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Indoor Environment, Student Satisfaction and Performance in Higher Education

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Indoor Environment, Student Satisfaction and Performance in Higher Education*

Abstract

This study examines how improvements in indoor environmental quality affect student satisfaction and academic performance in higher education. We conducted a randomized field experiment involving 1,258 first-year undergraduate students at Maastricht University, who were randomly assigned to tutorial groups located either in a recently renovated building with improved indoor environmental quality or in a conventional control building. We find that students in the treatment building report significantly higher satisfaction with indoor environmental quality and the overall learning environment. However, these improvements do not translate into measurable effects on academic performance, study effort, or tutor evaluations.

JEL classification

I21, I23, I31, J24

Keywords

indoor environmental quality, higher education, human capital accumulation, satisfaction, field experiment

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1 Introduction

Higher education is an important determinant of economic growth and social welfare, making the effective accumulation of human capital a key objective of public policy (Pierce and Welch 1996; Black and Lynch 1996). This requires difficult choices for policymakers and educational institutions about the allocation of scarce resources to maximize student learning. While a large body of research has examined the role of factors such as teacher quality (Feld et al. 2020; Braga et al. 2016; Hoffmann and Oreopoulos 2009; Fleisher et al. 2002), peer effects (Elsner et al. 2021; Golsteyn et al. 2021), class size (Monks and Schmidt 2011), and external environmental factors (Ebenstein et al. 2016; Marie and Zölitz 2017), the physical infrastructure of the buildings in which higher education takes place has received almost no attention.

The lack of research on the impact of buildings on college and university educational outcomes is striking, given that evidence from environmental science and economics suggests that indoor environmental quality plays an important role in shaping occupants' health (Mujan et al. 2019), well-being (Altomonte et al. 2020) and cognitive performance (Wang et al. 2021). For instance, considering air quality as one factor determining the indoor environment, laboratory studies demonstrate that short-term exposure to poorly ventilated rooms impairs cognitive performance of individuals (Du et al. 2020). Additional field studies in primary and secondary schools and offices show that ventilation and indoor air quality influence learning outcomes and health (Wargocki et al. 2020; Palacios et al. 2022; Deng et al. 2023; Stafford 2015; Haverinen-Shaughnessy and Shaughnessy 2015). In addition to air quality, three additional factors commonly define indoor environmental quality, including thermal comfort, lighting, and noise, which may further impact cognitive performance and health among students and teaching staff (Flagner et al. 2025; Brink et al. 2021).

Despite this policy relevance, causal evidence on the educational return to investment in the physical infrastructure of colleges and universities is scant. Compared to primary and secondary education, higher education differs in several important respects, such as students' exposure time to the building, their age composition, and the type and complexity of the cognitive tasks. Regardless, existing studies are limited to office work or focus on primary and secondary education (Wang et al. 2021). The only exception is the meta-study by Brink et al. (2021), which summarizes small-scale experimental evidence on subjective, short-term outcomes, leaving open the question of whether sustained improvements in the indoor environment affect long-term academic achievement in higher education.

The lack of evidence is especially consequential given the substantial public investments de-

voted to higher education infrastructure. For the United States, public spending in education accounts for more than 5% of the annual Gross Domestic Product (Busemeyer 2007). Governments in the European Union spend around 3% of the Gross Domestic Product annually on the construction and renovation of education buildings (Ferrari and Meliciani 2022). The European Union’s green transition is expected to channel additional funds into upgrading educational facilities, with a focus on energy efficiency. The recent report from former president of the European Central Bank, Mario Draghi, emphasizes the importance of investments in education and labour skill development to improve the competitiveness of European economies (European Commission 2024). This policy agenda presents an opportunity not only to improve energy performance, but also to align investments with indoor environmental quality standards that promote student learning and health.

Therefore, this study provides the first causal evidence on the impact of building infrastructure on student satisfaction and learning performance in higher education. We conducted a randomized field experiment in which 1,258 first-year Bachelor students at the *School of Business and Economics at Maastricht University* were randomly assigned to either a recently renovated building or a control building. The renovated building has improved indoor environmental quality, with the explicit aim of supporting the health and well-being of occupants, as attested by the internationally recognized *WELL certificate* (WELL 2023; McArthur and Powell 2020). We deployed a building-wide monitor network to collect continuous measurements of indoor environmental quality, and evaluate both subjective assessments of the learning environment and objective learning outcomes in the form of students’ course grades. We find that the renovated building substantially improves students’ satisfaction with their learning environment, but that it does not translate into measurable effects on students’ course grades. Sensitivity analyses suggest that differences in indoor environmental quality explain only part of these subjective treatment effects.

This paper makes three main contributions. First, we combine a large-scale random assignment of university students to treatment and control buildings with high-frequency measurements of indoor environmental quality. This provides a unique setting in which the impact of building infrastructure can be causally linked to both subjective measures of student satisfaction and objective learning outcomes. Second, we extend the academic literature on the determinants of learning outcomes in higher education by documenting the role of the physical learning environment. In doing so, we complement existing research on teacher quality, peer effects, class size, and other factors, and provide policy-relevant evidence to guide universities when allocating

scarce resources to foster student learning. Third, our results also inform cost–benefit analyses of large-scale investments in education infrastructure, particularly in the context of recent initiatives such as the European Union’s green transition, by highlighting returns to student learning in addition to energy savings.

The paper is structured as follows. Section 2 explains the institutional background of the study including a description of the teaching system at Maastricht University as well as the features of the treatment and control building. Section 3 describes the sample and randomization procedure, the data collection and presents the empirical strategy. The results are presented in Section 4 and underlying mechanisms are discussed in Section 5. Section 6 concludes.

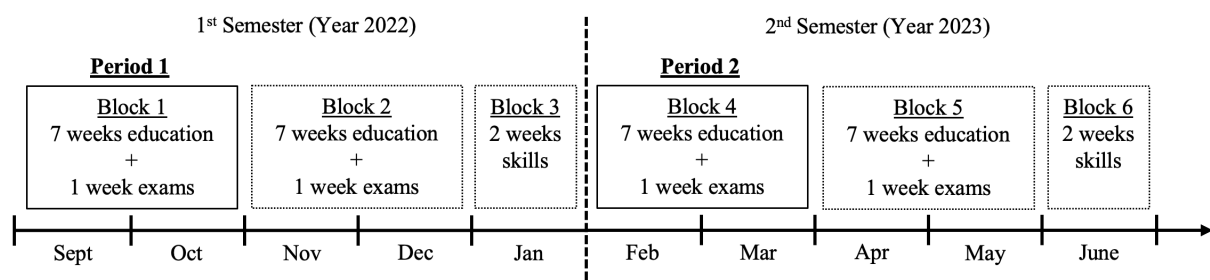
2 Institutional background

The field experiment took place at the *School of Business and Economics at Maastricht University*. During the academic year 2022/2023, we randomly assigned first-year BSc students to education rooms located either in a newly renovated building (treatment) or in an existing building (control). To understand the experimental design presented in Section 3, it is essential to describe both the teaching system at *Maastricht University* and the characteristics of the two buildings.

2.1 Teaching system at Maastricht University

Maastricht University employs a problem-based learning (PBL) system (Servant-Miklos 2019), which fundamentally differs from traditional lecture-based higher education models. The academic year is organized into four eight-week teaching blocks, each consisting of seven weeks of instruction followed by one examination week. In addition, two shorter skills blocks are dedicated to skills training (Figure 1). Students typically take two courses per block and one skills training per skills block, resulting in eight full courses as well as two skills trainings over the academic year.

Figure 1: Overview of academic year



Teaching within each course is centered around small tutorial groups of up to 15 students, guided by a tutor. In contrast to conventional lecture-based instruction, lectures play a complementary role, while the majority of contact hours occur in these tutorials. Students meet twice per week for two-hour sessions per course, implying approximately eight hours of classroom exposure per week across both courses. Attendance is mandatory, and, conditional on course choice, students are randomly assigned to tutorial groups defined by a fixed time slot and tutor. Students are not allowed to switch tutorial groups preventing endogenous selection out of the treatment (see Mengel et al. (2019), for a detailed description of the allocation of students to tutorial groups at the School of Business and Economics at Maastricht University).¹

The PBL format is highly interactive and student-driven. During tutorial sessions, students collaboratively work on case studies and assignments designed to stimulate discussion and problem-solving. The tutor acts primarily as a facilitator rather than a lecturer. Assessment is multidimensional and includes in-class participation, presentations, assignments, and a final written exam. The final course grade is a weighted average of partial grades, with the exam having the largest weight (ranging from 50-100% in the selected courses for our experiment). Importantly, exams are administered centrally in large examination halls outside the tutorial buildings, ensuring that all students take the exam under identical environmental conditions.

These institutional features have several implications for our study. First, students are repeatedly exposed to the indoor environment of tutorial rooms over a period of seven weeks, allowing for the analysis of cumulative exposure effects. Second, the PBL setting closely resembles classroom-based learning environments in primary and secondary education, facilitating comparability with prior literature. At the same time, exposure to the classroom environment is limited: while students spend at least eight hours per week in tutorials, a substantial share of learning takes place outside these rooms. Figure A1 in the Appendix confirms that the majority of students in our estimation sample prefers to study either at home (48% to 55%) or in other buildings such as the library (about 26% to 33%). A rather small share of students (6% to 10%) occasionally stays in the education buildings for study purposes. Consequently, it is important to keep in mind that the treatment captures only part of students' total learning environment.

2.2 The renovated and the control building

For the purposes of this study, we focus on the two university buildings in which teaching at the *School of Business and Economics* takes place. Until 2020, all tutorial meetings were held

¹Switching tutorial groups is only allowed under very special circumstances, e.g., for medical reasons or for top-athletes. Given that this affects about 0.3% of the student population each year, it is negligible in our analysis.

in a single building (hereafter: control building), which was originally constructed in the 1930s and most recently renovated in the early 2000s (see Figures A2a and A2c in the Appendix). In response to substantial growth in student numbers, a second building was added in 2020 (hereafter: treatment building). This building, originally constructed in 1919 as a military facility, was extensively renovated and refurbished prior to its use for teaching (see Figures A2b and A2d in the Appendix).

Both buildings contain tutorial rooms, lectures halls and offices. Tutorial rooms in both buildings are comparable in size, with a maximum of 15 students per group, and are scheduled throughout the day in identical time slots. The two buildings are located approximately 500 metres apart and share similar external surroundings, with exposure to both green areas and urban traffic.

Table 1 provides an overview comparing the main features of the treatment and control buildings. It can be seen that the two buildings differ in several dimensions that are directly related to the indoor environment. Most importantly, the treatment building is equipped with a modern heating, ventilation, and air conditioning system. Its ventilation is balanced and demand-controlled, with airflow adjusted to room occupancy on the basis of real-time carbon dioxide (CO₂) measurements. As a result, ventilation rates respond automatically to classroom use and are less dependent on manual window opening. The building further incorporates air filtration systems and low-emission materials designed to reduce indoor exposure to volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs).²

In addition to improved air quality, the renovation addressed other dimensions of the indoor environment. Indoor temperature is regulated automatically through an integrated building management system that combines heating and cooling, thereby providing a more stable thermal environment. Section 3.2.1 quantifies the differences between the treatment and the control buildings in terms of the indoor environmental conditions, showing that the treatment building provides consistently better air quality and more stable thermal conditions. Moreover, lighting conditions were designed to improve visual comfort, including measures to reduce glare from natural and artificial light sources and to avoid flicker. Acoustic conditions were also improved through stronger sound insulation and lower background noise levels.

Altogether, these design features were instrumental in obtaining the WELL Silver certification for the treatment building (WELL 2023). The WELL standard is one of the most prominent

²During the COVID-19 period, the treatment building was subject to high ventilation rates for extended periods, which likely further reduced pollutant concentrations that can be elevated after renovation (Holøs et al. 2019).

Table 1: Comparison of treatment and control buildings

	Treatment building	Control building
Construction and renovation	Originally built in 1919; extensively renovated and refurbished for educational use (2020)	Originally built in 1930s; last major renovation in early 2000s
Ventilation system	Balanced, demand-controlled mechanical ventilation (CO ₂ -based)	Static mechanical ventilation and natural ventilation via windows
Air quality management	Advanced filtration; low-emission materials (VOC/SVOC control)	No targeted measures for pollutant reduction
Thermal comfort	Automated heating and cooling via building management system; stable temperatures	Radiator-based heating; no air conditioning; greater temperature variability
Lighting	Optimised for visual comfort and circadian rhythm; glare control	Standard lighting; no targeted optimisation
Acoustics	Enhanced sound insulation and reduced background noise	Limited acoustic optimisation
Building certification	WELL Silver certified	No certification related to indoor environmental quality

Note: The overview summarizes the main differences between the treatment and control building.

certification systems aimed at promoting healthy indoor environments in offices, schools, and public buildings. It integrates requirements across several domains, including air, thermal comfort, light, materials, and acoustics. For the purposes of our analysis, this is important because the treatment should be understood as an improvement in overall indoor environmental quality rather than as a change in one specific pollutant or building characteristic.

By contrast, the control building represents a more conventional university teaching environment. Some classrooms are equipped with mechanical ventilation and radiators for heating, but ventilation is not demand-controlled and there is no air conditioning. Windows can be opened manually, implying that ventilation and thermal conditions are more sensitive to occupant behaviour and outdoor conditions. The control building also lacks targeted interventions aimed at improving acoustics or lighting quality. In addition, its insulation and interior fit-out reflect an earlier renovation standard, and its furniture and materials have been in use for substantially longer.

3 Experimental design, data and empirical strategy

This section describes the experimental design and the data used in the analysis. We first outline the study sample and the random assignment of students and tutors to tutorial groups in the treatment and control buildings. We then describe the collection and the distribution of indoor

environmental quality measures in the sampled classrooms, followed by the administrative and survey data used to capture student satisfaction, study effort, and academic performance.

3.1 Sample and randomization

The study population consists of first-year students enrolled in the BSc programmes in *Economics and Business Economics* (EBE), *International Business* (IB), and *Fiscal Economics* (FE) during the academic year 2022/2023. The experiment was implemented in Block 1 (September–October 2022) and Block 4 (February–March 2023), which we refer to as Period 1 and Period 2, respectively (see Figure 1).

The analysis covers five compulsory first-year courses. In Period 1, all three degree programmes took the same two courses, *Quantitative Methods I* and *Management of Organisation and Marketing*. In Period 2, the three programmes shared *Quantitative Methods II*, while the second course was programme-specific: EBE and FE students took *Macroeconomics*³ while IB students took *Strategy*. The course portfolio therefore combines more technical and less technical subjects, which improves the external validity of the design within the first-year business and economics curriculum. All courses followed the standard Maastricht University format described in Section 2.1. Each course included one weekly lecture held in a central lecture hall on Mondays and two two-hour tutorial meetings per week held from Tuesday to Friday. Tutorial meetings were scheduled in four fixed time slots: 08:30–10:30, 11:00–13:00, 13:30–15:30, and 16:00–18:00.

Within each course taken within the selected periods, students were randomly assigned to tutorial groups that were scheduled either in the treatment building or in the control building. Therefore, randomization took place at the tutorial-group level within courses, implying that treatment status varied within course and period. Because assignment occurred separately by course, students could in principle be exposed to different buildings across their two courses within a period. This occurred frequently in Period 1, when 35% of students were assigned to the same building in both courses and the remaining 65% switched buildings across courses. In Period 2, by contrast, the design implied that all students were assigned to the same building for both courses.

The final estimation sample comprises 31 tutorial classrooms, of which 14 are located in the treatment building and 17 in the control building. Across these rooms, we observe 324 tutorial groups taught by 114 tutors and attended by 1,258 students. Tutors typically taught multiple tutorial groups within the same course per day. The majority of tutors had two to three tutorial

³The course macroeconomics was also taken by students enrolled in the BSc programme *Econometrics and Operations Research*.

groups per day, with an average teaching load of roughly 2.8 tutorial groups per course (see Figure A3 in the Appendix). A key feature of the design is that tutors taught in both buildings within the same course. Approximately half of tutors switched buildings during Period 1, and about 95% did so during Period 2 (see Table A1 in the Appendix). This feature is important because it ensures that comparisons between treatment and control groups are less likely to capture persistent differences in tutor quality or teaching style rather than differences in the indoor environment. We exploit this variation by including tutor fixed effects in our econometric specification (see Section 3.3 below).

Students and tutors were not informed about the purpose of the study. In particular, they were unaware that indoor environmental conditions were being monitored for research purposes. This reduces the scope for behavioural responses that could otherwise confound the estimated treatment effect.

Table A2 in the Appendix presents evidence supporting the validity of the randomization procedure. Panel A shows that the allocation of students across the treatment and control building is close to balanced within courses and periods. Moreover, Panel B of Table A2 demonstrates that observable student characteristics, such as sex and age, as well as scheduling characteristics such as tutorial-group time slots, are well balanced across buildings. We also verify that prior academic performance in Period 1 does not predict building assignment in Period 2. Together, these patterns support the internal validity of the experimental design and suggest that subsequent differences in outcomes can plausibly be attributed to differences in the indoor learning environment rather than to pre-existing differences between students.

3.2 Data

3.2.1 Indoor environmental data

To document indoor environmental conditions in both buildings, we continuously monitored all 31 sampled classrooms throughout the two teaching periods. Measurements were taken every five minutes using *Foobot SAT* monitors installed in each tutorial room⁴. The monitored variables comprise carbon dioxide (CO₂), total volatile organic compounds (TVOC), particulate matter (PM₁, PM_{2.5}), temperature, and relative humidity. The monitors were mounted on interior walls at a height of 1.5 metres above the floor, away from windows, doors, and ventilation outlets, so as to avoid direct interference from airflow or solar radiation (according to ASHRAE 2023).

The raw monitoring data were cleaned to retain only observations recorded during scheduled

⁴The accuracy of the Foobot monitor is validated against other commercial sensors in Zheng et al. (2022).

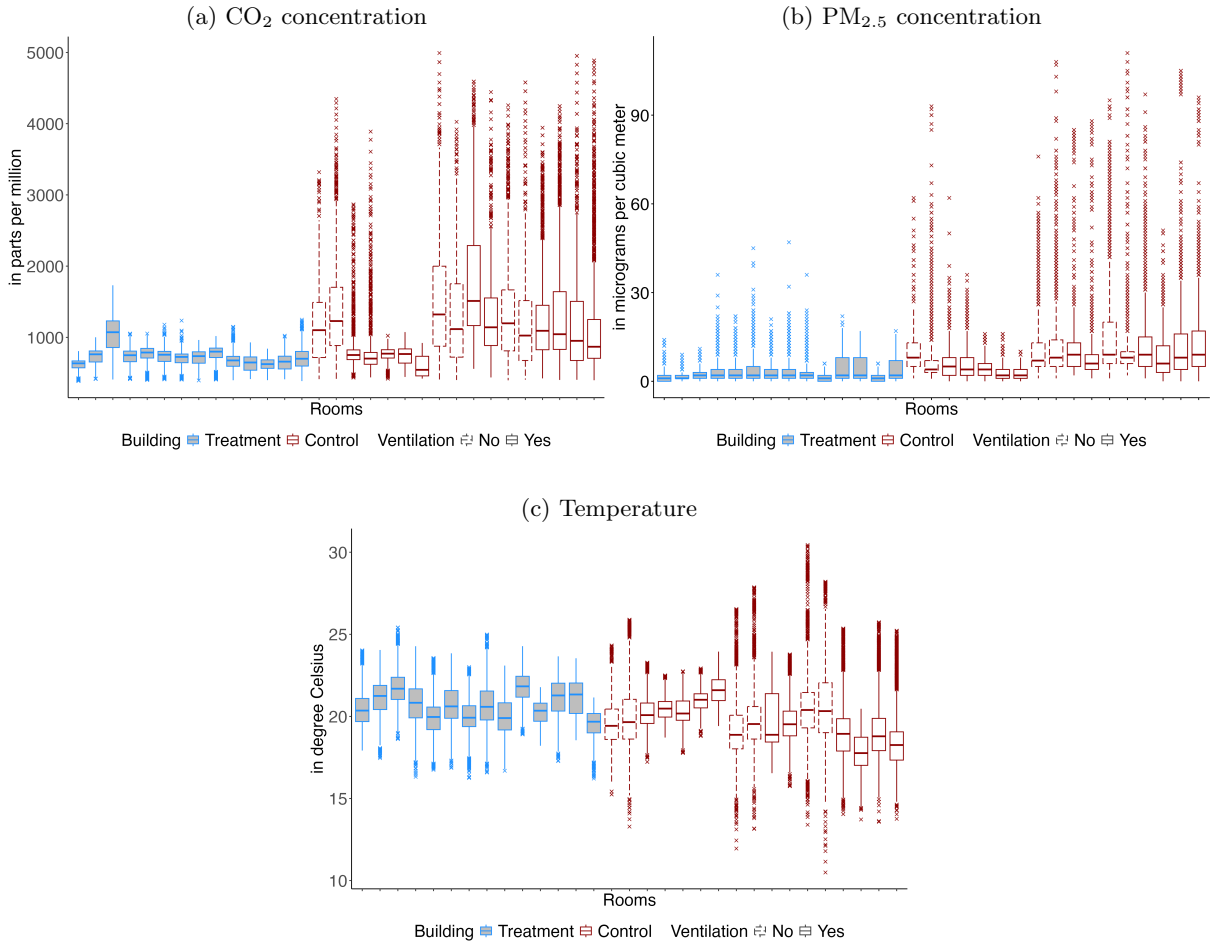
Table 2: Indoor environmental quality and outdoor temperature across treatment and control buildings

	Control				Treatment				t-test signif.
	Mean	St. Dev.	Min	Max	Mean	St. Dev.	Min	Max	
Panel A: IEQ in period 1									
CO ₂ (in ppm)	1,212	693	383	4,952	769	191	387	1,731	$p < 0.01$
PM _{2.5} (in $\mu\text{g}/\text{m}^3$)	9.6	10	0	111	1.8	1.5	0	18	$p < 0.01$
TVOC (in ppb)	1,090	783	6	5,490	665	342	9	2,984	$p < 0.01$
Temperature (in °C)	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	$p < 0.01$
PM _{2.5} (in $\mu\text{g}/\text{m}^3$)	11	12	0	108	4.2	4.3	0	47	$p < 0.01$
TVOC (in ppb)	1,565	1,090	8	8,798	792	486	7	7,500	$p < 0.01$
Temperature (in °C)	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 (Sep–Oct)				Period 2 (Feb–Mar)				
	Mean	Sd	Min	Max	Mean	Sd	Min	Max	t-test signif.
Peak outdoor temperature (in °C)	18	3.8	11	30	11	4.2	3.7	18	$p < 0.01$
Average outdoor temperature (in °C)	13	3.4	8.6	22	6.6	4.5	-0.1	13	$p < 0.01$

Note: The table reports descriptive statistics on classroom indoor environmental quality (IEQ) aggregated at the building level separately for both periods in panel A and B. In addition, Panel C reports daily peak and daily average outdoor temperatures. CO₂ = carbon dioxide; TVOC = total volatile organic compounds; PM_{2.5} = fine particulate matter. The last column reports the statistical significance of differences in mean values between the two buildings based on independent t-tests.

tutorial meetings. We therefore exclude nights, weekends, holidays, and the breaks between classes. This yields room-level measures of the indoor environment during actual treatment exposure. In addition, we merge the indoor data with daily outdoor weather conditions, including outdoor temperature, to assess the extent to which external conditions translate into classroom conditions in the two buildings.

Figure 2: Indoor environmental quality conditions



Note: The figure shows the CO₂ concentration, fine particulate matter concentration, PM_{2.5}, and temperature in the treatment (blue) and control building (red). 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 (×). The dashed boxplots indicate classrooms with no mechanical ventilation.

The measurement data confirm that the treatment and control buildings differ systematically in terms of indoor environmental quality. Table 2 shows the distribution of the environmental quality measures aggregated at the building level, and Figure 2 presents the distribution of the main indoor air quality measures (CO₂, PM_{2.5}) as well as indoor temperature, across tutorial rooms.⁵ The treatment building exhibits lower average CO₂ and PM_{2.5} concentrations, indicating better indoor air quality overall. Classrooms in the control building regularly exceeded 1,000 ppm CO₂, a threshold commonly used in building guidelines, with values below 1,000 ppm generally considered indicative of good indoor air quality (ASHRAE 2019; DIN 2007). Although average PM_{2.5} concentrations in both buildings remained below the recommended 24-hour exposure threshold of 15 µg/m³ (World Health Organization 2021), the control building recorded average

⁵The distribution of additional indoor environmental measures (PM₁, TVOC and humidity) are shown in Figure A4 in the Appendix.

PM_{2.5} levels approximately three times higher than those in the treatment building.

Given the observed differences in indoor air quality between the two buildings, existing evidence from the literature would suggest potential effects on student performance. For example, the meta-study by Wargocki et al. (2020) on elementary school settings finds that an increase in average CO₂ concentrations of 400-500 ppm, similar in magnitude to the difference observed between the two buildings in our setting, is associated with a 2% to 4% decline in exam performance. The authors further show that the relationship is non-linear, with stronger declines in performance at CO₂ concentrations above 1,000 ppm. Regarding PM_{2.5} exposure, Ebenstein et al. (2016) find that a one standard deviation increase in PM_{2.5} exposure ($11 \mu\text{g}/\text{m}^3$) during high school examinations reduces student performance by 3.9% of a standard deviation. However, it is important to note that these estimates are derived from settings examining performance during exposure (short-term effect), whereas our study focusses on the cumulative effect of exposure over the course of the study period (long-term effect). This difference limits the comparability of our setting to the existing evidence.

Regarding indoor thermal environment, Table 2 and Figure 2 show that the treatment building provides a more stable thermal environment, with substantially less variation in indoor temperature across classrooms and over time. Relative humidity differs less strongly between the two buildings, although the treatment building exhibits somewhat lower dispersion (see Figure A4 in the Appendix). These patterns are consistent with the building characteristics discussed in Section 2.2 and support the treatment-control distinction in terms of actual environmental exposure.

The potential impact of the observed differences in indoor temperature on student performance is less clear. Wargocki et al. (2019) report that classroom performance declines when temperatures increase from 20 degree Celsius (68 degrees Fahrenheit) to 30 degrees Celsius (86 degrees Fahrenheit), and suggest that optimal performance is achieved at temperatures below 22 degree Celsius (72 degrees Fahrenheit). In contrast, evidence from a global study linking temperature exposure and PISA test scores indicates significant negative effects on performance primarily at temperatures above 26 degrees Celsius (80 degrees Fahrenheit) (Park et al. 2021). More generally, the literature suggests that heat stress impairs cognitive performance mainly at temperature levels that substantially affect core body temperature, which itself depends on acclimatization and exposure duration. Thus, existing evidence suggests that temperatures below 29.4 degrees Celsius (85 degree Fahrenheit) are unlikely to substantially affect core body temperature (Hancock and Vasmatzidis 2003).

Finally, we investigate the relationship between indoor and outdoor conditions in both buildings. Figure A5 in the Appendix shows that indoor CO₂ and indoor temperature are more strongly related to outdoor temperature in the control building. This pattern is consistent with the greater role of manual window opening and the absence of centralized climate control in the control building. By contrast, indoor conditions in the treatment building are much less sensitive to outdoor fluctuations validating the impact of the fully automated ventilation system. Moreover, it underlines the importance to consider both periods separately in our analysis, given the influence of outdoor weather conditions on indoor environmental conditions in the control building.

3.2.2 Outcome variables

Our analysis combines administrative data on student performance with survey-based measures of student perceptions. Objective academic performance is measured using final course grades obtained from Maastricht University’s administrative records. Grades are recorded on the standard Dutch grading scale from 1 - Lowest to 10 - Highest (with a grade of 5.5 as the passing criteria). Importantly, we observe final course grades only; information on separate grade components, such as participation, presentations, or intermediate assignments, is not available in the administrative data. Each student record is linked to a tutorial group within a certain course and thereby to one specific classroom located either in the treatment or control building. Table A5 in the Appendix shows the distribution of the course grades by treatment status and teaching period.

Subjective outcomes are measured using a questionnaire embedded in the standard end-of-course evaluation survey administered during the final week of teaching. Because the survey is tied to the tutorial group, responses can be matched to the classroom in which students attended tutorials. However, survey responses are anonymous and cannot be linked to an individual student’s administrative grade record. Embedding the questionnaire in the regular course evaluation resulted in a relatively high average response rate of 84%. To assess potential selective attrition, we regress tutorial-level response rates on the treatment indicator and all outcome variables. Table A6 in the Appendix shows that response rates are independent of treatment assignment and all outcome measures⁶, supporting the absence of endogenous selection into survey participation.

The survey elicits two sets of perceptions. First, students report their satisfaction with the

⁶Table A6 shows a weakly statistically significant correlation between response rates and study hours. However, the effect size is negligible: a one standard deviation increase in weekly study hours is associated with a 0.6% decrease in the response rate.

indoor environmental quality using questions adapted from the Center for the *Built Environment* questionnaire (Zagreus et al. 2004; Graham et al. 2021). Specifically, students indicate on seven-point Likert scales the extent to which air quality, lighting, noise, and temperature 1 - hindered or 7 - supported their ability to perform well during the tutorial meetings over the preceding seven weeks teaching period. Second, we measure broader perceptions of the learning experience and tutorial environment, including whether students found it difficult to concentrate in the tutorial room (1 - Never to 7 - Always), whether they liked attending the tutorials (1 - Not at all to 7 - Very much), whether they found the room interior appealing (1 - Not appealing at all to 7 - Very appealing), and whether they perceived the interior as affecting their mood and performance (1 - Negatively affecting to 7 - Positively affecting). Appendix Table A4 describes the distribution of the satisfaction and perception variables. It can be seen that students are predominately satisfied with the indoor environmental quality and interior design, with slightly larger values in the treatment building.

In addition to these student-reported perceptions, we use two further variables from the course evaluation system. Students evaluate teaching quality on a scale from 1 - Very low to 10 - Very high, which we use as a complementary measure to assess whether building assignment is correlated with the perceived performance of tutors. The survey also asks students to report their weekly study hours outside the classroom, which provides a proxy for study effort. Together, these administrative and survey-based measures allow us to examine whether improved indoor environmental quality affects not only academic performance, but also students' satisfaction with the learning environment and their self-assessed ability to perform well. Appendix Table A5 shows the distribution of the tutor evaluation scores and study hours. Overall, students spent on average 13 hours per week studying for the courses, and tutors received on average a grade of 8.7 indicating a high student satisfaction with tutor performance.

3.3 Econometric model and identification

We estimate the effect of exposure to the treatment building on student outcomes using a linear fixed-effects regression model. The empirical specification exploits the random assignment of students to tutorial groups that are held either in the treatment or control building within each course and period.

Let Y_{ictj} denote the outcome of student i in course c , assigned to a tutorial group that meets in time slot t and is taught by tutor j . The outcome variables correspond to those described in Section 3.2.2 and include measures of student satisfaction, final course grades, tutor evaluations,

and self-reported study effort. We estimate the following regression model:

$$Y_{ictj} = \delta Treatment_{ic} + \tau_c + \lambda_t + \theta_j + \varepsilon_{ictj} \quad (1)$$

The binary variable $Treatment_{ic}$ equals one if student i attends tutorial meetings for course c in the treatment building, and zero otherwise. Because assignment to tutorial groups (and hence buildings) is random within courses, δ identifies the causal effect of exposure to the improved indoor environment on the outcome of interest.

All outcome variables are standardized at the course level and expressed in standard deviation units (z-scores), which facilitates comparability across courses with different grading scales and survey distributions.

The specification includes course fixed effects τ_c , time-slot fixed effects λ_t , and tutor fixed effects θ_j . Course fixed effects absorb differences in grading standards and course content. More importantly, they restrict identification to within-course variation, which is essential because the random allocation of students to tutorial groups (and hence buildings) occurs within courses. Time-slot fixed effects control for systematic differences across teaching times during the day. Tutor fixed effects account for differences in teaching style and instructor quality. Importantly, as described in Section 3, tutors frequently teach tutorial groups in both buildings within the same period, which ensures that tutor fixed effects are separately identified from building assignment. The identifying variation therefore arises from comparisons of students within the same course, time slot, and tutor who are randomly assigned to tutorial groups located in different buildings.

Standard errors are clustered at the tutorial group level to account for within-group correlation in outcomes and treatment exposure. The sample comprises 324 tutorial groups, providing a sufficiently large number of clusters for inference. Finally, as discussed in Section 3.2.1, we estimate the model separately for Period 1 and Period 2 to account for seasonal differences in outdoor conditions, which may affect indoor environmental quality and its relationship to student outcomes.

4 Results

This section presents the main findings of the experiment. Figure 3 provides a summary of the estimated treatment effects (δ in Equation 1) across all outcome variables, while Tables A7 and A8 in the Appendix report the corresponding absolute and relative effect sizes in detail.

The results reveal a clear pattern. Exposure to the treatment building leads to substantial

improvements in students' satisfaction with the indoor environmental quality and their perceptions of the learning setting. However, these improvements do not translate into measurable differences in objective outcomes such as course grades, study effort, or evaluations of teaching quality. We first present the results for subjective outcomes, followed by the analysis of objective performance measures.

4.1 Satisfaction and perception outcomes

Figure 3a and 3b show the estimated effects and confidence intervals of the treatment building on students' satisfaction with the indoor environmental quality and their perceptions of the learning setting. Across both teaching periods, the results indicate consistent and statistically significant improvements in several subjective evaluations.

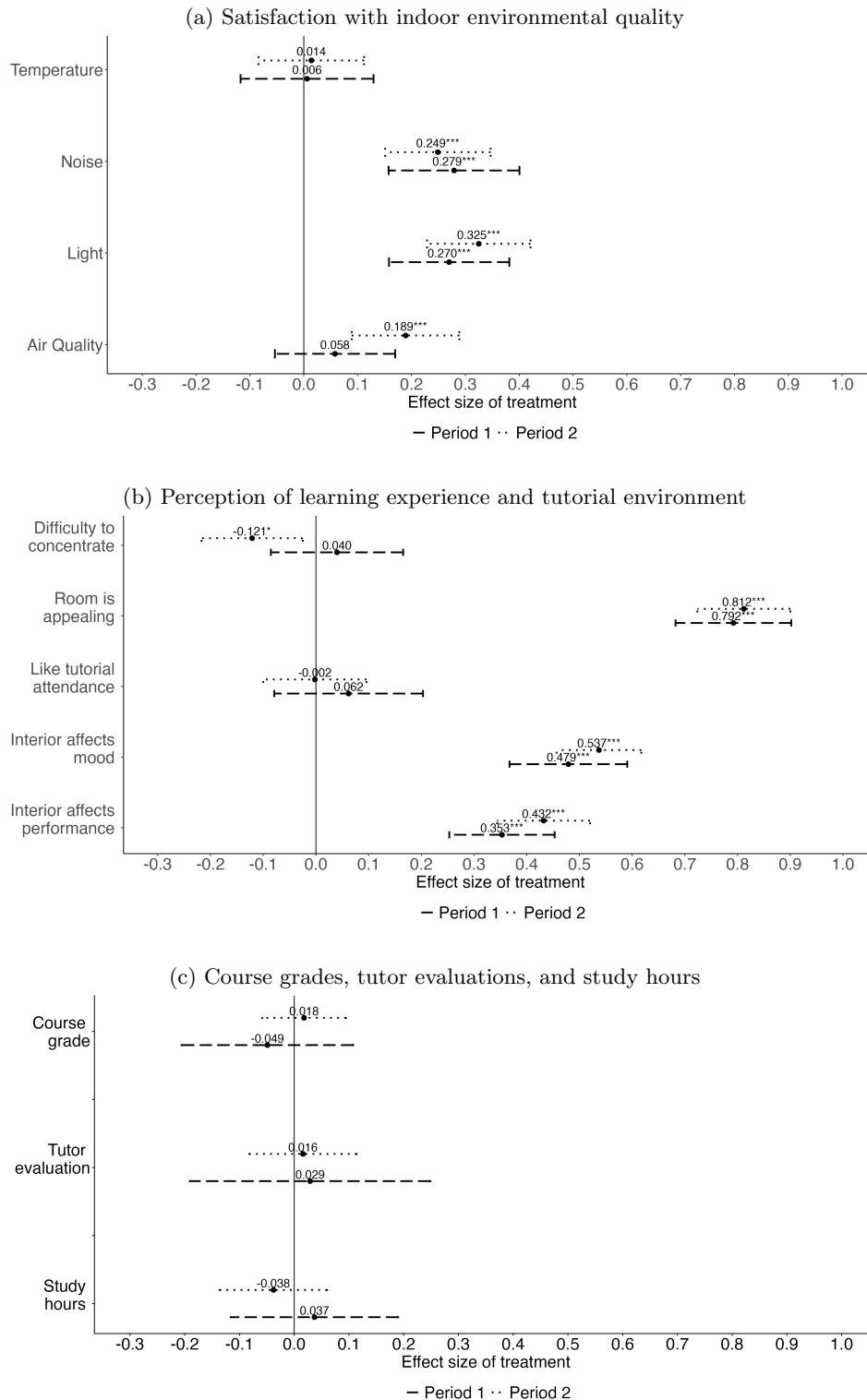
For indoor environmental quality, students in the treatment building report significantly higher satisfaction with lighting and noise conditions in both periods ($p < 0.001$). The magnitude of these effects corresponds to increases of approximately 7–10% relative to the sample mean (see Table A7 in the Appendix). By contrast, perceived support from air quality and temperature shows weaker and less consistent effects. In particular, differences in air quality perceptions are only significant in Period 2, which is consistent with Figure A5 showing continuous high CO₂ concentrations in the control building during the winter season (Period 2) driven by low outdoor temperatures resulting in less manual ventilation (window opening). Temperature evaluations do not differ significantly between buildings in either period, which might be explained by very low differences in indoor temperatures in both buildings (see Table 2).

Stronger effects emerge for broader perceptions of the learning environment (Figure 3b). Students in the treatment building consistently report that the interior design has a more positive effect on both their mood and their perceived performance, with relative effect sizes ranging between 12-17% and strong statistical significance (Table A7 in the Appendix). In addition, rooms in the treatment building are rated as substantially more appealing, with effect sizes of around 0.8 standard deviations, corresponding to differences of 23% and 25% relative to the mean in Period 1 and 2, respectively (Table A7 in the Appendix).

In contrast, there is no statistically significant difference in whether students report liking tutorial attendance. Perceived difficulties in concentrating only differ in Period 2 (similar to perceived air quality), where students in the treatment building report slightly fewer difficulties.

Overall, the results show that improvements in the physical learning environment lead to sizeable increases in student satisfaction and perceived support for learning. Notably, these effects

Figure 3: Estimated treatment effects on satisfaction, perception and student performance



Note: The figure presents the estimated treatment effects (δ in Equation 1) across all outcome variables separately for Period 1 and Period 2. The dots indicate the point estimates, while the horizontal lines represent the corresponding 95% confidence intervals. All outcome variables are standardized at the course level and expressed in standard deviation units. Tables A7 and Table A8 in the Appendix report the corresponding regression results in detail, including the relative effect sizes and course-specific treatment effects. Significance levels are indicated as *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

are substantially stronger for interior design features than for traditional indoor environmental quality measures such as air quality or temperature.

4.2 Grades, study effort, and tutor evaluations

We next examine whether the improvements in perceived learning conditions translate into measurable differences in objective outcomes. Figure 3c summarizes the estimated effects on course grades, tutor evaluations, and self-reported study effort, with detailed results reported in Table A8 in the Appendix.

Across all specifications, we find no statistically significant effects of the treatment building on course grades. The estimated coefficients are small in magnitude and close to zero in both periods. Similarly, there is no evidence that the treatment affects students' study effort. Self-reported weekly study hours do not differ significantly between students assigned to the treatment and control buildings. This suggests that students do not adjust their effort in response to differences in the learning environment.

Finally, we also find no significant differences in tutor evaluations across buildings. This indicates that the indoor environment does not systematically affect perceived teaching quality, consistent with the experimental design in which tutors teach in both buildings and tutor fixed effects are included in the regression.

Taken together, these results show that, despite substantial improvements in satisfaction and perceived performance, the treatment building does not have a measurable impact on objective indicators of academic performance or behaviour.

4.3 Indoor environmental quality as a mechanism

As described in Section 2.2, the treatment building differs from the control building along several dimensions of the physical learning environment. In addition to improved indoor air quality and thermal comfort, the renovated building incorporates enhanced lighting conditions, improved acoustics, modern interior design, and automated climate control systems. Therefore, the estimated treatment effects presented in Sections 4.1 and capture the combined effect of these improvements rather than the effect of any single environmental dimension in isolation.

However, the descriptive evidence presented in Section 3.2.1 suggests that indoor environmental quality may constitute one of the most relevant channels through which the treatment affects student outcomes. In particular, the treatment building exhibits substantially lower CO₂ and PM_{2.5} concentrations, as well as more stable indoor temperatures, relative to the control

building. Moreover, the existing literature reviewed in Section 3.2.1 documents that air quality and thermal conditions are among the indoor environmental factors most consistently associated with cognitive performance and learning outcomes in educational settings.

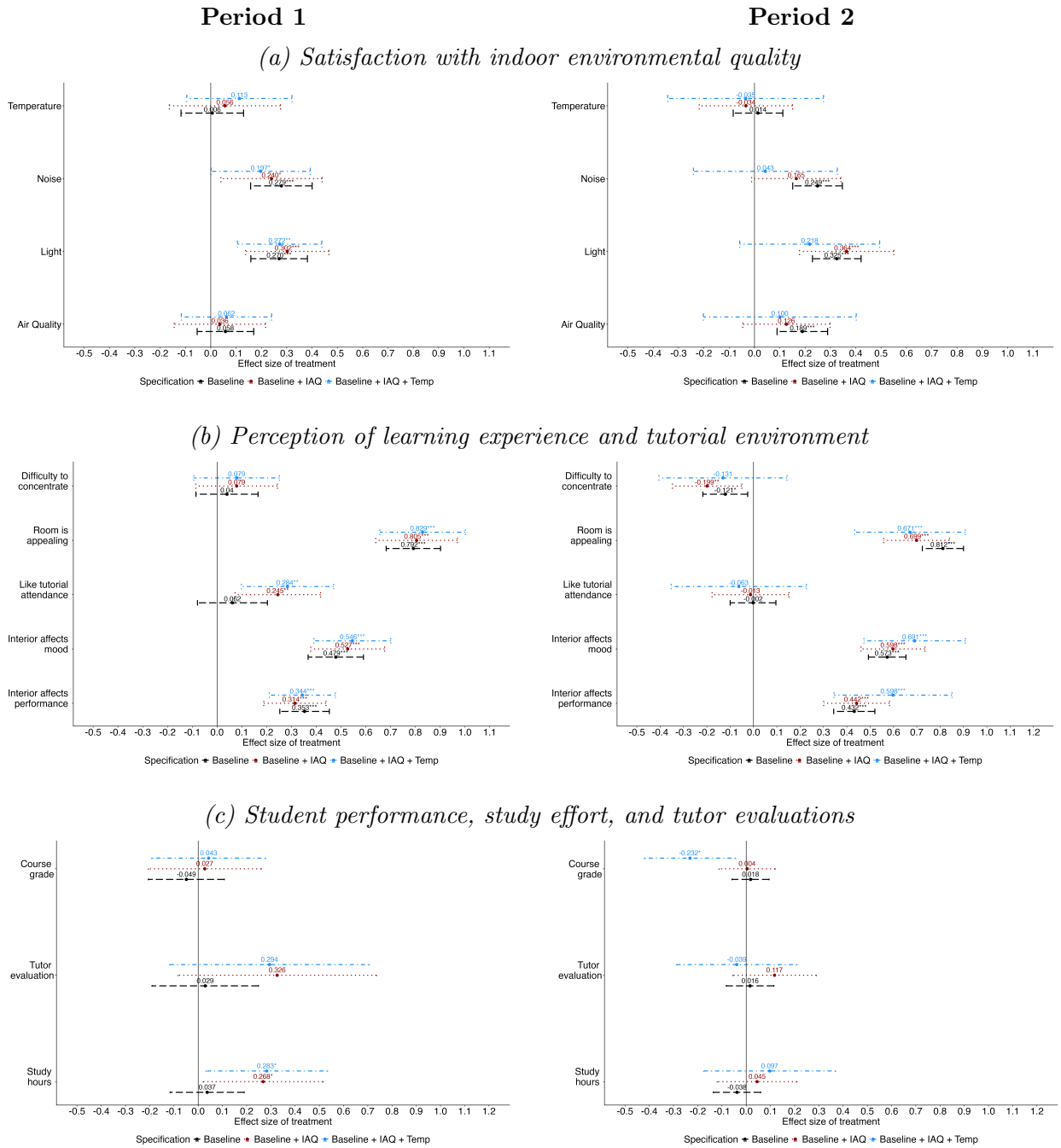
To assess the extent to which the estimated treatment effects are explained by differences in indoor environmental quality, we re-estimate our baseline specification while additionally controlling for classroom-level measures of CO₂, PM_{2.5}, and indoor temperature. Since indoor environmental conditions are themselves outcomes of the treatment, the additional controls are not intended to identify causal mediation effects. Accordingly, Figure 4 only reports the treatment coefficients from specifications that additionally condition on observed indoor environmental conditions. Because these variables capture the most salient environmental differences between the two buildings, the analysis provides insight into whether the estimated treatment effects primarily reflect differences in indoor environmental quality or whether other dimensions of the renovated learning environment also contribute independently to the results.

Figure 4 shows that the estimated treatment effects are only moderately affected by additionally controlling for classroom-level measures of CO₂, PM_{2.5}, and indoor temperature. Overall, the treatment coefficients remain qualitatively similar across specifications, suggesting that differences in indoor environmental quality explain only part of the observed treatment effects.

For satisfaction with indoor environmental quality (Panel a), controlling for indoor environmental conditions moderately reduces the estimated treatment effects, particularly for perceived air quality and noise, with somewhat stronger reductions in Period 2. By contrast, the treatment effects on broader perceptions of the learning experience and tutorial environment (Panel b) remain largely unchanged across specifications. In particular, the strong positive effects on room appeal and the perceived effect of the interior on mood and performance remain highly stable. Finally, Panel (c) shows that the absence of treatment effects on course grades, tutor evaluations, and study effort is robust to conditioning on indoor environmental conditions.

Taken together, the results suggest that indoor environmental quality explains part of the treatment effects on subjective evaluations of the physical environment itself, but cannot fully account for the broader improvements in students' perceptions of the learning experience.

Figure 4: Sensitivity of treatment effects to indoor environmental controls



Note: The figure presents the estimated treatment effects (δ in Equation 1) across alternative specifications and outcome groups. In each row, the left panel reports results for Period 1 and the right panel reports results for Period 2. The specifications include: (1) the baseline specification used in the main analysis; (2) the baseline specification additionally controlling for indoor air quality measures (CO_2 and $\text{PM}_{2.5}$); and (3) the baseline specification additionally controlling for indoor air quality measures and indoor temperature. The dots indicate point estimates, while the horizontal lines represent 95% confidence intervals. All outcome variables are standardized at the course level and expressed in standard deviation units. Full estimation results are reported in Tables A9, A10, and A11 in the Appendix. Significance levels are indicated as *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

5 Discussion of results

This study provides causal evidence on the impact of improvements in the physical learning environment on student outcomes in higher education. The results reveal a clear pattern: while exposure to the renovated building substantially improves students' satisfaction with the indoor environment and their perceived ability to perform, it does not translate into measurable effects on objective outcomes such as course grades.

This divergence between subjective and objective outcomes is central to the interpretation of our findings. In what follows, we discuss three mechanisms that can explain why improved indoor environmental quality leads to higher satisfaction, but not to improved academic performance.

Limited exposure to the classroom environment. A first explanation relates to the amount of time students are exposed to the indoor environment. As described in Section 2.1, students spend approximately four hours per week per course in tutorial rooms, however, the majority of learning takes place outside the classrooms, for example through self-study at home or in other learning spaces such as the library.

This limited exposure to the renovated building contrasts sharply with primary and secondary education settings, where students spend several hours per day in the same classroom. Existing studies that find effects of indoor environmental quality on academic performance typically examine such settings with substantially higher exposure (Wargocki et al. 2020; Palacios et al. 2022; Stafford 2015; Haverinen-Shaughnessy and Shaughnessy 2015). In our context, the relatively short and infrequent exposure to classroom conditions may be insufficient for improvements in the indoor environment to accumulate into measurable differences in academic achievement.

Moderate differences in indoor environmental quality. A second explanation concerns the magnitude of the treatment. Although the treatment building exhibits consistently better indoor environmental quality, the differences between the two buildings remain moderate. For example, average CO₂ concentrations differ by approximately 470 ppm (see Table 2), with the average CO₂ concentrations measured in the control building only moderately exceeding commonly used guideline thresholds (1000 ppm). Existing laboratory and field studies usually investigate larger differences in indoor air quality. For instance, Wargocki et al. (2020) show a 4% decrease in children's performance in national tests in primary and secondary education in response to an increase in indoor CO₂ concentrations from 900 to 2100 ppm in classrooms. In

our setting, the combination of moderate improvements in air quality and limited exposure time may result in treatment effects that are too small to be detected in aggregate academic outcomes such as final course grades. This interpretation is consistent with the sensitivity analysis in Section 4.3, which shows that controlling for classroom-level measures of CO₂, PM_{2.5}, and indoor temperature explains only a limited share of the estimated treatment effects.

Institutional features of higher education and grading. A third explanation relates to the specific structure of learning in higher education and the specific assessment policy at Maastricht University. As explained in Section 2.1, course grades are primarily determined by centrally administered exams which are identical for all students and mostly include standardized exercises, and are taking place outside the tutorial rooms. As a result, the contribution of the tutorial environment to final grades may be limited relative to other inputs, such as individual study effort, prior knowledge, and peer interactions.

Moreover, learning in higher education is less confined to the classroom than in primary and secondary education. Students rely heavily on self-study and often engage in learning activities across multiple environments (with 80% of students studying outside tutorial buildings). This reduces the relative importance of the physical conditions in any single classroom. Consistent with this interpretation, we do not observe any differences in study effort between treatment and control groups, suggesting that students do not adjust their behaviour in response to differences in the indoor environment.

Taken together, these mechanisms provide a coherent explanation for the observed pattern of results. Improvements in the indoor environment are salient and directly experienced by students, which explains the strong effects on satisfaction and perceived performance. However, the combination of limited exposure, moderate treatment intensity, and the structure of learning and assessment in higher education may explain why these improvements do not translate into measurable gains in academic performance.

6 Conclusion

This paper provides the first causal evidence on the impact of building infrastructure on student satisfaction and learning performance in higher education. Using a large-scale randomized field experiment at the School of Business and Economics at Maastricht University, we compare first-year BSc students who were assigned to tutorial groups in a recently renovated and WELL-certified building with students assigned to a conventional control building. A sensor network

measuring the indoor environmental quality in each classroom confirms that the treatment building offered objectively better indoor environmental quality, including lower concentrations of air pollutants and more stable thermal conditions.

Our findings reveal a clear contrast between subjective and objective outcomes. Students in the treatment building report significantly higher satisfaction with the indoor environment and the overall learning setting. They evaluate lighting, noise, and interior design more positively and are more likely to perceive the learning environment as supportive of their performance. However, these improvements do not translate into measurable effects on objective outcomes. We find no statistically significant differences in course grades, study effort, or tutor evaluations between students assigned to the treatment and control buildings.

These results contribute to the literature on the determinants of learning outcomes in higher education by showing that the physical learning environment, while highly relevant for student satisfaction and well-being, does not necessarily improve academic achievement in university settings. In this respect, our findings complement existing research on teacher quality, peer effects, class size, and external conditions, while also highlighting an important distinction between higher education and the primary and secondary school settings that dominate the existing literature on indoor environmental quality and learning outcomes. In higher education, exposure to the classroom environment is more limited and learning is less confined to a single physical space. Moreover, the sensitivity analysis shows that conditioning on indoor air quality and temperature explains only a limited share of the estimated treatment effects, suggesting that the broader improvements in students' perceptions primarily reflect the multidimensional nature of the renovated learning environment.

The findings also have direct policy implications. At a time when governments and universities devote substantial resources to the construction and renovation of educational buildings, our results suggest that improvements in indoor environmental quality can yield meaningful benefits in terms of student satisfaction and well-being, but may not generate comparable returns in terms of academic performance in settings with limited classroom exposure. This implies that investments aimed primarily at raising learning outcomes may yield higher returns in environments where students spend a larger share of their time, such as in earlier stages of education or in dedicated study spaces within higher education. At the same time, the strong effects on student satisfaction indicate that investments in the built environment can improve the overall student experience and should therefore be considered as part of broader welfare-oriented cost-benefit calculations.

Overall, this study shows that an objectively better indoor environment does not automatically translate into better academic performance in higher education. Future research should examine whether stronger effects emerge in settings with longer exposure durations, more intensive use of shared learning spaces, or alternative outcome measures that capture dimensions of student well-being and academic development beyond final course grades.

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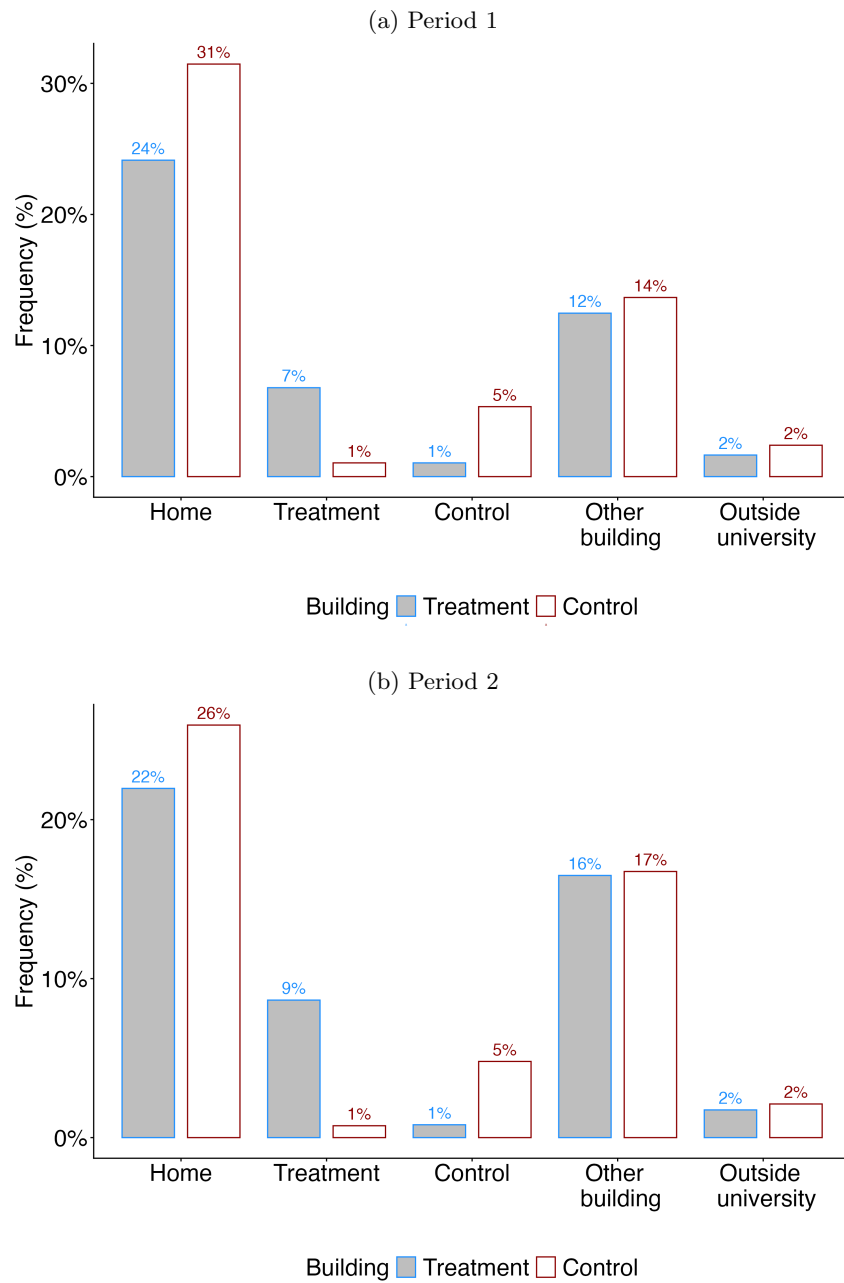
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8 Appendix

8.1 Appendix figures

Figure A1: Self-reported preferred study place



Note: The figure shows students' responses to the question: "Where have you studied most of the time for this course?" The y-axis reports the percentage of students in the full sample who selected the respective location as their primary study place. Bars with blue lines and grey shading represent students assigned to the treatment building, while bars with red lines and no shading represent students assigned to the control building. Results are shown separately for the two study periods.

Figure A2: Treatment and control building

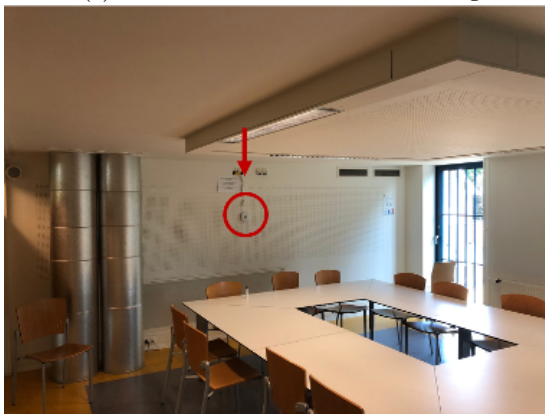
(a) Control building



(b) Treatment building



(c) Classroom in the control building

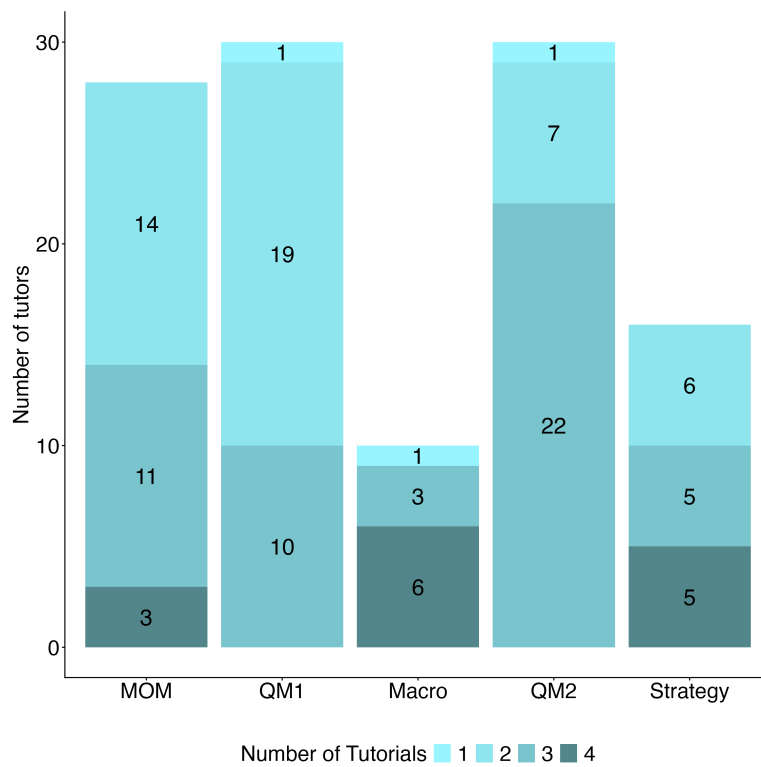


(d) Classroom in the treatment building



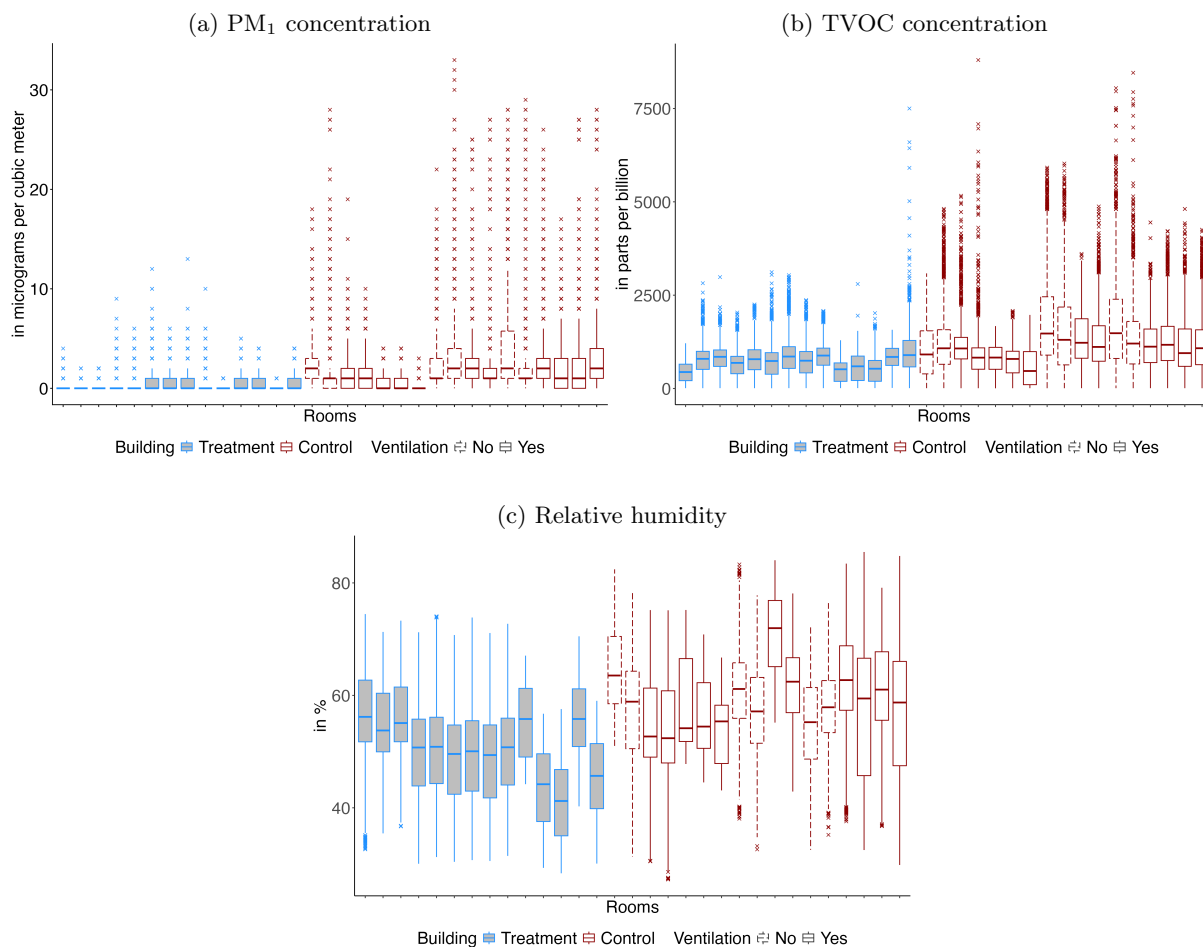
Note: The circle in Figures A2c and A2d indicates the position of the indoor environmental quality monitor which was installed for the purpose of this study.

Figure A3: Number of tutorial groups per tutor per course



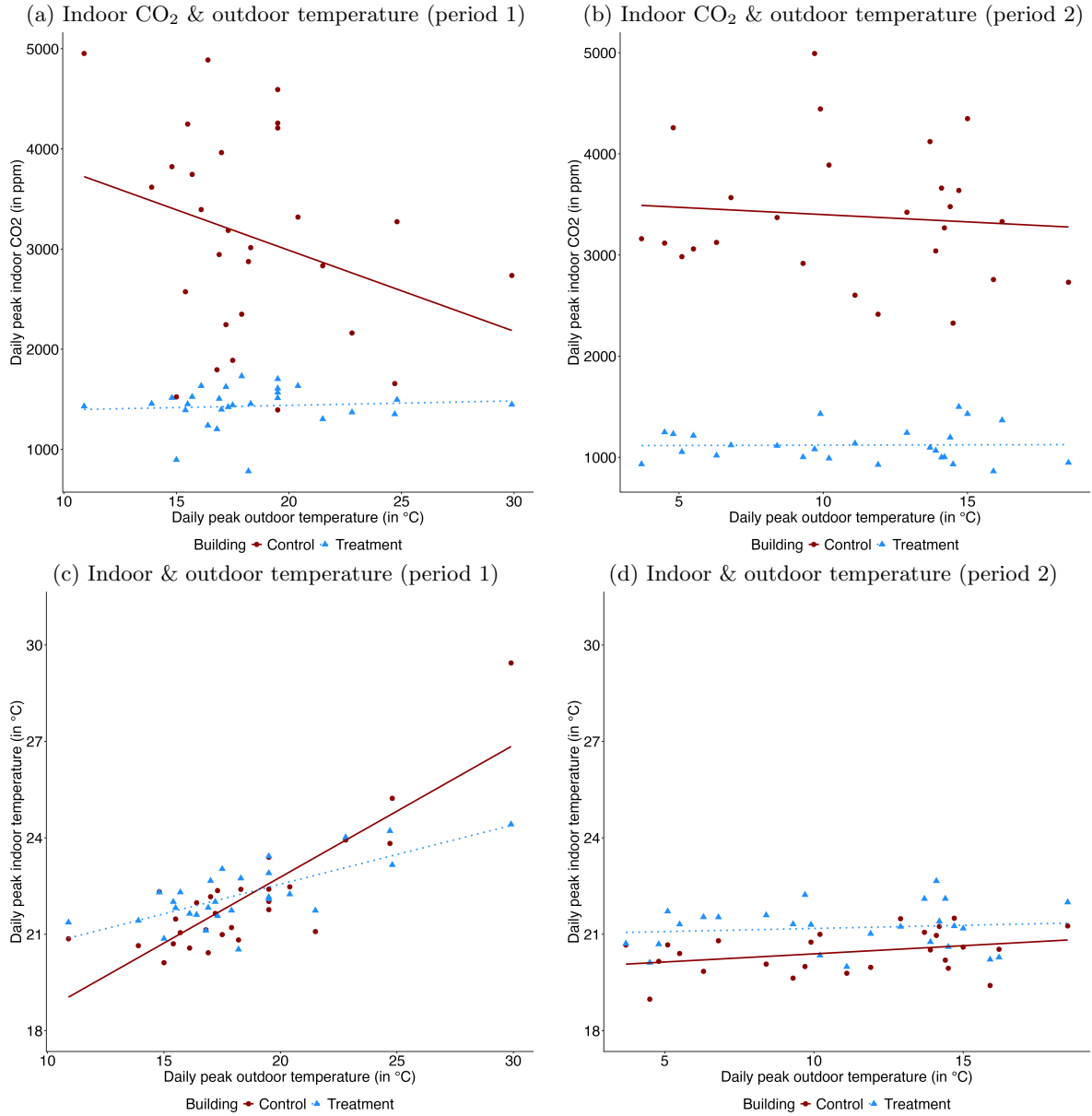
Note: The figure shows the number of tutorial groups per tutor per course. The number shown in each bar indicates the number of tutors with a particular number of tutorial groups. "MOM" - Management of Organisation and Marketing, "QM1" and "QM2" - Quantitative Methods 1 and 2, "Macro" - Macroeconomics.

Figure A4: Indoor environmental quality conditions in buildings - PM, TVOC and humidity



Note: The figure shows the fine particulate matter concentration, PM_1 , the total volatile organic compounds (TVOC) concentration, and relative humidity in the treatment (blue, gray shaded) and control building (red, no shading). 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 (\times). The dashed boxplots indicate classrooms with no mechanical ventilation.

Figure A5: Correlation between indoor environmental conditions and outdoor temperature



Note: The figure shows the linear relationship of outdoor temperature with indoor CO₂ and indoor temperature for both periods. The dots and solid line in red indicate the control building, and the triangles and dotted line in blue indicate the treatment building. The line shows a simple linear regression model fitted to the observations.

8.2 Appendix tables

Table A1: Distribution of tutors between the treatment and control building

	Total # tutors	Number of tutors taught in		
		both treatment and control building	treatment building only	control building only
Courses in period 1				
Management of Organisation & Marketing	28	11 (39%)	8 (29%)	9 (32%)
Quantitative Methods 1	30	14 (47%)	8 (27%)	8 (27%)
Courses in period 2				
Macroeconomics	10	9 (90%)	1 (10%)	0 (0%)
Quantitative Methods 2	30	29 (97%)	0 (0%)	1 (3%)
Strategy	16	15 (94%)	1 (6%)	0 (0%)

Note: The table shows the distribution of tutors across the treatment and control building at the course level. The column "Total # tutors" reports the total number of tutors teaching in each course (compare Figure A3). The last three columns show the number of tutors teaching tutorial groups in both buildings within the same course (column 3), exclusively in the treatment building (column 4), and exclusively in the control building only (column 5). Percentages in parentheses indicate the share of each group relative to the total number of tutors.

Table A2: Validity of the randomization procedure

Panel A: Student allocation within courses				
	Control		Treatment	
	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%	527	50%
Strategy	340	52%	318	48%
Panel B: Balancing test				
	DV: Treatment assignment			
	Period 1	Period 2		
Sex	-0.026 (0.023)	0.012 (0.025)		
Age	0.009 (0.010)	0.011 (0.011)		
Tutorial Time: 11am	-0.022 (0.113)	0.091 (0.115)		
Tutorial Time: 1.30pm	-0.008 (0.113)	0.104 (0.113)		
Tutorial Time: 4pm	0.013 (0.115)	0.031 (0.117)		
Grade in course QM1 of period 1			0.003 (0.006)	
Grade in course MOM of period 1			-0.014 (0.018)	
Course fixed effect	Y	Y	Y	
Observations	1,838	1,541	1,969	
R ²	0.002	0.009	0.003	
Adj. R ²	-0.001	0.004	0.001	

Note: The table provides evidence supporting the validity of the randomization procedure. Panel A reports the allocation of students across the treatment and control buildings at the course level. Panel B presents the results of balancing tests in which the treatment indicator (equal to one if student is assigned to treatment building) is regressed on available observable characteristics, including sex, age, tutorial-group time slots, and course grades in period 1. The regressions include course fixed effects because the randomization of students occurred at the course level. The results provide evidence of covariate balance between the treatment and control groups. Standard errors clustered at the tutorial group level are shown in parentheses. Statistical significance is indicated as *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Table A3: Correlation of indoor environmental quality 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 particulate matter (PM_{2.5}), carbon dioxide (CO₂), total volatile organic compounds (TVOC), indoor temperature and relative humidity. Significance levels are indicated as *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Table A4: Descriptive statistics of satisfaction by building

	Control					Treatment				
	N	Mean	St. Dev.	Min	Max	N	Mean	St. Dev.	Min	Max
Panel A: Satisfaction in period 1										
<i>Satisfaction with indoor environmental quality</i>										
Air Quality	1,050	5.0	1.6	1.0	7.0	902	5.2	1.6	1.0	7.0
Light	1,043	5.5	1.5	1.0	7.0	897	5.4	1.5	1.0	7.0
Noise	1,047	5.0	1.7	1.0	7.0	899	5.3	1.9	1.0	7.0
Temperature	1,049	5.1	1.6	1.0	7.0	902	5.2	1.6	1.0	7.0
<i>Satisfaction with interior design</i>										
Interior affects performance	1,042	4.1	1.4	1.0	7.0	888	4.7	1.5	1.0	7.0
Interior affects mood	1,042	4.1	1.4	1.0	7.0	890	5.0	1.5	1.0	7.0
Like tutorial attendance	1,074	5.7	1.2	1.0	7.0	917	5.7	1.2	1.0	7.0
Room is appealing	1,053	4.6	1.5	1.0	7.0	904	5.8	1.2	1.0	7.0
Difficulties to concentrate	1,056	3.2	1.8	1.0	7.0	897	3.2	1.8	1.0	7.0
Panel B: Satisfaction in period 2										
<i>Satisfaction with indoor environmental quality</i>										
Air Quality	779	5.0	1.6	1.0	7.0	769	5.3	1.6	1.0	7.0
Light	778	5.4	1.5	1.0	7.0	765	5.9	1.4	1.0	7.0
Noise	783	5.0	1.7	1.0	7.0	766	5.4	1.8	1.0	7.0
Temperature	781	5.2	1.5	1.0	7.0	767	5.2	1.6	1.0	7.0
<i>Satisfaction with interior design</i>										
Interior affects performance	763	4.0	1.3	1.0	7.0	769	4.7	1.5	1.0	7.0
Interior affects mood	766	4.0	1.3	1.0	7.0	766	4.9	1.4	1.0	7.0
Like tutorial attendance	813	5.5	1.3	1.0	7.0	797	5.6	1.3	1.0	7.0
Room is appealing	779	4.4	1.5	1.0	7.0	769	5.6	1.3	1.0	7.0
Difficulties to concentrate	764	3.3	1.9	1.0	7.0	759	3.1	1.9	1.0	7.0

Note: The table shows the sample size N, mean, standard deviation St. Dev., minimum and maximum recorded values for the satisfaction parameters for both buildings and periods separately. The sample size is the number of responses for each question, taking into account that students answered these questions multiple times within a period for each course separately. A description of the parameters can be found in Section 3.2.2.

Table A5: Descriptive statistics of grades, tutor evaluation and study hours by building

	Control					Treatment				
	N	Mean	St. Dev.	Min	Max	N	Mean	St. Dev.	Min	Max
Grades in period 1										
Management of Organisation & Marketing	589	7.6	1.1	1.0	10.0	528	7.6	1.1	1.0	10.0
Quantitative Methods 1	604	6.8	2.3	1.0	10.0	530	6.8	2.3	1.5	10.0
Grades in period 2										
Macroeconomics	191	7.0	1.3	5.0	10.0	219	7.0	1.3	5.0	10.0
Quantitative Methods 2	521	5.7	2.6	1.0	10.0	527	5.8	2.6	1.0	10.0
Strategy	340	7.0	1.2	2.0	9.5	318	7.1	1.2	2.5	9.0
Tutor evaluation in period 1										
Management of Organisation & Marketing	543	9.1	1.3	1.0	10.0	477	9.1	1.1	4.0	10.0
Quantitative Methods 1	520	8.7	1.3	2.0	10.0	439	8.3	1.8	2.0	10.0
Tutor evaluation in period 2										
Macroeconomics	153	8.3	1.9	1.0	10.0	153	8.0	2.1	2.0	10.0
Quantitative Methods 2	421	8.6	1.5	2.0	10.0	414	8.7	1.5	1.0	10.0
Strategy	241	8.7	1.5	2.0	10.0	229	8.4	1.6	2.0	10.0
Study hours per week in period 1										
Management of Organisation & Marketing	500	8.9	7.2	1.0	54.0	446	9.3	8.2	0.0	60.0
Quantitative Methods 1	494	18.2	12.1	1.0	60.0	403	18.2	12.0	2.0	60.0
Study hours per week in period 2										
Macroeconomics	129	15.1	10.7	1.0	60.0	138	14.4	8.4	1.0	60.0
Quantitative Methods 2	375	14.3	9.9	1.0	60.0	379	14.6	10.1	2.0	60.0
Strategy	211	9.4	6.9	1.0	50.0	216	8.6	6.0	1.0	50.0

Note: The table shows the sample size N, mean, standard deviation St. Dev., minimum and maximum recorded values for course grades, teacher evaluation and weekly study hours for both buildings and periods separately.

Table A6: Association of survey response rate with treatment and outcome variables

	Treatment	Course grade	Tutor grade	Study hours	
Effect coefficient	-0.016 (0.014)	-0.001 (0.002)	0.002 (0.003)	-0.006* (0.003)	
Observations	3,663	4,367	3,590	3,291	
R ²	0.469	0.545	0.469	0.469	
Adj. R ²	0.455	0.536	0.455	0.454	
Satisfaction with indoor environmental quality					
	Air Quality	Light	Noise	Temperature	
Effect coefficient	0.001 (0.002)	-0.000 (0.002)	0.001 (0.002)	0.000 (0.002)	
Observations	3500	3483	3495	3499	
R ²	0.463	0.463	0.465	0.462	
Adj. R ²	0.449	0.448	0.450	0.448	
Satisfaction with interior design					
	Interior affect performance	Interior affect mood	Liking tutorial attendance	Room appealing	Difficulty to concentrate
Effect coefficient	0.001 (0.002)	-0.001 (0.002)	-0.000 (0.002)	-0.001 (0.003)	0.000 (0.002)
Observations	3,462	3,464	3,601	3,505	3,476
R ²	0.466	0.466	0.469	0.467	0.463
Adj. R ²	0.452	0.452	0.456	0.453	0.448
Fixed Effects					
Schedule	Y	Y	Y	Y	Y
Course	Y	Y	Y	Y	Y
Tutor	Y	Y	Y	Y	Y

Note: The dependent variable is the survey response rate per tutorial group. The independent variables are the standardized z-scores for the variables on course grade, tutor evaluation, study hours, and the satisfaction outcomes. 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: Absolute and relative treatment effects - Satisfaction with indoor environmental quality, learning experience and tutorial environment

	Sample size (N)	Mean (μ)	St. Dev. (σ_{pooled})	Effect size (δ)	Absolute effect ($\delta \cdot \sigma_{pooled}$)	%-Change ($\frac{\delta \cdot \sigma_{pooled}}{\mu}$)	p-value
Indoor environmental quality satisfaction in period 1							
Air Quality	1,952	5.12	1.59	0.06	0.09	1.76 %	0.306
Light	1,940	5.68	1.52	0.27	0.41	7.22 %	2.82×10^{-6}
Noise	1,946	5.12	1.83	0.28	0.51	9.97 %	6.09×10^{-6}
Temperature	1,951	5.13	1.60	0.01	0.01	0.20 %	0.92
Indoor environmental quality satisfaction in period 2							
Air Quality	1,548	5.12	1.63	0.19	0.31	6.05 %	1.94×10^{-4}
Light	1,543	5.63	1.51	0.33	0.49	8.70 %	4×10^{-11}
Noise	1,549	5.18	1.73	0.25	0.43	8.30 %	5.65×10^{-7}
Temperature	1,548	5.21	1.55	0.01	0.02	0.38 %	0.785
Perception of learning experience and tutorial environment in period 1							
Interior affects performance	1,930	4.38	1.49	0.35	0.53	12.10 %	3.87×10^{-12}
Interior affects mood	1,932	4.49	1.47	0.48	0.70	15.60 %	2×10^{-16}
Like tutorial attendance	1,991	5.72	1.15	0.06	0.07	1.22 %	0.392
Room is appealing	1,957	5.13	1.52	0.79	1.20	23.40 %	2×10^{-16}
Difficulties to concentrate	1,953	3.20	1.80	0.04	0.07	2.19 %	0.528
Perception of learning experience and tutorial environment in period 2							
Interior affects performance	1,532	4.32	1.42	0.43	0.61	14.10 %	2×10^{-16}
Interior affects mood	1,532	4.43	1.42	0.57	0.82	18.50 %	2×10^{-16}
Like tutorial attendance	1,610	5.53	1.27	-0.002	0.00	0.00 %	0.965
Room is appealing	1,548	5.01	1.56	0.81	1.26	25.20 %	2×10^{-16}
Difficulties to concentrate	1,523	3.21	1.89	-0.12	-0.23	-7.16 %	0.0133

Note: The table shows the sample size, as well as the mean μ and standard deviation σ_{pooled} (St. Dev.) for each outcome variable as observed in the sample. The effect δ is based on the regression analysis (Equation 1) and is shown in Figure 3. The absolute effect takes into account that the outcome variables were standardized on course level. The calculation formula is: $\sigma_{pooled} = \sqrt{\frac{\sum_c (n_c - 1) \sigma_c^2}{\sum_c (n_c - 1)}}$. The percentage change is expressed as change in outcome variables relative to the mean within the corresponding sample. The significance levels are derived from the regression model.

Table A8: Absolute and relative treatment effects - Course grades, tutor evaluations, and study hours

	Sample size (N)	Mean (μ_c)	St. Dev. (σ_c)	Effect size (δ)	Absolute effect ($\delta \cdot \sigma_c$)	%-Change ($\frac{\delta \cdot \sigma_c}{\mu_c}$)	p-value
Grades in period 1							
Management of Organisation & Marketing	1,117	7.56	1.06	-0.05	-0.05	-0.69 %	0.535
Quantitative Methods 1	1,134	6.76	2.31	-0.05	-0.11	-1.67 %	0.535
Total effect (with pooled St. Dev.)	2,251	7.16	1.80	-0.05	-0.09	-1.24 %	0.535
Grades in period 2							
Macroeconomics	410	6.99	1.27	0.02	0.02	0.33 %	0.645
Quantitative Methods 2	1,048	5.73	2.58	0.02	0.05	0.81 %	0.645
Strategy	658	7.04	1.18	0.02	0.02	0.34 %	0.645
Total effect (with pooled St. Dev.)	2,116	6.38	2.01	0.02	0.04	0.57 %	0.645
Tutor evaluation in period 1							
Management of Organisation & Marketing	1,020	9.09	1.19	0.03	0.04	0.39 %	0.797
Quantitative Methods 1	959	8.49	1.55	0.03	0.05	0.55 %	0.797
Total effect (with pooled St. Dev.)	1,979	8.80	1.38	0.03	0.04	0.45 %	0.797
Tutor evaluation in period 2							
Macroeconomics	306	8.14	1.99	0.02	0.04	0.49 %	0.746
Quantitative Methods 2	835	8.65	1.51	0.02	0.03	0.35 %	0.746
Strategy	470	8.51	1.54	0.02	0.03	0.36 %	0.746
Total effect (with pooled St. Dev.)	1,611	8.51	1.62	0.02	0.03	0.30 %	0.746
Study hours per week in period 1							
Management of Organisation & Marketing	946	9.04	7.64	0.04	0.31	3.38 %	0.636
Quantitative Methods 1	897	18.20	12.03	0.04	0.48	2.64 %	0.636
Total effect (with pooled St. Dev.)	1,843	13.50	10.02	0.04	0.37	2.75 %	0.636
Study hours per week in period 2							
Macroeconomics	267	14.75	9.58	-0.04	-0.38	-2.60 %	0.453
Quantitative Methods 2	754	14.46	9.98	-0.04	-0.40	-2.76 %	0.453
Strategy	427	9.00	6.44	-0.04	-0.26	-2.86 %	0.453
Total effect (with pooled St. Dev.)	1,448	12.90	9.00	-0.04	-0.34	-2.65 %	0.453

Note: The table shows the sample size, as well as the mean μ and standard deviation σ_{pooled} (St. Dev.) for each outcome variable as observed in the sample. The effect δ is based on the regression analysis (Equation 1) and is shown in Figure 3. The absolute effect takes into account that the outcome variables were standardized on course level. The calculation formula is: $\sigma_{pooled} = \sqrt{\frac{\sum_c (n_c - 1) \sigma_c^2}{\sum_c (n_c - 1)}}$. The percentage change is expressed as change in outcome variables relative to the mean within the corresponding sample. The significance levels are derived from the regression model.

Table A9: Treatment effects conditional on IAQ and temperature - Satisfaction with indoor environmental quality

	Period 1			Period 2		
	(1)	(2)	(3)	(4)	(5)	(6)
Air quality						
Treatment	0.058 (0.057)	0.036 (0.092)	0.062 (0.091)	0.189*** (0.051)	0.126 (0.088)	0.100 (0.154)
Observations	1,952	1,952	1,952	1,548	1,548	1,548
R ²	0.042	0.043	0.043	0.070	0.072	0.072
Adj. R ²	0.011	0.011	0.011	0.033	0.034	0.033
Light						
Treatment	0.270*** (0.057)	0.302*** (0.084)	0.272** (0.085)	0.325*** (0.049)	0.364*** (0.095)	0.218 (0.141)
Observations	1,940	1,940	1,940	1,543	1,543	1,543
R ²	0.045	0.045	0.046	0.077	0.078	0.079
Adj. R ²	0.014	0.013	0.013	0.041	0.040	0.041
Noise						
Treatment	0.279*** (0.062)	0.240* (0.102)	0.197* (0.100)	0.249*** (0.050)	0.165 (0.090)	0.043 (0.145)
Observations	1,946	1,946	1,946	1,549	1,549	1,549
R ²	0.038	0.040	0.042	0.067	0.068	0.069
Adj. R ²	0.007	0.008	0.009	0.030	0.030	0.030
Temperature						
Treatment	0.006 (0.063)	0.056 (0.112)	0.113 (0.106)	0.014 (0.050)	-0.034 (0.094)	-0.035 (0.157)
Observations	1,951	1,951	1,951	1,548	1,548	1,548
R ²	0.052	0.053	0.055	0.063	0.064	0.064
Adj. R ²	0.022	0.021	0.023	0.026	0.026	0.025
Fixed effects						
Schedule	Y	Y	Y	Y	Y	Y
Course	Y	Y	Y	Y	Y	Y
Tutor	Y	Y	Y	Y	Y	Y
Controlled for						
Indoor air quality	N	Y	Y	N	Y	Y
Temperature	N	N	Y	N	N	Y

Note: The table presents the estimated treatment effects (δ in Equation 1) across all outcome variables separately for Period 1 and Period 2. The dependent variables are standardized on course level and expressed as z-score. Column (1) and (4) report the main results using the baseline specification (see Figure 3). Results shown in column (2) and (5) are estimated based on the baseline specification and additionally controlling for indoor air quality (CO₂ and PM_{2.5}). Column (3) and (6) report results based on the baseline specification and additionally controlling for indoor air quality (CO₂ and PM_{2.5}) and indoor temperature. 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 A10: Treatment effects conditional on IAQ and temperature - Perception of the learning experience and tutorial environment

	Period 1			Period 2		
	(1)	(2)	(3)	(4)	(5)	(6)
Interior affects performance						
Treatment	0.353*** (0.051)	0.314*** (0.064)	0.344*** (0.068)	0.432*** (0.045)	0.442*** (0.072)	0.598*** (0.129)
Observations	1,930	1,930	1,930	1,532	1,532	1,532
R ²	0.073	0.074	0.075	0.098	0.100	0.101
Adj. R ²	0.043	0.043	0.043	0.062	0.063	0.063
Interior affects mood						
Treatment	0.479*** (0.057)	0.527*** (0.076)	0.546*** (0.079)	0.573*** (0.041)	0.598*** (0.070)	0.691*** (0.111)
Observations	1,932	1,932	1,932	1,532	1,532	1,532
R ²	0.110	0.112	0.112	0.117	0.119	0.120
Adj. R ²	0.081	0.082	0.081	0.082	0.083	0.083
Like tutorial attendance						
Treatment	0.062 (0.072)	0.245** (0.088)	0.284** (0.095)	-0.002 (0.050)	-0.013 (0.084)	-0.063 (0.148)
Observations	1,991	1,991	1,991	1,610	1,610	1,610
R ²	0.090	0.093	0.094	0.121	0.123	0.123
Adj. R ²	0.061	0.063	0.064	0.087	0.088	0.088
Room is appealing						
Treatment	0.792*** (0.056)	0.805*** (0.084)	0.829*** (0.088)	0.812*** (0.045)	0.699*** (0.072)	0.671*** (0.121)
Observations	1,957	1,957	1,957	1,548	1,548	1,548
R ²	0.197	0.198	0.198	0.197	0.199	0.199
Adj. R ²	0.171	0.171	0.171	0.165	0.166	0.166
Difficulties to concentrate						
Treatment	0.040 (0.064)	0.079 (0.084)	0.079 (0.088)	-0.121* (0.049)	-0.199** (0.076)	-0.131 (0.140)
Observations	1,953	1,953	1,953	1,523	1,523	1,523
R ²	0.031	0.031	0.031	0.056	0.059	0.059
Adj. R ²	-0.000	-0.001	-0.002	0.018	0.020	0.019
Fixed effects						
Schedule	Y	Y	Y	Y	Y	Y
Course	Y	Y	Y	Y	Y	Y
Tutor	Y	Y	Y	Y	Y	Y
Controlled for						
Indoor air quality	N	Y	Y	N	Y	Y
Temperature	N	N	Y	N	N	Y

Note: The table presents the estimated treatment effects (δ in Equation 1) across all outcome variables separately for Period 1 and Period 2. The dependent variables are standardized on course level and expressed as z-score. Column (1) and (4) report the main results using the baseline specification (see Figure 3). Results shown in column (2) and (5) are estimated based on the baseline specification and additionally controlling for indoor air quality (CO₂ and PM_{2.5}). Column (3) and (6) report results based on the baseline specification and additionally controlling for indoor air quality (CO₂ and PM_{2.5}) and indoor temperature. 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 A11: Treatment effects conditional on IAQ and temperature - Course grades, tutor evaluation, and study hours

	Period 1			Period 2		
	(1)	(2)	(3)	(4)	(5)	(6)
Course grades						
Treatment	-0.049 (0.080)	0.027 (0.119)	0.043 (0.120)	0.018 (0.039)	0.004 (0.059)	-0.232* (0.096)
Observations	2, 251	2, 251	2, 251	2, 116	2, 116	2, 116
R ²	0.054	0.057	0.057	0.057	0.057	0.060
Adj. R ²	0.028	0.030	0.030	0.030	0.029	0.031
Tutor evaluation						
Treatment	0.029 (0.112)	0.326 (0.209)	0.294 (0.210)	0.016 (0.050)	0.117 (0.088)	-0.039 (0.127)
Observations	1, 979	1, 979	1, 979	1, 611	1, 611	1, 611
R ²	0.156	0.171	0.172	0.244	0.248	0.249
Adj. R ²	0.129	0.144	0.144	0.215	0.219	0.219
Study hours						
Treatment	0.037 (0.078)	0.268* (0.126)	0.283* (0.128)	-0.038 (0.050)	0.045 (0.084)	0.097 (0.139)
Observations	1843	1843	1843	1448	1448	1448
R ²	0.050	0.056	0.056	0.039	0.045	0.045
Adj. R ²	0.017	0.022	0.022	-0.002	0.003	0.002
Fixed effects						
Schedule	Y	Y	Y	Y	Y	Y
Course	Y	Y	Y	Y	Y	Y
Tutor	Y	Y	Y	Y	Y	Y
Controlled for						
Indoor air quality	N	Y	Y	N	Y	Y
Temperature	N	N	Y	N	N	Y

Note: The table presents the estimated treatment effects (δ in Equation 1) across all outcome variables separately for Period 1 and Period 2. The dependent variables are standardized on course level and expressed as z-score. Column (1) and (4) report the main results using the baseline specification (see Figure 3). Results shown in column (2) and (5) are estimated based on the baseline specification and additionally controlling for indoor air quality (CO₂ and PM_{2.5}). Column (3) and (6) report results based on the baseline specification and additionally controlling for indoor air quality (CO₂ and PM_{2.5}) and indoor temperature. Clustered standard errors at tutorial group level are shown in parentheses and significance levels are indicated as *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.