desondanks is een deel van het bewijs tegenstrijdig; veel van het onderzoek is gebaseerd op zelfgerapporteerde gezondheid- en prestatiemaatstaven, en laboratoriumstudies domineren, terwijl veldstudies over de invloed van luchtkwaliteit binnenshuis op cognitieve prestaties schaars blijven. Het doel van dit proefschrift is om het huidige onderzoek naar luchtkwaliteit binnenshuis uit te breiden. Dit proefschrift presenteert twee veldstudies in onderwijsgebouwen, een laboratoriumstudie over de invloed van kooldioxide (CO_2), en een overzicht van de economische implicaties van een betere luchtkwaliteit binnenshuis, en nog breder, een verbeterde binnenmilieu kwaliteit.

Hoofdstuk 2 presenteert de bevindingen van een veldstudie uitgevoerd op zeven basisscholen. Gedurende een schooljaar werd de luchtkwaliteit gemeten in 61 klaslokalen, waarbij de concentratie van CO_2 als maatstaf voor de luchtkwaliteit werd gebruikt. Verder werden gegevens per kind verzameld over de resultaten van een gestandaardiseerde test en het aantal ziekteverzuimdagen gedurende het schooljaar. Het doel van de studie is om de relaties tussen luchtkwaliteit binnenshuis, ziekteverzuim en testresultaten te onderzoeken. Meer specifiek wordt de hypothese gesteld dat ziekteverzuim de belangrijkste weg is waardoor luchtkwaliteit binnenshuis de behaalde testresultaten beïnvloedt.

De resultaten van de studie tonen aan dat kinderen die worden blootgesteld aan slechte luchtkwaliteit binnenshuis, aangegeven door hoge concentraties CO_2, lagere testresultaten behalen. Ziekteverzuim wordt echter niet beïnvloed door de luchtkwaliteit binnenshuis, noch is het gerelateerd aan testresultaten. Deze bevindingen wijzen erop dat luchtkwaliteit binnenshuis de academische prestaties van schoolkinderen direct beïnvloedt, onafhankelijk van ziekteverzuim als een mogelijke verklaring. Deze bevinding heeft belangrijke beleidsimplicaties, aangezien het aantoont dat het verbeteren van de gezondheid van kinderen door schoolinterventies niet voldoende is om ook de prestaties op school te verbeteren. Interventies moeten een breder perspectief hebben, gericht op het verbeteren van de gezondheid van kinderen, terwijl ze hen ook voorzien van een gezonde en prestatiebevorderende binnenomgeving in klaslokalen en schoolgebouwen.

Hoofdstuk 3 presenteert een tweede veldstudie waarin de invloed van een gerenoveerd universiteitsgebouw op de tevredenheid van studenten over de binnenomgeving en hun behaalde cijfers in het hoger onderwijs wordt onderzocht. Een cohort van eerstejaarsstudenten werd opgesplitst in twee groepen: De ene groep volgde lessen in een conventioneel universiteitsgebouw, terwijl de andere groep lessen volgde in een gerenoveerd en opgeknapt universiteitsgebouw. De studie omvatte twee academische periodes van elk zeven weken, in de herfst van 2022 en de lente van 2023, en bestreek vijf lesblokken in deze periodes. Het gerenoveerde gebouw was gecertificeerd door *WELL* voor het bieden van een binnenomgeving die de gezondheid en het welzijn van de bewoners bevordert. De binnenmilieu kwaliteit werd gemonitord in 31 klaslokalen in beide gebouwen.

De analyse toont aan dat de luchtkwaliteit binnenshuis in het gerenoveerde gebouw significant beter was, met lagere concentraties CO_2 en andere luchtverontreinigende stoffen. Daarentegen vertoonde het conventionele gebouw alleen gunstige binnenluchtkwaliteitomstandigheden op warme zomerdagen, waarschijnlijk doordat studenten en docenten ramen openden voor ventilatie. Tijdens koudere dagen bleven de concentraties van verontreinigende stoffen echter hoog in het conventionele gebouw, terwijl het gerenoveerde gebouw consequent betere luchtkwaliteit binnenshuis behield. Deze bevindingen ondersteunen de effectiviteit van het moderne ventilatiesysteem in het gerenoveerde gebouw om een gezonde luchtkwaliteit binnenshuis te handhaven.

De belangrijkste analyse in dit hoofdstuk toont aan dat studenten in het gerenoveerde gebouw de binnenomgeving aanzienlijk anders waarnamen in vergelijking met studenten in het conventionele gebouw. Toen hen specifiek werd gevraagd naar de invloed van de binnenmilieu kwaliteit, rapporteerden studenten in het gerenoveerde gebouw een positieve invloed van luchtkwaliteit, temperatuur, verlichting en geluid op hun prestaties in de klas. Bovendien vonden studenten het interieurontwerp van het gerenoveerde gebouw veel aangenamer en geloofden ze dat dit hun stemming en prestaties in de klas positief beïnvloedde. Interessant is dat er ondanks de verbeterde luchtkwaliteit in het gerenoveerde gebouw geen significante verschillen werden gevonden in de behaalde cijfers tussen de twee studenten groepen. Het gebouw waarin een student tutorial lessen volgde, had geen meetbaar effect op hun academische prestaties.

Deze bevindingen benadrukken een discrepantie tussen de waarnemingen van studenten over de binnenomgeving en de werkelijke invloed daarvan op hun prestaties. Enerzijds gaven studenten in het gerenoveerde gebouw een positieve invloed van de binnenomgeving en het interieurontwerp aan hun zelfbeoordeelde prestaties. Anderzijds bleven objectief gemeten prestatie-indicatoren, zoals cijfers, onveranderd. Dit suggereert dat een betere binnenmilieu kwaliteit, hoewel deze de tevredenheid en zelfbeoordeelde prestaties verbetert, niet noodzakelijkerwijs leidt tot verbeterde academische resultaten.

Deze studie is om verschillende redenen relevant. Ten eerste toont het aan dat bevindingen over de relatie tussen luchtkwaliteit binnenshuis en leerresultaten in basisscholen en middelbare scholen niet noodzakelijkerwijs kunnen worden gegeneraliseerd naar het hoger onderwijs. Terwijl **Hoofdstuk 2** een negatief effect van slechte luchtkwaliteit binnenshuis op testresultaten bij basisschoolkinderen identificeert, kan **Hoofdstuk 3** een dergelijke negatieve relatie tussen luchtkwaliteit binnenshuis en academische resultaten voor universiteitsstudenten niet bevestigen. Deze discrepantie kan worden toegeschreven aan verschillen in blootstellingsduur door verschillende lesroosters, leermaterialen of de organisatie van het onderwijs op universitair niveau. Bovendien verschillen universiteitsstudenten van schoolkinderen op het gebied van leeftijd, gezondheids gedragingen en andere fysiologische kenmerken, die de resultaten zouden kunnen beïnvloeden.

Daarom suggereert de studie dat investeren in de binnenmilieu kwaliteit van universiteitsklaslokaal misschien niet de meest effectieve manier is om leerresultaten van studenten te verbeteren. In tegenstelling hiermee is het bewijs voor de positieve invloed van verbeterde luchtkwaliteit binnenshuis op leerresultaten in basisschool- en middelbare schoolklaslokaal consistenter. Echter, **Hoofdstuk 3** benadrukt de waarde van investeringen in de binnenomgeving van universiteitsgebouwen om het algemene welzijn van studenten te verbeteren.

Terwijl de twee veldstudies in **Hoofdstuk 2** en **Hoofdstuk 3** CO_2 gebruiken als een maat voor algemene luchtkwaliteit binnenshuis, blijft het onduidelijk of CO_2 cognitieve prestaties en menselijke fysiologie direct beïnvloedt bij blootstellingsniveaus die doorgaans binnenshuis worden aangetroffen. Om deze vraag te beantwoorden, presenteert **Hoofdstuk 4** een laboratoriumstudie die de invloed van CO_2 op menselijke cognitieve prestaties, economisch besluitvormingsgedrag en gezondheidsresultaten onderzoekt.

Het enkelblinde gerandomiseerde crossover-experiment betrof 20 gezonde volwassenen die werden blootgesteld aan twee concentratieniveaus: 3.000 ppm (parts per million, deeltjes per miljoen) en 900 ppm CO_2. De deelnemers brachten acht uur door in een luchtdichte ademkamer in beide condities. Ventilatiesnelheden werden in beide scenario's hoog gehouden om dezelfde concentratie van andere luchtverontreinigende stoffen te behouden en eventuele waarneembare effecten toe te schrijven aan de CO_2-blootstelling. Chemisch puur CO_2 werd in de kamer gebracht om de 3.000 ppm-conditie te bereiken. Dergelijke concentraties werden aangetroffen in basisschool- en universiteitsklaslokalen in **Hoofdstuk 2** en **Hoofdstuk 3**, wat bevestigt dat concentraties van 3.000 ppm CO_2 gebruikelijk zijn in onderwijsgebouwen.

De deelnemers werden willekeurig toegewezen aan hun startconditie: 10 deelnemers begonnen met de 900 ppm CO_2-conditie en wisselden naar de 3.000 ppm-voorwaarde op hun tweede testdag, terwijl de overige 10 deelnemers de omgekeerde volgorde volgden. Cognitieve tests werden twee keer uitgevoerd tijdens elke 8-uur durende testdag, waarbij psychomotorische controle, aandacht, executive functies en geheugen werden gemeten. Bovendien beantwoordden de deelnemers een reeks economische besluitvormingsopdrachten, waarbij ze kozen tussen twee betalingsopties met verschillende waarschijnlijkheden van optreden. Deze tests worden veel gebruikt in economisch onderzoek om risicogedrag en het niveau van ongeduld te meten bij individuen die keuzes maken over monetaire betalingen. Gedurende de testdag werden verschillende fysiologische parameters continu gemonitord, zoals hartslag, bloeddruk, bloed CO_2-niveaus, zuurstofverbruik, fysieke activiteit en ademhalingsfrequentie.

De resultaten in **Hoofdstuk 4** tonen aan dat blootstelling aan een CO_2-concentratie van 3.000 ppm niet leidde tot slechtere prestaties in de cognitieve tests, noch vertoonden de deelnemers enige verandering in risicogedrag of het niveau van ongeduld in de economische besluitvormingstaken. Bovendien werden er geen significante veranderingen in fysiologische parameters waargenomen gedurende de dag, die een nadelige gezondheid reactie zouden kunnen aantonen. Echter, er werd een lichte verhoging van de ademhalingsfrequentie opgemerkt tijdens de cognitieve tests toen deelnemers werden blootgesteld aan de verhoogde CO_2-concentratie, wat een compenserend mechanisme zou kunnen zijn.

Deze bevindingen lijken eerdere studies te weerleggen die een negatief effect van CO_2 op cognitieve prestaties rapporteerden. Eerder onderzoek heeft aangegeven dat verhoogde CO_2-niveaus strategische besluitvorming negatief beïnvloeden. Echter, eerdere bevindingen wijzen erop dat de invloed van CO_2 op cognitieve prestaties afhankelijk lijkt te zijn van factoren zoals blootstellingsduur, taakcomplexiteit en de kenmerken van de onderzochte populatie. De studie in **Hoofdstuk 4** draagt bij aan ons begrip van CO_2-blootstelling door aan te tonen dat concentratieniveaus die doorgaans binnenshuis worden aangetroffen, de prestaties bij basale cognitieve taken of economische besluitvorming niet verstoren. Bovendien tonen de bevindingen aan dat verhoogde CO_2-niveaus niet noodzakelijkerwijs nadelige fysiologische reacties veroorzaken.

Gezien het onderzoek naar de invloed van luchtkwaliteit binnenshuis - en breder, binnenmilieu kwaliteit, inclusief thermische omstandigheden, verlichting en geluidsniveaus - op menselijke prestaties en gezondheid, vereist het renoveren en ontwerpen van gebouwen om een geoptimaliseerde binnenomgeving te bieden een aanzienlijke financiële investering van vastgoedontwikkelaars en eigenaren. Dergelijke investeringen moeten financieel haalbaar en winstgevend zijn om de kapitaalmarkt te stimuleren om de ontwikkeling van gezondere gebouwen te ondersteunen.

Om deze kwestie aan te pakken, bespreekt **Hoofdstuk 5** bestaande literatuur over de economische waarde van investeren in een geoptimaliseerde binnenmilieu kwaliteit. Het hoofdstuk begint met het bespreken van studies over de invloed van de omgevingsfactoren luchtkwaliteit, temperatuur, licht en geluid op gebouwbewoners. Er is steeds meer bewijs dat blootstelling aan slechte binnenluchtkwaliteit, thermisch ongemakkelijke omstandigheden, onvoldoende binnenverlichting en hoge geluidsniveaus kan leiden tot nadelige gezondheidseffecten en verminderde cognitieve prestaties. Bovendien tonen studies aan dat deze factoren het welzijn van bewoners beïnvloeden, hoewel het minder duidelijk is in welke mate, evenals hoe deze factoren elkaar beïnvloeden bij het bepalen van het welzijn van mensen.

In de tweede helft geeft **Hoofdstuk 5** een samenvatting van bestaande literatuur die de economische kosten en voordelen van het verbeteren van de binnenmilieu kwaliteit van gebouwen evalueert. Hoewel talloze studies de negatieve effecten van suboptimale binnenmilieu kwaliteit op prestaties en gezondheid documenteren, proberen maar weinig studies de bijbehorende economische kosten en voordelen in te schatten. De studies die er wel zijn, berusten voornamelijk op schattingen van energieverbruik, onvoldoende proxies voor productiviteit en werkprestaties, zoals salarisgegevens, en zelfgerapporteerde gezondheidsmaatregelen, om te beoordelen of investeringen in binnenmilieu kwaliteit kostenefficiënt zijn.

Al met al benadrukt **Hoofdstuk 5** de noodzaak van verder onderzoek om de tastbare voordelen van verbeterde binnenmilieu kwaliteit vast te stellen. Het huidige onderzoek biedt onvoldoende inzicht in of de bijkomende kosten, die gepaard gaan met het verbeteren van de binnenmilieu kwaliteit, kunnen worden gecompenseerd door verbeteringen in de werkprestatie, gezondheid en welzijn. Er is een sterke behoefte aan studies die zowel objectieve als subjectieve prestatiewaarden verzamelen om de economische waarde van dergelijke verbeteringen nauwkeurig in te schatten. Inzicht in hoe verbeteringen in prestaties, gezondheid en welzijn van bewoners zich verhouden tot de bijbehorende kosten, zoals verhoogd energieverbruik of operationele kosten, is essentieel. Dergelijke inzichten zijn cruciaal om een overtuigend zakelijk argument voor investeringen in het optimaliseren van de binnenmilieu kwaliteit te formuleren.

Concluderend, **Hoofdstukken 2 tot 5** benadrukken verschillende belangrijke bevindingen: Ten eerste, de negatieve effecten van slechte luchtkwaliteit binnenshuis op academische prestaties van basisschoolkinderen, alhoewel deze effecten niet werden waargenomen in het hoger onderwijs. Ten tweede, het potentieel van verbeterde binnenmilieu kwaliteit om het welzijn van universiteitsstudenten te verbeteren. Daarnaast toont de laboratoriumstudie aan dat CO_2, hoewel een nuttige maat voor luchtkwaliteit binnenshuis, geen nadelige gezondheidsreacties veroorzaakt of cognitieve prestaties verstoort bij niveaus die doorgaans binnenshuis worden aangetroffen. Tot slot benadrukt het proefschrift de dringende behoefte aan verder onderzoek naar de economische waarde van verbeterde binnenmilieu kwaliteit.

Zusammenfassung

Luftqualität stand oft auf der Agenda von politischen Entscheidungsträgern, die darauf abzielen, die öffentliche Gesundheit zu verbessern, wobei der Fokus hauptsächlich auf der Außenluftverschmutzung durch Verkehr und industrielle Aktivitäten lag. Seit der COVID-19-Pandemie ist jedoch das Bewusstsein für die Luftqualität in Innenräumen von Wohn- und öffentlichen Gebäuden gestiegen. Die Forschung zu den Auswirkungen der Luftqualität in Innenräumen auf die menschliche Gesundheit und die kognitive Leistungsfähigkeit ist jedoch viel älter als die COVID-19 Pandemie.

Aktuelle Evidenz zeigt die Beziehung einer schlechte Luftqualität in Innenräumen mit einer geringeren kognitiven Leistungsfähigkeit bei Erwachsenen, schlechteren schulischen Leistungen bei Kindern sowie negativen gesundheitlichen Auswirkungen, die zu höheren Fehlzeiten führen können. Dennoch sind einige dieser Belege widersprüchlich; viele beruhen auf selbstberichteten Daten zu Gesundheit und Leistung, während Laborstudien dominieren und Feldstudien zu den Auswirkungen der Luftqualität in Innenräumen auf die kognitive Leistungsfähigkeit selten sind.

Ziel dieser Dissertation ist es, die aktuelle Forschung zur Luftqualität in Innenräumen zu erweitern. Sie umfasst zwei Feldstudien in Bildungseinrichtungen, eine Laborstudie über die Wirkung von Kohlenstoffdioxid (CO_2), sowie eine Untersuchung zu den wirtschaftlichen Implikationen einer besseren Luftqualität in Innenräumen und insgesamt eines verbesserten Innenraumklimas.

Kapitel 2 präsentiert die Ergebnisse einer Feldstudie, die in sieben Grundschulen durchgeführt wurde. Über den Verlauf eines Schuljahres hinweg wurde die Luftqualität in 61 Klassenzimmern gemessen, wobei die CO_2-Konzentration als Indikator für die Luftqualität verwendet wurde. Zusätzlich wurden pro Kind Daten über die Ergebnisse eines standardisierten Tests und die Anzahl der Krankheitstage während des Schuljahres erhoben. Ziel der Studie ist es, die Zusammenhänge zwischen Luftqualität, Krankheitsausfällen und Testergebnissen zu untersuchen. Insbesondere wird angenommen, dass die Luftqualität die Testergebnisse vor allem dadurch beeinflusst, dass sie zu mehr Krankheitsfällen unter den Kinder führt.

Die Ergebnisse der Studie zeigen, dass Kinder, die einer schlechten Luftqualität in Innenräumen ausgesetzt sind, wie durch hohe CO_2-Konzentrationen angezeigt, schlechtere Testergebnisse erzielen. Krankheitsausfälle wurden jedoch weder von der Luftqualität beeinflusst noch standen sie in Zusammenhang mit den Testergebnissen. Diese Ergebnisse deuten darauf hin, dass die Luftqualität in Innenräumen die schulischen Leistungen von Kindern direkt und unabhängig von Krankheitsausfällen beeinflusst. Diese Resultate sind besonders wichtig für Entscheidungsträger im Bildungssektor, da es zeigt, dass die Verbesserung der Gesundheit von Kindern durch schulische Interventionen allein nicht ausreicht, um auch die schulischen Leistungen zu verbessern. Interventionen sollten einen breiteren Ansatz verfolgen, der sowohl die individuelle Gesundheit der Kinder als auch ein gesundes und leistungsförderndes Innenraumklima in Klassenzimmern und Schulgebäuden berücksichtigt.

Kapitel 3 stellt eine zweite Feldstudie vor, die die Auswirkungen eines renovierten Universitätsgebäudes auf die Zufriedenheit der Studierenden mit der Innenraumumgebung und ihre erzielten Kursnoten untersucht. Ein gesamter Bachelorjahrgang von Erstsemesterstudierenden wurde in zwei Gruppen aufgeteilt: Eine Gruppe besuchte den Unterricht in einem herkömmlichen Universitätsgebäude, während die andere Gruppe den Unterricht in einem renovierten und modernisierten Universitätsgebäude hatte. Die Studie umfasste zwei akademische Perioden, die jeweils sieben Wochen dauerten, im Herbst 2022 und im Frühjahr 2023, und umfasste fünf Kurse über diese Zeitspanne hinweg. Das renovierte

Gebäude wurde mit dem *WELL* Zertifikat ausgezeichnet und bietet ein Innenraumklima, das auf die Förderung der Gesundheit und des Wohlbefindens der Nutzer ausgelegt ist. Das Innenraumklima wurde in 31 Klassenzimmern in beiden Gebäuden überwacht.

Die Analyse zeigt, dass die Luftqualität in dem renovierten Gebäude signifikant besser war, mit niedrigeren CO_2-Konzentrationen und anderen Luftschadstoffen. Im Gegensatz dazu wies das herkömmliche Gebäude nur an warmen Sommertagen günstige Bedingungen der Luftqualität auf, wahrscheinlich weil Studierende und Lehrkräfte die Fenster zur Belüftung öffneten. An kälteren Tagen blieben die Schadstoffkonzentrationen jedoch im herkömmlichen Gebäude hoch, während das renovierte Gebäude durchgängig eine bessere Luftqualität aufwies. Diese Resultate unterstreichen die Wirksamkeit des modernen Lüftungs- und Ventilationssystems im renovierten Gebäude zur Aufrechterhaltung einer gesunden Luftqualität.

Die Hauptanalyse dieses Kapitels zeigt, dass die Studierenden im renovierten Gebäude das Innenraumklima deutlich positiver wahrnahmen als die Studierenden im herkömmlichen Gebäude. Insbesondere berichteten Studierende im renovierten Gebäude, dass die Luftqualität, die Temperatur, die Beleuchtung und der Geräuschpegel ihre Leistung im Unterricht positiv beeinflussten. Außerdem empfanden sie die Innenarchitektur des renovierten Gebäudes als viel angenehmer und glaubten, dass es ihr Wohlbefinden und ihre Leistung während des Unterrichts positiv beeinflusste. Interessanterweise wurden trotz der verbesserten Luftqualität im renovierten Gebäude keine signifikanten Unterschiede in den erzielten Kursnoten zwischen den beiden Studierendengruppen festgestellt. Das Gebäude, in dem ein Studierender den Unterricht besuchte, hatte keinen messbaren Einfluss auf seine Kursleistungen.

Diese Ergebnisse verdeutlichen eine Diskrepanz zwischen der Wahrnehmung der Studierenden vom Innenraumklima und ihrem tatsächlichen Einfluss auf die Leistung. Einerseits führten die Studierenden im renovierten Gebäude die positive Wirkung des

Raumklima und der Innenarchitektur auf ihre selbstbewertete Leistung zurück. Andererseits blieben objektiv gemessene Leistungsindikatoren, wie Kursnoten, unverändert. Dies deutet darauf hin, dass ein besseres Innenraumklima zwar die Zufriedenheit und die wahrgenommene Leistung verbessert, aber nicht unbedingt zu besseren Leistungen im universitären Bereich führt.

Diese Studie ist aus mehreren Gründen relevant. Erstens zeigt sie, dass Ergebnisse zur Beziehung zwischen Luftqualität in Innenräumen und Lernergebnissen in Grund- und weiterführenden Schulen nicht unbedingt auf die Hochschulbildung übertragbar sind. Während **Kapitel 2** einen negativen Effekt schlechter Luftqualität in Innenräumen auf Testergebnisse bei Grundschulkindern identifiziert, kann **Kapitel 3** keinen solchen negativen Zusammenhang zwischen Luftqualität in Innenräumen und Kursnoten bei Universitätsstudierenden bestätigen. Diese Diskrepanz könnte auf Unterschiede in der Expositionszeit des Raumklimas aufgrund unterschiedlicher Stundenpläne, Lernmaterialien oder der organisatorischen Struktur des Hochschulunterrichts zurückzuführen sein. Zudem unterscheiden sich Universitätsstudierende von Schulkindern hinsichtlich Alter, Gesundheitsverhalten und anderen physiologischen Merkmalen, die die Ergebnisse beeinflussen könnten.

Daher legt die Studie nahe, dass Investitionen in das Innenraumklima von Universitätsklassenräumen möglicherweise nicht der effektivste Weg sind, um die Lernergebnisse der Studierenden zu verbessern. Im Gegensatz dazu ist die Evidenz zu den positiven Auswirkungen einer verbesserten Luftqualität in Klassenzimmern von Grund- und weiterführenden Schulen auf die Lernergebnisse konsistenter. **Kapitel 3** unterstreicht jedoch den Wert von Investitionen in die Klassenraumumgebung von Universitätsgebäuden, um das allgemeine Wohlbefinden der Studierenden zu verbessern.

Während die beiden Feldstudien in **Kapitel 2** und **Kapitel 3** CO_2 als Maß für die allgemeine Luftqualität in Innenräumen verwenden, bleibt unklar, ob CO_2 die kognitive Leistungsfähigkeit und die menschliche Physiologie für Konzetrationen beeinflusst, die üblicherweise in Innenräumen vorkommen. Um diese Frage zu klären, präsentiert **Kapitel 4** eine Laborstudie, die die Auswirkungen von CO_2 auf die kognitive Leistungsfähigkeit, wirtschaftliche Entscheidungen und gesundheitliche Ergebnisse untersucht.

Die Einfachblindstudie mit randomisiertem Crossover-Design umfasste 20 gesunde Erwachsene, die zwei CO_2-Konzentrationsniveaus ausgesetzt waren: 3.000 ppm (Teile pro Million, Englisch: *parts per million*) und 900 ppm CO_2. Die Teilnehmer verbrachten jeweils acht Stunden in einer luftdichten Kammer unter beiden Bedingungen. Die Ventilationsraten wurden in beiden Szenarien hoch gehalten, um die gleiche Konzentration anderer Luftschadstoffe zu gewährleisten und jegliche beobachtbare Wirkung der CO_2-Aussetzung zuzuschreiben. Chemisch reines CO_2 wurde in die Kammer eingeführt, um die Bedingung von 3.000 ppm zu erreichen. Solche Konzentrationen wurden in **Kapitel 2** und **Kapitel 3** in Klassenzimmern von Grundschulen und Universitäten festgestellt, was bestätigt, dass Konzentrationen von 3.000 ppm CO_2 in Bildungsgebäuden häufig vorkommen.

Die Ergebnisse in **Kapitel 4** zeigen, dass die Exposition gegenüber einer CO_2-Konzentration von 3.000 ppm weder zu schlechteren Leistungen in den kognitiven Tests führte, noch einen Einfluss auf das Risikoverhalten oder die Ungeduld bei finanziellen Entscheidungen festgestellt wurde. Außerdem wurden keine signifikanten Veränderungen der physiologischen Parameter über den Tag hinweg festgestellt, die auf eine negative Gesundheitsreaktion hindeuten würden. Eine leichte Erhöhung der Atemfrequenz während der kognitiven Tests wurde jedoch bei den Teilnehmern unter der erhöhten CO_2-Konzentration festgestellt, was ein kompensatorischer Mechanismus sein könnte.

Diese Ergebnisse scheinen früheren Studien zu widersprechen, die einen negativen Effekt von CO_2 auf die kognitive Leistungsfähigkeit berichteten. Frühere Forschungen haben gezeigt, dass erhöhte CO_2-Werte die strategische Entscheidungsfindung negativ beeinflussen. Allerdings weisen frühere Belege darauf hin, dass der Einfluss von CO_2 auf die kognitive Leistungsfähigkeit von Faktoren wie der Expositionsdauer, der Komplexität der Aufgabe und den Merkmalen der untersuchten Population abhängt. Die Studie in **Kapitel 4** trägt zum Verständnis der CO_2-Aussetzung bei, indem sie zeigt, dass Konzentrationsniveaus, die üblicherweise in Innenräumen auftreten, die Leistung bei grundlegenden kognitiven Aufgaben oder wirtschaftlichen Entscheidungen nicht beeinträchtigen. Darüber hinaus zeigen die Ergebnisse, dass erhöhte CO_2-Werte nicht notwendigerweise negative physiologische Reaktionen hervorrufen.

Angesichts der Forschung zu den Auswirkungen des Innenraumklimas auf die menschliche Leistungsfähigkeit und Gesundheit, erfordert die Renovierung und Gestaltung von Gebäuden erhebliche finanzielle Investitionen von Immobilienentwicklern und Gebäudeeigentümern. Solche Investitionen müssen finanziell tragfähig und profitabel sein, um den Kapitalmarkt zu motivieren, die Entwicklung gesünderer Gebäude (*Healthy Buildings*) zu unterstützen.

Kapitel 5 fasst die vorhandene Literatur zum wirtschaftlichen Wert von Investitionen in ein optimiertes Innenraumklima zusammen. Das Kapitel beginnt mit der Überprüfung von Studien zu den Einflüssen der Umweltfaktoren Luftqualität, Temperatur, Licht und Lärm auf die Gebäudenutzer. Es gibt immer mehr Studien dazu, die die Exposition gegenüber schlechter Luftqualität in Innenräumen, zu kalten oder zu warmen Innenraumtemperaturen, unzureichender Innenbeleuchtung und hohen Lärmpegeln zu negativen Gesundheitseffekten und einer geringeren kognitiven Leistungsfähigkeit führen kann. Zudem zeigen Studien, dass diese Faktoren das Wohlbefinden der Nutzer beeinflussen, obwohl unklar ist, in welchem Ausmaß und wie diese Faktoren miteinander interagieren.

Im zweiten Teil fasst **Kapitel 5** die bestehende Literatur zusammen, die die wirtschaftlichen Kosten und Vorteile einer Verbesserung des Innenraumklimas bewertet. Obwohl zahlreiche Studien die negativen Auswirkungen eines suboptimalen Innenraumklimas auf Leistungsfähigkeit und Gesundheit dokumentieren, versuchten nur wenige Studien, die damit verbundenen wirtschaftlichen Kosten und Vorteile zu schätzen. Diese Studien basieren hauptsächlich auf Schätzungen des Energieverbrauchs, unzureichenden Indikatoren für Produktivität und Arbeitsleistung wie Gehaltsdaten, sowie selbst eingeschätzter Gesundheit, um zu beurteilen, ob Investitionen in das Innenraumklimas kosteneffizient sind.

Insgesamt unterstreicht **Kapitel 5** den Bedarf an weiterer Forschung, um die messbaren Vorteile eines verbesserten Innenraumklimas zu bestimmen. Aktuelle Studien untersuchen nicht ausreichend, ob die zusätzlichen Kosten, die mit der Verbesserung des Innenraumklimas verbunden sind, durch Verbesserungen der Arbeitsleistung, Gesundheit und des Wohlbefindens ausgeglichen werden können. Es besteht ein starker Bedarf an Studien, die sowohl objektive als auch subjektive Leistungs-, Gesundheits- und Wohlfühlmaße sammeln, um den wirtschaftlichen Wert solcher Verbesserungen genau zu schätzen. Es ist wichtig zu verstehen, wie Verbesserungen der Leistungsfähigkeit, Gesundheit und des Wohlbefindens die höheren Kosten eines optimierten Innenraumklimas, wie erhöhtem Energieverbrauch oder Betriebskosten, ausgleichen. Solche Einblicke sind der Schlüssel, um ein überzeugendes Geschäftsmodell für Investitionen in die Optimierung des Innenraumklima zu schaffen.

Abschließend betonen die **Kapitel 2 bis 5** mehrere zentrale Ergebnisse: Erstens die negativen Auswirkungen schlechter Luftqualität in Innenräumen auf die schulischen Leistungen von Grundschulkindern, wobei diese Auswirkungen in der weiterführenden universitären Bildung nicht beobachtet wurden. Zweitens das Potenzial eines verbesserten Innenraumklimas zur Förderung des Wohlbefindens von Universitätsstudierenden. Zusätzlich zeigt die präsentierte Laborstudie, dass CO_2 selber zwar ein nützlicher Indikator für die Luftqualität in Innenräumen ist, aber bei Konzentrationen, die üblicherweise in Innenräumen vorkommen, keine negativen gesundheitlichen Reaktionen hervorruft oder die kognitive Leistungsfähigkeit beeinträchtigt. Schließlich hebt die Dissertation die dringende Notwendigkeit weiterer Forschung zum wirtschaftlichen Wert einer verbesserten Innenraumklimas hervor.

Résumé

La qualité de l'air est souvent au cœur des préoccupations des décideurs politiques visant à améliorer la santé publique, en se concentrant principalement sur la pollution de l'air extérieur causée par le trafic et les activités économiques. Cependant, depuis la pandémie de COVID-19, la prise de conscience de la qualité de l'air intérieur dans les bâtiments résidentiels et publics a augmenté. La recherche sur l'impact de la qualité de l'air intérieur sur la santé humaine et la performance cognitive est bien plus ancienne que l'apparition du COVID-19.

Cette littérature lie une mauvaise qualité de l'air intérieur à une baisse de la performance cognitive chez les adultes, une moins bonne réussite scolaire chez les enfants, ainsi que des effets néfastes sur la santé, qui peuvent entraîner des taux d'absentéisme plus élevés. Cependant, certaines preuves sont contradictoires ; une grande partie de la recherche repose sur des mesures auto-déclarées de la santé et de la performance, et les études en laboratoire dominent, tandis que les études sur le terrain concernant l'impact de la qualité de l'air intérieur sur la performance cognitive restent rares. L'objectif de cette thèse est d'étendre la recherche actuelle sur la qualité de l'air intérieur. Cette thèse présente deux études de terrain dans des bâtiments éducatifs, une étude en laboratoire sur l'influence du dioxyde de carbone (CO_2), et une revue sur les implications économiques d'une meilleure qualité de l'air intérieur et, dans une plus large mesure, de l'amélioration de la qualité de l'environnement intérieur.

Le chapitre 2 présente les résultats d'une étude de terrain réalisée dans sept écoles primaires. Au cours d'une année scolaire, la qualité de l'air intérieur a été mesurée dans 61 salles de classe, en utilisant la concentration de CO_2 comme indicateur de la qualité de l'air intérieur. De plus, des données concernant chaque enfant, telles que les résultats à un test standardisé et le nombre de jours d'absence

pour cause de maladie pendant l'année scolaire, ont été recueillies. L'objectif de l'étude est d'examiner les relations entre la qualité de l'air intérieur, l'absentéisme et les résultats des tests. Plus précisément, il est hypothéqué que l'absentéisme est le principal moyen par lequel la qualité de l'air intérieur affecte les résultats scolaires obtenus.

En effet, les résultats de l'étude montrent que les enfants exposés à une mauvaise qualité de l'air intérieur, comme l'indiquent des concentrations élevées de CO_2, obtiennent des résultats moins bons aux tests. Cependant, l'absentéisme n'est ni influencé par la qualité de l'air intérieur, ni lié aux résultats des tests. Par conséquent, ces résultats indiquent que la qualité de l'air intérieur a un impact direct sur la réussite scolaire des enfants, indépendamment de l'absentéisme comme mécanisme potentiel. Cette découverte a des implications importantes pour les politiques publiques, car elle montre que l'amélioration de la santé des enfants grâce à des interventions scolaires ne suffit pas à améliorer également leurs performances scolaires. Les interventions doivent avoir un champ d'action plus large, en se concentrant sur l'amélioration de la santé individuelle des enfants, tout en leur fournissant un environnement intérieur sain et favorable à la performance dans les salles de classe et les bâtiments scolaires.

Le chapitre 3 présente une deuxième étude de terrain sur l'impact d'un bâtiment universitaire rénové sur la satisfaction des étudiants vis-à-vis de l'environnement intérieur et leurs résultats aux cours dans l'enseignement supérieur. Une cohorte d'étudiants de première année a été répartie en deux groupes : un groupe a suivi les cours dans un bâtiment universitaire classique, tandis que l'autre groupe a suivi ses cours dans un bâtiment universitaire rénové. L'étude s'est déroulée sur deux périodes académiques, chacune durant sept semaines, pendant l'automne 2022 et le printemps 2023, et a couvert cinq cours pendant ces périodes. Le bâtiment rénové était certifié par le programme *WELL* pour fournir un environnement intérieur conçu pour favoriser la santé et le bien-être des occupants. La qualité de l'environnement intérieur a été surveillée dans 31 salles de classe des deux bâtiments.

L'analyse révèle que la qualité de l'air intérieur dans le bâtiment rénové était significativement meilleure, avec des concentrations de CO_2 et d'autres polluants de l'air plus faibles. En revanche, le bâtiment classique ne présentait des conditions de qualité de l'air favorable que lors des journées chaudes d'été, probablement en raison de l'ouverture des fenêtres pour la ventilation par les étudiants et les enseignants. Cependant, pendant les journées plus froides, les concentrations de polluants restaient élevées dans le bâtiment classique, tandis que le bâtiment rénové maintenait constamment une meilleure qualité de l'air intérieur. Ces résultats soutiennent l'efficacité du système de ventilation moderne dans le bâtiment rénové pour maintenir une qualité de l'air intérieur saine.

L'analyse principale de ce chapitre montre que les étudiants dans le bâtiment rénové percevaient l'environnement intérieur de manière nettement différente de ceux dans le bâtiment classique. Lorsqu'on leur a spécifiquement demandé l'impact de la qualité de l'environnement intérieur, les étudiants dans le bâtiment rénové ont rapporté un effet positif de la qualité de l'air, de la température, de l'éclairage et du bruit sur leur performance en classe. De plus, les étudiants ont trouvé que la conception intérieure du bâtiment rénové et réaménagé était beaucoup plus agréable et pensaient qu'elle influençait positivement leur humeur et leurs performances pendant les cours. Fait intéressant, malgré la qualité de l'air intérieur améliorée dans le bâtiment rénové, aucune différence significative n'a été trouvée dans les résultats des cours entre les deux groupes d'étudiants. Le bâtiment dans lequel un étudiant suivait ses cours n'a eu aucun effet mesurable sur sa performance aux cours.

Ces résultats mettent en évidence une divergence entre les perceptions des étudiants concernant l'environnement intérieur et son impact réel sur leur performance. D'une part, les étudiants dans le bâtiment rénové ont attribué un effet positif de l'environnement intérieur et de la conception intérieure à leur performance auto-évaluée. D'autre part, les indicateurs de performance mesurés objectivement, tels que les résultats des cours, sont restés inchangés. Cela suggère qu'une meilleure qualité de l'environnement intérieur, bien qu'elle améliore la satisfaction et la performance perçue, ne se traduit pas nécessairement par de meilleurs résultats académiques.

Cette étude est pertinente pour plusieurs raisons. Premièrement, elle montre que les résultats concernant la relation entre la qualité de l'air intérieur et les résultats d'apprentissage dans les écoles primaires et secondaires ne peuvent pas nécessairement être généralisés à l'enseignement supérieur. Tandis que le chapitre 2 identifie un effet négatif d'une mauvaise qualité de l'air intérieur sur les résultats des tests chez les enfants des écoles primaires, le chapitre 3 ne parvient pas à confirmer une telle relation négative entre la qualité de l'air intérieur et les résultats des cours pour les étudiants universitaires. Cette divergence peut être attribuée à des différences dans la durée d'exposition due aux différents horaires des cours, aux matériaux d'apprentissage ou à la structure organisationnelle de l'éducation au niveau universitaire. De plus, les étudiants universitaires diffèrent des enfants d'école primaire en termes d'âge, de comportements de santé et d'autres caractéristiques physiologiques, ce qui pourrait influencer les résultats.

Ainsi, l'étude suggère que l'investissement dans la qualité de l'environnement intérieur des salles de classe universitaires pourrait ne pas être la manière la plus efficace d'améliorer les résultats d'apprentissage des étudiants. En revanche, les preuves soutenant l'impact positif d'une meilleure qualité de l'air intérieur sur les résultats d'apprentissage dans les salles de classe des écoles primaires et secondaires sont plus cohérentes. Cependant, le chapitre 3 souligne la valeur des investissements dans l'environnement des salles de classe des bâtiments universitaires pour améliorer le bien-être général des étudiants.

Alors que les deux études de terrain dans le chapitre 2 et le chapitre 3 utilisent le CO_2 comme mesure de la qualité générale de l'air intérieur, il reste incertain si le CO_2 affecte directement la performance cognitive et la physiologie humaine à des niveaux d'exposition couramment rencontrés à l'intérieur. Pour répondre à cette question, le chapitre 4 présente une étude en laboratoire sur l'impact du CO_2 sur la performance cognitive humaine, la prise de décision économique et les résultats de santé.

L'expérience croisée randomisée en simple aveugle a impliqué 20 adultes en bonne santé exposés à deux niveaux de concentration : 3 000 ppm (parties par million, en anglais: *parts per million*) et 900 ppm de CO_2. Les participants ont passé huit heures dans une chambre de respiration étanche sous chaque condition. Les taux de ventilation ont été maintenus élevés dans les deux scénarios pour maintenir la même concentration d'autres polluants de l'air et attribuer tout effet observable à l'exposition au CO_2. Du CO_2 chimiquement pur a été introduit dans la chambre pour atteindre la condition de 3 000 ppm. De telles concentrations ont été trouvées dans les salles de classe des écoles primaires et des universités dans le chapitre 2 et le chapitre 3, confirmant que des concentrations de 3 000 ppm de CO_2 sont couramment atteintes dans les bâtiments éducatifs.

Les participants ont été assignés au hasard à leur condition de départ : 10 participants ont commencé avec la condition de 900 ppm de CO_2 et sont passés à la condition de 3 000 ppm lors de leur deuxième jour de test, tandis que les 10 autres ont suivi l'ordre inverse. Des tests cognitifs ont été effectués deux fois pendant chaque journée de test de huit heures, évaluant le contrôle psychomoteur, l'attention, le fonctionnement exécutif et la mémoire. De plus, les participants ont répondu à une série de tâches de prise de décision économique, où ils choisissaient entre deux options de paiement avec des probabilités de survenue variables. Ces tests sont couramment utilisés dans la recherche économique pour mesurer le comportement en matière de risque et le niveau d'impatience des individus lorsqu'ils sont confrontés à des choix incluant des paiements monétaires. Tout au long de la journée de test, plusieurs paramètres physiologiques ont été surveillés en continu, notamment le rythme cardiaque, la pression artérielle, les niveaux de CO_2 dans le sang, la consommation d'oxygène, les niveaux d'activité physique et le rythme respiratoire.

Les résultats dans le chapitre 4 montrent que l'exposition à une concentration de 3 000 ppm de CO_2 n'a pas entraîné de performances pires dans les tests cognitifs, ni de changement dans le comportement de risque ou le niveau d'impatience dans les tâches de prise de décision économique. De plus, aucune modification significative des paramètres physiologiques n'a été enregistrée au cours de la journée, ce qui révélerait une réaction négative pour la santé. Cependant, une légère augmentation du rythme respiratoire a été notée pendant les tests cognitifs lorsque les participants étaient exposés à la concentration élevée de CO_2, ce qui pourrait être un mécanisme compensatoire.

Ces résultats semblent contredire des études précédentes qui ont rapporté un effet négatif du CO_2 sur la performance cognitive. Des recherches antérieures ont indiqué que des niveaux élevés de CO_2 nuisent à la prise de décision stratégique. Cependant, les preuves passées montrent que l'influence du CO_2 sur la performance cognitive semble dépendre de facteurs tels que la durée de l'exposition, la complexité des tâches et les caractéristiques de la population étudiée. L'étude dans le chapitre 4 contribue à notre compréhension de l'exposition au CO_2 en démontrant que les niveaux de concentration couramment rencontrés à l'intérieur n'altèrent pas la performance dans les tâches cognitives de base ou la prise de décision économique. De plus, les résultats indiquent que des niveaux élevés de CO_2 ne déclenchent pas nécessairement des réactions physiologiques néfastes.

En considérant la recherche sur l'impact de la qualité de l'air intérieur - et, plus largement, de la qualité de l'environnement intérieur, y compris les conditions thermiques, l'éclairage et le bruit - sur la performance humaine et la santé, rénover et concevoir des bâtiments pour fournir un environnement intérieur optimisé nécessite un investissement financier considérable de la part des promoteurs immobiliers et des propriétaires. De tels investissements doivent être économiquement viables et rentables pour inciter le marché du capital à soutenir le développement de bâtiments plus sains.

Pour aborder cette question, le chapitre 5 passe en revue les recherches existantes sur la valeur économique de l'investissement dans une qualité optimisée de l'environnement intérieur. Le chapitre commence par examiner les études sur l'influence des facteurs environnementaux tels que la qualité de l'air, la température, la lumière et le bruit sur les occupants des bâtiments. Les preuves s'accumulent montrant que l'exposition à une mauvaise qualité de l'air intérieur, des conditions thermiquement inconfortables, un éclairage insuffisant et des niveaux de bruit élevés peuvent entraîner des effets négatifs sur la santé et une baisse de la performance cognitive. De plus, des études montrent que ces facteurs influent sur le bien-être des occupants de l'environnement intérieur, bien que la mesure dans laquelle ils interagissent pour façonner le bien-être des individus soit moins claire.

Dans la deuxième partie, le chapitre 5 résume la littérature existante évaluant les coûts et avantages économiques de l'amélioration de la qualité de l'environnement intérieur des bâtiments. Bien que de nombreuses études documentent les effets négatifs d'une qualité suboptimale de l'environnement intérieur sur la performance et la santé, très peu d'études tentent d'estimer les coûts et les avantages économiques associés. Les études existantes s'appuient principalement sur des estimations de la consommation d'énergie, des proxys insuffisants pour la productivité et la performance au travail, tels que les données salariales, et des mesures de santé auto-déclarées pour évaluer si les investissements dans la qualité de l'environnement intérieur sont rentables.

Dans l'ensemble, le chapitre 5 souligne la nécessité de recherches supplémentaires pour déterminer les avantages tangibles d'une meilleure qualité de l'environnement intérieur. La recherche actuelle manque d'investigations suffisantes sur la manière dont les coûts supplémentaires associés à l'amélioration de la qualité de l'environnement intérieur peuvent être compensés par des améliorations de la performance des travailleurs, de la santé et du bien-être. Il existe un besoin impérieux d'études recueillant à la fois

des mesures objectives et subjectives de la performance, de la santé et du bien-être pour estimer avec précision la valeur économique de telles améliorations. Comprendre comment les améliorations de la performance, de la santé et du bien-être des occupants se comparent aux coûts associés, tels que l'augmentation de la consommation d'énergie ou des dépenses opérationnelles, est essentiel. Ces informations sont essentielles pour établir un argument économique solide en faveur de l'investissement dans l'optimisation de la qualité de l'environnement intérieur.

En conclusion, les chapitres 2 à 5 soulignent plusieurs résultats clés : D'abord, les effets négatifs d'une mauvaise qualité de l'air intérieur sur la réussite académique des enfants des écoles primaires, bien que ces effets n'aient pas été observés dans l'enseignement supérieur. Deuxièmement, le potentiel d'amélioration de la qualité de l'environnement intérieur pour favoriser le bien-être des étudiants universitaires. De plus, l'étude en laboratoire incluse démontre que le CO_2, bien qu'un bon indicateur de la qualité de l'air intérieur, ne semble pas provoquer de réactions physiologiques négatives ni altérer la performance cognitive à des niveaux couramment trouvés à l'intérieur. Enfin, la thèse met l'accent sur le besoin critique de recherches supplémentaires sur la valeur économique d'une qualité de l'environnement intérieur améliorée.

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Having six supervisors in two faculties and three departments was without any doubts an unique experience. I think they balanced each other out very well, always reminding me that there is not one answer. It sometimes felt like I was dancing on two weddings (a German saying), trying to balance different duties, expectations and needs between the two different faculties. Economics and Health Sciences are on the surface very different, but as Guy once said it to me: "We use different approaches, but in the end, we investigate the same question". Therefore, being part of two academic worlds is truly a valuable experience, because it has taught me so much more than I could have learned being part of only one side. It is important to emphasize that all of my supervisors understood at all times the challenges of being part of two teams, and I am grateful for their support and patience.

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Moving to the other side of the Maas river, I would like to thank my

TherMu team as well. **Hannah Pallubinsky**, who not only shared valuable lessons and advice with me, but also became a supporting power during my time as a PhD. I could always go to her for advice, but I also appreciate that we have the same German slang humour, which kept us both humble. Hannah taught me the value of collaboration, building a network, and never underestimating the strength you receive if you are part of a team. I would like to thank her for having an open ear to my concerns, guiding me in my decisions, and supporting me also hands on with building up my career. This makes her beyond a colleague to be also a good friend. When I started my time with the TherMu team, I had the pleasure to work with **Wei Luo**, aka "The R wizard". I am deeply impressed by the skills, talent and knowledge Wei has. He set the standard in the team very high, and that motivated me to push myself in becoming better every day. I had also the pleasure to work alongside **Adam Sellers**, the man who did not just bring an original English accent into the team, but also helped me to find my way into the world of health sciences. Of course I also need to mention **Pascal Rense**, whose work was essential for the TherMu team to run smoothly. He was the man who kept it all together when PhDs started to loose track of their work. Into my second year, **Cynthia Ly** joined our team, from whom I learned very valuable lessons. I don't know anyone else who works harder than her, and I highly respect her for her work ethics. I also learned from her the importance to be precise in my work, always expand my knowledge, and stay stoic when things become hard. Cynthia taught me these valuable lessons, which makes me incredibly grateful that I have worked alongside her. Towards the end of my time, our newest additions to the team **Sofia Pappa** as well as our former internship students **Veerle de Haan** and **Paris Sklavakis** joined our TherMu team. They are not just continuing the excellent work of Hannah, Guy and Wouter, but also brought a new and fresh wind into the team. Sofia and Paris, aka "The Greeks" taught me the importance of team spirit and how much easier work can be if you conduct it with friends, especially if you are stuck in the MRUM lab, aka "the dungeon". Veerle taught me what it means to strive for precision in my work, and how this can make my work from

being good to becoming excellent.

Some other people had a substantial and positive influence on me and supported me way before the start of the PhD. I would like to express my gratitude to **Tim Brückner**, who started as my mentor at the Friedrich Ebert Foundation in 2014, and became a good friend over the last few years. Tim gave me valuable lessons for my career, but also for life. He has the talent to advise me without giving me the feeling that he wants to steer me in any direction. When he shares his advice, it is always a critical piece of information or experience which helped me in my decision-making. I am thankful for the trust he has in me and the time he took for a young man at the beginning of his adult life, helping me in making better decisions for my life.

I would also like to mention the **Friedrich Ebert Foundation** (FES) for their support. Receiving a scholarship from the FES is truly an honour and had a remarkable impact on me. It helped me to shape my skills, expand my knowledge and provided me with a platform to get to know countless new people, who shared their valuable advice with me. Being promoted by the FES, together with being part of the **Social Democratic Party of Germany** had an incredible impact on my character development, because it helped me expand my capabilities. It also reminds me that in our society, one should not forget that every success is also possible because it is the society we live in that provides the environment for us to strive. This should not just result in gratefulness, but also to remind us of our duties to give something back and help others, as others helped us. By no means, being a valuable member of the society and your community is a maxim where by any scientists should strive for.

Of course, there are many people to thank who made my time much more pleasant and enjoyable, people who started as colleagues and quickly became friends. On the SBE side, I would like to express my gratitude to have met and worked alongside an excellent cohort of PhD candidates, especially during the Covid restrictions. The group consists of **Wiebke Heinze**, **Eline Wijns**, **Anna Wittich**, **Eric Schaap**, ”the

chef" **Iver Wiertz**, **Max Körber**, **Kimberley an der Heijden**, **Benjamin Noordermeer**, **Freija van Lent**, **Katlijn Haesebrouck**, **Melisa Yildiz**, **Robin Aarts**, **Anne Friesacher**, **Marten Laudi**, **Colin Tissen**, **Flavio de Carolis**, and countless more. I am happy to have spend my PhD time with **Frederique Bouwman**, a woman who is eager to expand her capabilities, doing an impressive amount of two research visits. I am also happy to have worked alongside **Hugo Schyns**, the man who assembles his own car! Hugo is a true *Jouisseur* of life and a hard worker. Hugo became a good friend and I am looking forward joining him to Switzerland. I am grateful for the business and research talks I had with **Dennis Bams**, who not just gave me excellent advices, but also kindly inviting me and Rachel for dinner with his amazing and lovely family. Dennis shows an incredible eagerness to learn, which always impressed me. I am particularly grateful to have worked alongside **Bram van der Kroft**, a man truly of excellent skills and knowledge from whom I have learned a lot. I do not often meet someone like Bram who knows so much, and is still so eager to absorb more knowledge and learn from others. I would also like to thank *tovarăşe* **Marco Ceccarelli**, from whom I received valuable advice about research, work, and life and who became a good friend.

I am also happy to have met my Hyrox brother, our Deutsche Bank boy, **André Tomano**, aka "Kampfschwimmer". André is a man who from the first day as a PhD is getting after it, always eager to work hard, learn new things and improve. André and I share the experience of working in the finance industry first, and both knows the specific struggle of switching from corporate life to PhD. I have the highest of respect for him and I truly believe he will do great. André, you have beaten me twice during a Hyrox race[1], so enjoy your victory for now, because I will work hard to redeem myself! Along André, **Jonas Wogh** is also important to mention. I am not just sharing a mutual enthusiasm for sports with Jonas, but he is also a hard working PhD, striving to improve himself, while at the same time knowing how to enjoy life with sports and nature. Simply a true Bavarian boy! I have

[1] I am writing these lines the day after our Hyrox Maastricht race.

the deepest of respect for Jonas.

A man who will soon start his own PhD journey is **Enver Muftić**. Enver is not just an excellent student, he is also a true philosopher, he is the Aristotle from the Balkan. I am particularly grateful remembering the walks we had around Maastricht, talking about life, work, research, and sports. I don't know anyone else who is so in peace with himself, and shows a level of maturity and life experience many people do not acquire in a life time. Enver is someone who is eager to push his limits further and work hard on himself. I feel honoured to call him my friend.

On the FHML side, I want to express my special thanks to the Movement Sciences group, including **Hans Essers**, **Bas van Hooren**, **Bart Bongers**, **Brenda Berendsen**, **H.Q. Chim**, **Kenneth Meijers**, **Hans Savelberg**, **Chris McCrum**, **Kyra Theunissen**, and **Rosanne Beijers**. I am grateful that this group took me, the economist, as one of their own, and I have many good memories with this group and its members, particularly playing football (soccer) in a cow field. I was just afraid Bas will break is ankle and it's our fault that his running career is over. Luckily that did not happen. I would like to make a special mention to Hans Essers, and while he always looked tired (this man has 2 lovely, but very active kids at home, soon will be 3), he always spread out a positive mood, besides having excellent humour. A special thank you goes to Chris who is an excellent adviser in career questions. I have the highest level of respect for Chris and his achievements, and despite a crazy busy schedule, he still made time for me and my questions. I also remember my attempt to run with Bas, the fastest PhD and man in the Netherlands. I could last for 3 minutes. He called it a warm-up run, I called it a sprint. Bas taught me what it really means to be fast.

There is not just the Movement Sciences group, but also others in the VBW department which I am grateful to have spend my PhD time with, including **Evi Koene**, who with her enlightening kind spirit makes the time in the office much more pleasant and fun for everyone. I cannot forget to mention **Frieder Harmsen**, an excellent researcher and friend, who shared his advise with me, but was also in the mood for some jokes and half-serious talks. During my time as a PhD, I always strived for the high standards Frieder set ahead. People who also made my time in the department a pleasant experience and substantially contributed to a good atmosphere are **Jeremy Basset**, **Sten van Beek**, **Pip van Lier**, **Ivo Habets**, **Koen Frenken**, **Gillian Larik**, and **Marco Chavez**, a man who was not tired to remind me with his Latin American charm how stiff we Europeans can be. I particularly would like to mention **Dzhansel Hashim**, a woman who started as an intern, but quickly became an excellent researcher in our department who I highly respect. I have learned from Dzhansel the value of hard work, expending your knowledge, and striving to improve yourself. Of course there is also the HB group, including **Thorben Aussieker**, **Cas Fuchs** and **Jerry Kaiser**. These three guys are machines, in the office and in the gym, and I learned a lot from them. I am particularly impressed that Cas has always, and I mean always, a smile on his face, enlightening the room with his spirit.

Of course, I cannot forget to mention the countless and iconic moments with **Paul Schoffelen** and **Marc Souren** in the MRUM lab. Paul is a true legend. His retirement is the textbook example of a brain drain. I remember countless moments with him in the labs, trying to follow his engineering thoughts about how to solve problems with our CO_2 study, while also sharing jokes about Star Trek (the old, real one, not that new stuff they produced a couple of years ago). He also educated me on Monty Python, and what it means to be a real expert in something. Luckily, Paul left Marc with his engineering knowledge, taught him all he knew (if that is even possible), so that the department is blessed to have Marc in the labs. Marc helped me many times and together with Paul, they were a true backbone of my success with the CO_2 study. I am particularly grateful that they were open-minded about the questions only an economist who finds himself in a health sciences lab could ask.

I enjoyed working with **Nicolás Durán** on our schools study, who taught me a lot about research and life. I remember how I ended up in London for a night when my flight to New Orleans got cancelled, spontaneously texting Nico for a beer and he was ready to meet in the city. He did that even after I accidentally called him an Argentinian and he should enjoy the Argentinian BBQ. Big mistake! I had to make it up to him by sending him a hand-written, A4-size, double-sided paper covered with the sentence ”Uruguayan barbeques are the best”. This is how I never forgot. Nico became not just a colleague and co-author, he became a good friend and I am grateful that I have the honour to know him.

Of course, what would I do without **Francien** and **Monique**, our two secretaries at Finance. Their office is the engine room of the department. Countless times they helped me, from organising a symposium, dealing with reimbursement requests, and supporting me in my daily work. Every department can be grateful to have such excellent people working every day in the background to keep things running. They are truly silent heroes. I want to express a general thank you to the **Finance department**, who consist of a group of excellent researchers. This department does a great job in providing an environment for PhDs to be challenged, strive and become better. We might not be Harvard, but the unwritten agenda of this department is it to make it the Harvard of the Maas, and they work hard for this. I feel grateful that I was part of such an amazing department, the best environment to become better every day and set the important first steps for a successful career in work and life!

Among the department, I particularly want to thank **Jaap Bos** and **Jeroen Derwall**. Jaap was the first person I met from the department, when he presented during the Masters Open Day for the Sustainable Finance department in 2017. Back then, I told him I wanted to go into Investment Banking, but he probably saw the doubt in my eyes, and convinced me to do this Masters, which clearly brought me to all this. Jeroen does a great job to create a community among the Sustainable Finance students, and he made us feel like we are part of a family. I also had the honour to work with **Paul Smeets** for some short time, a man who is probably the most curious person I have ever met. Paul is like a sponge who wants to learn from everyone and therefore gives everyone the feeling to be heard.

I want to mention that I am over all very, very grateful that not just Guy, Wouter and Rick gave an economist a chance to prove himself in health sciences, but that before that, **Ijmert Kant**, **Inge Houkes**, **Angelique de Rijk**, and **Nicole Jansen** allowed an economist in 2019 to join their occupational health master program. They opened the door for me into health sciences and with their decision, they laid the path for my interdisciplinary work. Within this Master, **Emmelie Hazelzet** is in particular to mention, because she is not just an excellent teacher, but also was one of the first persons to whom I expressed my interest in a PhD. She was there to gave me valuable advice. Emmelie is an asset for every research and teaching department, and I am happy to see that she does great work at MUMC.

Mentioning them last, but only to emphasise their importance for me, I want to thank my paranymphs **Kimon Ivanov** and **Rachel Hoekstra**. Kimon was there from the start, first as a tutor in Paul Smeets' Sustainable Finance course in 2018, but very quickly as my friend. We share a mutual interest for hikes in nature and movement. We even ended up both at PwC in Luxembourg, which made my time there special, because I knew there was at least one other person in the building who likes standing desks! I will always remember the moment when we would be life-long friends. One day in front of the PwC office, he screamed at me "Why do we move?". My answer was clear: "Because we can!". Kimon is truly a N of 1, a man of its own kind. I have never, and probably will never, meet a person of such positivity about life. A man who enlightens every room with his spirit, who was there for me during good and bad times. I am grateful to have him as my friend and proud that he will stand behind me during my defense.

Of course Rachel has the most special role. I met her during her studies of Human Movement Sciences in 2021, and we quickly started to date. She was really always there for me during these years. Behind every

man stands a strong woman. Rachel is my rock in the surf. She is the only one who knows what I went through to make this all happen, all the doubts, struggles and hard work. How can I even use language and put into words the love and gratefulness I have for having Rachel on my side. Without her, I could not have achieved what I have done. Without her, I would have been lost, incomplete. Rachel, you are my light guiding me.

Stefan Flagner
Maastricht
2025-03-19

Appendix

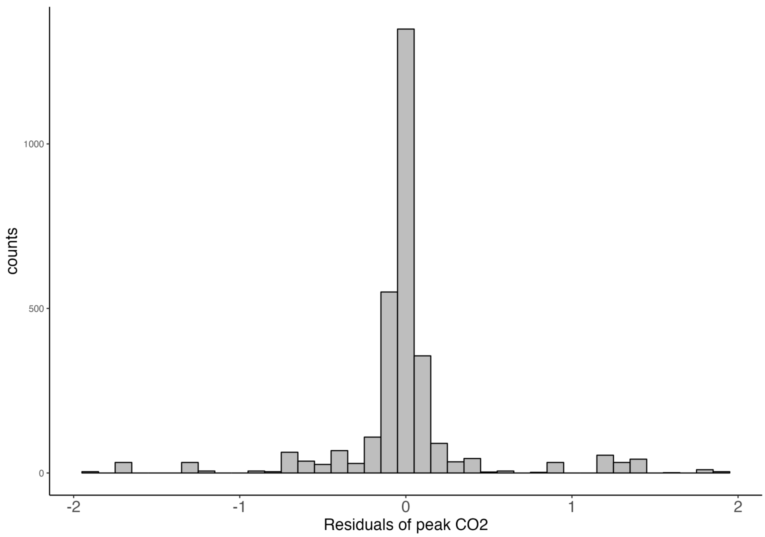
1 Appendix for Chapter 2

Table A1: Correlation of indoor environmental quality parameters

	CO_2	Temperature	Humidity
CO_2			
Temperature	-0.14		
Humidity	0.47***	0.16	
PM_{10}	0.73***	-0.22*	0.46***

Note: Significance is indicated as $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

Figure A1: Conditional within-child distribution of CO_2 exposure



Note: The histogram shows the distribution of residuals for regressing the standardized daily peak CO_2 concentration (Z-Score) on the children fixed effect. This figure illustrates the conditional variation of CO_2 exposure within a child over the testing periods.

Table A2: Absence days and test scores

	DV: Test score					
	IV: Sickness absence				IV: Non-sickness absence	IV: Total absence
	(1)	(2)	(3)	(4)	(5)	(6)
Days absent (z-score)	−0.103***	−0.061**	−0.063**	0.005	0.033	0.019
	(0.023)	(0.021)	(0.021)	(0.043)	(0.028)	(0.042)
Daily peak temperature (z-score)	0.013	−0.081	0.084	0.049	0.047	0.049
	(0.043)	(0.087)	(0.064)	(0.076)	(0.075)	(0.076)
Daily peak relative humidity (z-score)	−0.034	0.134	0.102	0.256	0.241	0.258
	(0.061)	(0.146)	(0.087)	(0.165)	(0.166)	(0.160)
Daily peak noise (z-score)	−0.139**	−0.344**	−0.083	−0.023	−0.010	−0.019
	(0.050)	(0.127)	(0.089)	(0.102)	(0.103)	(0.099)
Class size	0.040	−0.004	0.008	−0.010	−0.009	−0.010
	(0.023)	(0.021)	(0.025)	(0.025)	(0.025)	(0.025)
Class size^2	−0.000	0.000	−0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Fixed Effects						
Classroom	N	Y	Y	Y	Y	Y
Testing period	N	Y	Y	Y	Y	Y
Test domain	N	N	Y	Y	Y	Y
Years of schooling	N	N	Y	Y	Y	Y
Child	N	N	N	Y	Y	Y
Observation	3024	3024	3024	3024	3024	3024
R^2	0.035	0.184	0.213	0.779	0.779	0.779
Adj. R^2	0.033	0.166	0.189	0.711	0.711	0.711

Note: The dependent variable (DV) in all column is the standardized test score (z-score). Column (1) to (4) show the model described in equation 2.3, excluding daily average peak CO_2 concentration, and gradually adding fixed effects on classroom and testing period in column (2), testing domain and years of schooling in column (3) and a child fixed effect in column (4). Column (5) replaces the independent variable (IV) "Days absent" from days being absent due to sickness to days being absent for other reasons than sickness. Column (6) regresses all days of absence, due to sickness and non-sickness related, on test scores. Clustered standard errors at the classroom by period level are shown in parentheses and significance levels are indicated as $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

2 Appendix for Chapter 3

Table A3: Randomization check on treatment distribution

	DV: Treatment assignment		
	Period 1	Period 2	
	(1)	(2)	(3)
Intercept	0.334	0.201	0.796***
	(0.204)	(0.232)	(0.191)
Sex	−0.026	0.011	
	(0.023)	(0.025)	
Age	0.009	0.011	
	(0.010)	(0.011)	
Tutorial Time: 11am	−0.022	0.091	
	(0.113)	(0.115)	
Tutorial Time: 1.30pm	−0.008	0.104	
	(0.113)	(0.113)	
Tutorial Time: 4pm	0.014	0.030	
	(0.115)	(0.116)	
Grade in course QM1 of period 1			−0.021
			(0.013)
Grade in course MOM of period 1			−0.019
			(0.018)
Observations	1838	1541	1933
R^2	0.002	0.008	0.004
Adj. R^2	−0.001	0.005	0.003

Note: The table shows the results of regressing the building a student is assigned to on the factors sex, age, tutorial time and achieved course grade for the period 1 courses QM1 (Quantitative Methods 1) and MOM (Management of Organisation and Marketing). The dependent variable is a binary variable equals to 1 if a student has classes in the treatment building, and zero if the student has classes in the control building. A significant coefficient indicates that the corresponding factor predicts a higher or lower likelihood for a student to be assigned to a class in the treatment building. Column (1) includes the assigned building in period 1, and column (2) and column (3) include the assigned building in period 2. Clustered standard errors at tutorial group level are shown in parentheses and significance levels are indicated as $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

Table A4: Correlation of IEQ parameters by period

Period 1	$PM_{2.5}$	CO_2	TVOC	Temperature
$PM_{2.5}$				
CO_2	0.21***			
TVOC	0.04***	0.69***		
Temperature	-0.26***	-0.16***	-0.04***	
Humidity	0.40***	0.48***	0.27***	-0.19***
Period 2	$PM_{2.5}$	CO_2	TVOC	Temperature
$PM_{2.5}$				
CO_2	0.27***			
TVOC	0.21***	0.78***		
Temperature	-0.17***	0.00	-0.10***	
Humidity	-0.15***	0.40***	0.40***	-0.25***

Note: The table shows the Pearson correlation coefficients for the indoor environmental quality parameter fine particular matter ($PM_{2.5}$), carbon dioxide (CO_2), total volatile organic compounds concentration (TVOC), temperature and relative humidity. Significance levels are indicated as $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

Table A5: Correlation of indoor and outdoor conditions

Period 1	Treatment building		Control building	
	Outdoor temperature	Indoor CO_2	Outdoor temperature	Indoor CO_2
Indoor CO_2	0.08		-0.30	
Indoor temperature	0.73***	0.35	0.84***	-0.01
Period 2	Treatment building		Control building	
	Outdoor temperature	Indoor CO_2	Outdoor temperature	Indoor CO_2
Indoor CO_2	0.02		-0.09	
Indoor temperature	0.12	-0.06	0.33	0.29

Note: The table shows the Pearson correlation coefficients for the daily outdoor peak temperature, indoor peak temperature and indoor carbon dioxide (CO_2) concentration per period and building. Significance levels are indicated as $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

Table A6: Satisfaction with indoor environmental quality

Panel A: Period 1	Air Quality (1)	Light (2)	Noise (3)	Temperature (4)
Treatment	-0.120	0.344^{**}	0.057	-0.143
	(0.125)	(0.110)	(0.112)	(0.138)
Fixed effects				
Schedule fixed effect	Y	Y	Y	Y
Course fixed effect	Y	Y	Y	Y
Teacher fixed effect	Y	Y	Y	Y
Observations	1,952	1,940	1,946	1,951
R^2	0.064	0.061	0.044	0.060
Residual Std. Error	1.579	1.507	1.822	1.576
Panel B: Period 2	Air Quality (1)	Light (2)	Noise (3)	Temperature (4)
Treatment	0.473^{**}	0.405^{*}	0.433^{**}	0.379^{*}
	(0.167)	(0.184)	(0.164)	(0.191)
Fixed effects				
Schedule fixed effect	Y	Y	Y	Y
Course fixed effect	Y	Y	Y	Y
Teacher fixed effect	Y	Y	Y	Y
Observations	1,548	1,543	1,549	1,548
R^2	0.072	0.079	0.068	0.065
Residual Std. Error	1.604	1.474	1.704	1.525

Note: The table shows the results for students of both buildings who were asked if the stated indoor environmental quality parameters hinder or support their ability to perform well in class. The outcome variables are standardized and expressed in terms of standard deviation (z-score). Their response was indicated on a 7-point Likert scale ranging from 1 for ”hinder” to 7 for ”support”. Fixed effects on schedule (time of day of tutorial meeting), course and teacher are applied. Clustered standard errors at tutorial group level are shown in parentheses and significance levels are indicated as $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

Table A7: Satisfaction with the interior design

Panel A: Period 1	Interior affects performance (1)	Interior affects mood (2)	Like tutorial attendance (3)	Room is appealing (4)	Difficulties to concentrate (5)
Treatment	0.402**	0.584**	0.163	1.017**	0.030
	(0.106)	(0.117)	(0.132)	(0.105)	(0.133)
Fixed effects					
Schedule fixed effect	Y	Y	Y	Y	Y
Course fixed effect	Y	Y	Y	Y	Y
Teacher fixed effect	Y	Y	Y	Y	Y
Observations	1,930	1,932	1,991	1,957	1,953
R^2	0.077	0.121	0.125	0.227	0.065
Residual Std. Error	1.458	1.408	1.117	1.379	1.795
Panel B: Period 2	Interior affects performance (1)	Interior affects mood (2)	Like tutorial attendance (3)	Room is appealing (4)	Difficulties to concentrate (5)
Treatment	0.948***	1.050***	0.421***	1.387***	-0.176
	(0.135)	(0.144)	(0.154)	(0.139)	(0.217)
Fixed effects					
Schedule fixed effect	Y	Y	Y	Y	Y
Course fixed effect	Y	Y	Y	Y	Y
Teacher fixed effect	Y	Y	Y	Y	Y
Observations	1,532	1,532	1,610	1,548	1,523
R^2	0.107	0.126	0.146	0.206	0.062
Residual Std. Error	1.371	1.358	1.214	1.414	1.872

Note: The dependent variables, standardized and expressed as z-score, are the perceived effect of the interior design on performance in column (1) and mood in column (2), if students like coming to the tutorial in column (3), if the room is appealing in column (4), and lastly if they had difficulties to concentration during class in column (5). Students response to the questions of column (1) to (5) are indicated on a 7-point Likert scale, ranging from "negatively affecting" to "positively affecting" for column (1) and (2), "not at all" to "very much for column (3), "not appealing at all" to "very appealing" for column (4), and "Never" to "Always for column (5). Fixed effects on schedule (time of day of tutorial meeting), course and teacher are applied. Clustered standard errors at tutorial group level are shown in parentheses and significance levels are indicated as $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

Table A8: Student course grades and teacher evaluation

	Period 1		Period 2	
	Student grade (1)	Teacher evaluation (2)	Student grade (3)	Teacher evaluation (4)
Treatment	-0.036	0.034	0.044	0.055
	(0.106)	(0.281)	(0.255)	(0.486)
Fixed effects				
Schedule fixed effect	Y	Y	Y	Y
Course fixed effect	Y	Y	Y	Y
Teacher fixed effect	Y	Y	Y	Y
Observations	2,251	2,251	2,078	2,078
R^2	0.041	0.561	0.034	0.779
Residual Std. Error	0.993	0.579	1.000	0.457

Note: The dependent variables, standardized and expressed as z-score, are the student grades in column (1) and (3) and teacher evaluation in column (2) and (4). The student grade and teacher evaluation ranges from 1 for the lowest to 10 for the highest grade. Fixed effects on schedule (time of day of tutorial meeting), course and teacher are applied. Clustered standard errors at tutorial group level are shown in parentheses and significance levels are indicated as $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

Table A9: Self-reported study hours per week

	Treatment			Control			
	N	Mean	St. Dev.	N	Mean	St. Dev.	t-test signf.
Courses in period 1							
Management of Organisation	38	9.8	3.9	42	8.8	2.9	$p > 0.05$
Quantitative Methods 1	39	18	4.7	43	18	4.9	$p > 0.05$
Courses in period 2							
Macroeconomics	18	15	4.5	16	15	5.6	$p > 0.05$
Quantitative Methods 2	41	15	3.4	40	15	3.5	$p > 0.05$
Strategy	23	8.6	2.4	24	9.5	2.7	$p > 0.05$

Note: The table shows students' self-reported study hours per week. The available data included the study hour per tutorial group averaged over the individually reported study hours of all students in the particular tutorial group. Therefore, the sample size (N) represents the number of tutorial groups. The table shows the mean and standard deviation (St. Dev.) of the average study hour per tutorial group per course and treatment group. The last column indicates the significance of the difference in mean based on an independent t-test.

Table A10: Self-perceived impact of IEQ on teaching quality

	Treatment			Control			
	N	Mean	St. Dev.	N	Mean	St. Dev.	t-test signf.
Period 1	18	5.33	1.03	18	3.94	1.35	$p < 0.01$
Period 2	18	5.28	1.13	19	3.37	0.90	$p < 0.001$

Note: The table shows the response to a question sent to teachers asking ”Did the interior of the tutorial room affect your performance during the tutorial?”. Teachers indicated their response on a 7-point Likert scale, ranging from ”(1) - Negatively affecting” to ”(7) - Positively affecting”. The table shows the number of responses (N), the mean and standard deviation (St. Dev.) for each group. The last column indicates the significance of the difference in mean based on an independent t-test.

3 Appendix for Chapter 4

Table A11: Multiple price lists for risk preferences

		Option A		Option B		
Multiple price list	Choice	Coin shows heads	Coin shows tails	Coin shows heads	Coin shows tails	Implied CRRA
1.1	1	6.00 €	10.00 €	1.00 €	12.00 €	1.79
	2	6.00 €	10.00 €	1.00 €	14.00 €	1.17
	3	6.00 €	10.00 €	1.00 €	16.00 €	0.87
	4	6.00 €	10.00 €	1.00 €	18.00 €	0.69
	5	6.00 €	10.00 €	1.00 €	20.00 €	0.56
	6	6.00 €	10.00 €	1.00 €	22.00 €	0.47
	7	6.00 €	10.00 €	1.00 €	24.00 €	0.40
	8	6.00 €	10.00 €	1.00 €	28.00 €	0.29
	9	6.00 €	10.00 €	1.00 €	34.00 €	0.19
	10	6.00 €	10.00 €	1.00 €	44.00 €	0.09
1.2	11	0.40 €	8.00 €	5.00 €	9.00 €	NA
	12	0.40 €	10.00 €	5.00 €	9.00 €	2.243
	13	0.40 €	11.00 €	5.00 €	9.00 €	1.61
	14	0.40 €	12.00 €	5.00 €	9.00 €	1.292
	15	0.40 €	13.00 €	5.00 €	9.00 €	1.09
	16	0.40 €	14.00 €	5.00 €	9.00 €	0.948
	17	0.40 €	15.00 €	5.00 €	9.00 €	0.841
	18	0.40 €	19.00 €	5.00 €	9.00 €	0.584
	19	0.40 €	27.00 €	5.00 €	9.00 €	0.358
	20	0.40 €	43.00 €	5.00 €	9.00 €	0.184
2.1	21	30.00 €	30.00 €	30.00 €	1.00 €	NA
	22	25.00 €	25.00 €	30.00 €	1.00 €	3.8
	23	20.00 €	20.00 €	30.00 €	1.00 €	1.7
	24	17.00 €	17.00 €	30.00 €	1.00 €	1.1
	25	16.00 €	16.00 €	30.00 €	1.00 €	1.06
	26	15.00 €	15.00 €	30.00 €	1.00 €	0.94
	27	12.00 €	12.00 €	30.00 €	1.00 €	0.63
	28	10.00 €	10.00 €	30.00 €	1.00 €	0.45
	29	5.00 €	5.00 €	30.00 €	1.00 €	-0.06
	30	1.00 €	1.00 €	30.00 €	1.00 €	NA
2.2	31	14.00 €	17.00 €	17.00 €	1.00 €	NA
	32	14.00 €	17.00 €	20.00 €	1.00 €	2.8
	33	14.00 €	17.00 €	25.00 €	1.00 €	1.4
	34	14.00 €	17.00 €	28.00 €	1.00 €	1.1
	35	14.00 €	17.00 €	29.00 €	1.00 €	1.06
	36	14.00 €	17.00 €	30.00 €	2.00 €	0.93
	37	14.00 €	17.00 €	30.00 €	3.00 €	0.87
	38	14.00 €	17.00 €	32.00 €	8.00 €	0.21
	39	14.00 €	17.00 €	32.00 €	10.00 €	-1.04
	40	14.00 €	17.00 €	32.00 €	14.00 €	NA

Note: The table shows a total of four multiple price lists, MPL1.1, MPL1.2, MPL2.1 and MPL2.2, each containing a total of ten choices between two options labeled neutrally as A and B to elicit risk preferences. Participants repeatedly chose between choices with differing levels of risk. Utility over monetary gains is modeled assuming constant relative risk aversion (CRRA), as expressed in Equation 4.3, described in Section 4.2.5.

Table A12: Multiple price lists for time preferences

Multiple price list	Choice	Option A: Today	Option B: In one month	Yearly discount factor
3.1	1	18.20 €	18.00 €	1.14
	2	18.00 €	18.00 €	1.00
	3	17.80 €	18.00 €	0.87
	4	17.30 €	18.00 €	0.62
	5	16.80 €	18.00 €	0.44
	6	16.00 €	18.00 €	0.24
	7	14.00 €	18.00 €	0.05
	8	12.00 €	18.00 €	0.01
	9	10.00 €	18.00 €	0.00
	10	8.00 €	18.00 €	0.00
3.2	11	12.00 €	11.80 €	1.22
	12	12.00 €	12.00 €	1.00
	13	12.00 €	12.20 €	0.82
	14	12.00 €	12.50 €	0.61
	15	12.00 €	13.00 €	0.38
	16	12.00 €	14.00 €	0.16
	17	12.00 €	15.00 €	0.07
	18	12.00 €	16.00 €	0.03
	19	12.00 €	18.00 €	0.01
	20	12.00 €	22.00 €	0.00

Note: The table shows a total of two multiple price lists, MPL3.1 and MPL3.2, each containing a total of ten choices between two options labeled neutrally as A and B to elicit time preferences. Participants repeatedly chose between varying monetary payoffs at different points in time. Inter-temporal choices as measure of time preferences are modelled using a simple expected discounted utility model, as expressed in Equation 4.4, described in Section 4.2.5.

Table A13: Relative effect and prospective sample size

	Coefficient	SD (Outcome)	Relative effect	Sample size
Panel A: CANTAB cognition tests				
Reaction Time Task	3.588	49.696	0.072	111
Motor Screening Task	0.493	86.484	0.006	1311
Delayed Matching to Sample	3.550	8.712	0.407	22
Paired Associate Learning	0.500	2.974	0.168	49
Multitasking Test	-11.038	73.866	-0.149	55
One-Touch Stocking of Cambridge	0.450	1.598	0.282	30
Stop Signaling Task	6.239	25.333	0.246	34
Spatial Working Memory	-0.400	4.883	-0.082	98
Panel B: Economic decision-making				
Risk aversion	0.010	0.298	0.033	242
Discounting	0.009	0.120	0.068	118
Fechner error	0.053	0.394	0.134	61
Tremble error	-0.092	0.115	-0.793	13
Panel C: Physiological parameters				
Blood CO_2	-0.628	3.016	-0.208	40
Heart rate	0.637	9.971	0.064	125
Respiration rate	-0.007	0.046	-0.154	53
Systolic blood pressure	1.071	12.122	0.088	92
Diastolic blood pressure	1.482	8.334	0.178	48
Physical activity	12.379	46.851	0.264	32
Oxygen consumption	6.087	67.367	0.090	90

Note: Column 1 shows the estimated coefficient δ based on equation 4.1. Column 2 contains the standard deviation (SD) of the underlying distribution of the outcome variable in the full sample. Column 3 shows the relative effect as calculated by dividing the estimated effect δ by the standard deviation. Last, column 4 presents the required sample size resulting from a power analysis. For economic decision-making in Panel B, the standard deviation was calculated as the standard error of the estimated coefficient on the treatment dummy, multiplied by the square root of the number of participants. The power analysis is conducted based on a linear multiple fixed effect regression model, two-tailed, with an alpha error rate of 0.05, a power of 0.8 and 1 predictor.

Table A14: Comparison with related papers

Panel A: Studies with a combination of cognitive and physiological parameters

	This paper	[403, 404]	[345]	[402]	**[Liu2017]**
Testing room	Validated respiration chamber	Climate chamber	Office room	Climate chamber	Climate chamber
No. of subjects in room	1	In groups of 5	1	In groups of 4	In pairs of 2
Method to remove pollutants	High ventilation, pollution filter	Cleaned, baked at 40°C & high ventilation	High ventilation	High ventilation	High ventilation
Volatile organic compounds measured	Yes	No	No	No	No
Exposure levels (in ppm)	900 vs. 3,000	500 vs. 1,000 vs. 3,000	830 vs. 2,700	500 vs. 5,000	380 vs. 3,000 (at 35°C)
Exposure time (in min)	480	255	50	153	180
Time between test days	4 to 6 weeks	No days in between	Unspecified	1 day	No days in between
Study design	Within subject	Within subject	Within subject	Within subject	Within subject
Sample size	20	25	31	10	12
Blinding condition	Single blinded	Single blinded	Single blinded	Single blinded	Unspecified
Exposure order randomized	Yes	Yes	Yes	Yes	Yes
Population	Office workers	Students	Employees or students	Students	Unspecified
Significant physiological response	No	Yes	No	Yes	No
Significant cognitive response	No	No	Yes	No	No
Significant performance-induced response	Yes	Not measured	Not measured	Not measured	Not measured

Panel B: Studies with a focus on decision-making

	This paper	[331]	[7]	[322]	[313]
Testing room	Validated respiration chamber	Climate chamber	Office room	Office-like chamber	Hypo hyperbaric chamber
No. of subjects in room	1	In groups of 4 to 6	In groups	In groups of 4	In groups of 2 to 4
Method to remove pollutants	High ventilation, pollution filter	Unspecified	High ventilation	High ventilation	Unspecified
Volatile organic compounds measured	Yes	No	Yes	No	No
Exposure levels (in ppm)	900 vs. 3,000	600 vs. 1,200 vs. 2,500 vs. 5,000	550 vs. 945 vs. 1,400	600 vs. 1,000 vs.2,500	600 vs. 2,500 vs. 15,000
Exposure time (in min)	480	175	480	150	125
Time between test days	4 to 6 weeks	1 week	No days in between	1 hour	Not applicable
Study design	Within subject	Within subject	Within subject	Within subject	Between subjects
Sample size	20	22	24	22	36 (12 per group)
Exposure order randomized	Yes	Yes	No	Yes	Yes
Population	Office workers	Astronout-like subjects	Office workers	Unspecified	Male submariners
Significant cognitive response	No	Yes, but inconsistent	Yes	Yes	No

About the author

Stefan Flagner was born on April 25th, 1994 in Düsseldorf, Germany. He holds a Bachelor of Sciences degree in Economics (*Volkswirtschaftslehre*) from the University of Mannheim, which he completed between 2013 and 2017. During his Bachelor program, he visited the Norwegian University of Sciences and Technology (NTNU) in Trondheim, Norway, for an exchange semester. During his studies, Stefan worked at several companies, including an internship at Deloitte in Transaction Services and at Corpus Sireo Real Estate (Today: Swiss Life Asset Managers Deutschland GmbH) in Business Development.

Stefan continued his education at Maastricht University, graduating with distinction (Cum Laude) with a Master of Sciences in International Business, Specialization Sustainable Finance (2017 to 2018), for which he extended his Masters with an exchange semester at EM Lyon Business School in Lyon, France. During his studies, Stefan received a scholarship from the Friedrich-Ebert Foundation, supporting his professional and personal development. After graduating with the masters in Finance, he worked full-time as an associate consultant in financial advisory at PwC Luxembourg, until he decided to pursue a second Master degree in occupational health (Masters Work, Health, and Career), between 2019 and 2020.

Upon graduating from his second master, Stefan started his interdisciplinary PhD program at Maastricht University, where he is affiliated with the School of Business and Economics, Department of Finance, and the Faculty of Health, Medicine, and Life Sciences at the Department of Nutrition and Movement Sciences. During his PhD, he combined the methodology and knowledge from the field of economics and human physiology to investigate the impact of indoor air quality on cognitive performance and health of building occupants. He presented his work at several conferences, among them AREUEA in Cambridge, Curacao and New Orleans, Healthy Buildings conference in Aachen and Hawaii, and The Physiological Society conference in Harrogate.

Next to his research, Stefan was also involved in teaching Bachelor and Master courses in Economics and Biomedical Sciences, as well as co-coordinating the Sustainable Health Care Bachelor course. In 2023, he received the Dutch University Teaching Qualification (*Basiskwalificatie Onderwijs*).