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Positive effects of indoor environmental conditions on students and their performance in higher education classrooms: A between-groups experiment

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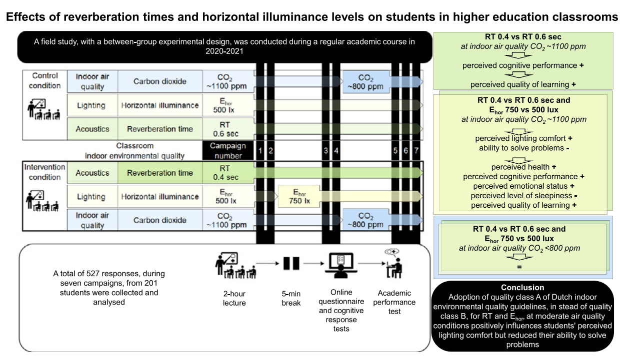
HIGHLIGHTS

- Between groups-experiment was conducted during a regular academic course.
- Effects of different illuminance levels and reverberation times were examined.
- The effects on both students' objective and subjective responses were measured.
- Acoustic and lighting conditions can positively influence students' perceptions.
- Lighting conditions can affect students' ability to solve problems.

GRAPHICAL ABSTRACT



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ABSTRACT

This study explores if multiple alterations of the classrooms' indoor environmental conditions, which lead to environmental conditions meeting quality class A of Dutch guidelines, result in a positive effect on students' perceptions and performance. A field study, with a between-group experimental design, was conducted during the academic course in 2020–2021. First, the reverberation time (RT) was lowered in the intervention condition to 0.4 s (control condition 0.6 s). Next, the horizontal illuminance (HI) level was raised in the intervention condition to 750 lx (control condition 500 lx). Finally, the indoor air quality (IAQ) in both conditions was improved by increasing the ventilation rate, resulting in a reduction of carbon dioxide concentrations, as a proxy for IAQ, from ~1100 to <800 ppm. During seven campaigns, students' perceptions of indoor environmental quality, health, emotional status, cognitive performance, and quality of learning were measured at the end of each lecture using questionnaires. Furthermore, students' objective cognitive responses were measured with psychometric tests of neurobehavioural functions. Students' short-term academic performance was evaluated with a content-related test.

From 201 students, 527 responses were collected. The results showed that the reduction of the RT positively influenced students' perceived cognitive performance. A reduced RT in combination with raised HI improved students' perceptions of the lighting environment, internal responses, and quality of learning. However, this experimental condition negatively influenced students' ability to solve problems, while students' content-related test scores were not influenced. This shows that although quality class A conditions for RT and HI improved students' perceptions, it did not influence their short-term academic performance.

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Furthermore, the benefits of reduced RT in combination with raised HI were not observed in improved IAQ conditions. Whether the sequential order of the experimental conditions is relevant in inducing these effects and/or whether improving two parameters is already beneficial, is unknown.

1. Introduction

This study explores the effect of the physical environment on students and their academic performance in higher education, either college or university (Wæraas and Solbakk, 2009). The physical environment of classrooms consists of a variety of aspects, such as the quality of the school building, the volume of the classroom, the cleanliness of the classroom, and the indoor environment (Wang and Degol, 2016). This study focuses on the indoor environmental quality (IEQ), which is defined as a system of four parameters: (1) indoor air quality, (2) thermal conditions, (3) acoustic conditions, and (4) lighting conditions (Frontczak and Wargocki, 2011), and by doing so, covers stimuli that can be perceived by human senses, i.e., vision, hearing, smell, and thermal sensation.

From a cognitive load theory perspective, the indoor environment of classrooms is typically treated as a control variable that is best kept constant (Choi et al., 2014). However, there is increasing support to treat this environment as an independent variable capable of directly influencing cognitive performance of humans (Choi et al., 2014). Furthermore, the indoor environment interacts with both learner characteristics and learning-task characteristics (Choi et al., 2014), indicating that optimal environmental conditions in classrooms are task-dependent (Brink et al., 2021). The acceptance of the indoor environment as being an independent variable that can positively influence learner experiences leads to the assumption that this environment can be designed in such a way that it may improve the quality of in-class activities and student learning, which in turn may have a positive effect on students' academic performance (Choi et al., 2014). An optimal indoor environment contributes to a better school climate (Wang and Degol, 2016) which in return fosters students' development and learning (Cohen et al., 2009).

To a certain extent, earlier research revealed the effect of single IEQ parameters on students' academic performance (Afren et al., 2017; Castro-Martínez et al., 2016; Chin and Saju, 2017; Hoque and Weil, 2016; Rouag-Saffidine and Benharkat, 2006). Furthermore, in the last decade the combined influence of IEQ parameters on students has been studied more often. However, studies that examine the influence of three or more IEQ parameters on students are rare (Brink et al., 2021). One of the reasons why it is important to assess multiple indoor environmental conditions simultaneously is that IEQ parameters interact with each other, as observed by Kim and de Dear (2012). For example, an empirical study by Jaber et al. (2017) addressing neurobehavioural tasks revealed that decreasing temperature from 25 °C and 23 °C to 20 °C, while decreasing carbon dioxide (CO_2) levels from 1800 ppm and/or 1000 ppm to 600 ppm, significantly improved female students' performance in an attention task. Xiong et al. (2018) performed an experiment and found that students' highest efficiency in a perception-oriented task came in thermoneutral (22 °C), relatively quiet (background noise 50 dB(A)), and bright conditions (horizontal illuminance 2200 lx); and students' ability to solve problems was the highest in a thermoneutral (22 °C), fairly quiet (background noise 40 dB(A)), and moderately light environment (horizontal illuminance 300 lx). These results lead us to expect that the effect of multiple improved IEQ parameters on students' cognitive performance may differ from the combined contribution of single improved IEQ parameters. Furthermore, a certain hierarchy between IEQ parameters, as observed by Kim and de Dear (2012) in an office environment, has not been identified in an academic context yet.

To gain more knowledge about the effect of simultaneously improving multiple IEQ parameters on students and their academic performance in higher education, this study specifically focuses on the effect of three factors: acoustics, lighting, and indoor air quality. Dutch guidelines list three quality classes (A, B and C) addressing the four major IEQ parameters (RVO, 2015). When building or renovating schools, school management must choose between quality class A or B. Quality class A is labelled as "excellent" and quality class B is labelled as "good". These guidelines have been formulated on the basis of consensus between the parties concerned.

To support this decision-making process, this study compares quality class A and B requirements for reverberation time (0.4 vs 0.6 s), horizontal illuminance level at the lecturer's desk (750 vs 500 lx), and indoor air quality (CO_2 < 800 vs >800 and <950 ppm) to determine the benefits for students in higher education when quality class A or B requirements are adopted (RVO, 2015). Reducing the reverberation time, as a control measure to improve classroom acoustics and as a consequence of adopting quality class A instead of B, can improve the speech intelligibility in these spaces (Castro-Martínez et al., 2016). Furthermore, adopting quality class A instead of B for the horizontal illuminance level, may improve students' perceptions of general lighting comfort and specifically the clarity of classrooms (Durak et al., 2007). Bright conditions can also positively influence students' perceived comfort, emotion, and cognitive performance; however, differences among humans must be taken into account (Maierova et al., 2016). And finally, it is likely that better indoor air quality, as prescribed in quality class A compared to B, may, improve students' perceived indoor air quality, reduce perceived physical health complaints, and improve perceived tiredness (Norbäck et al., 2013).

This study examined the following hypothesis: indoor environmental conditions, meeting quality class A of the Dutch guidelines, have a positive effect on students' perceptions, responses, and performance. To reveal the benefits of quality class A (experimental condition), compared to class B (control condition), this study was conducted in a naturally occurring setting of actual lectures during a regular academic course in a controlled thermal environment. Although the simultaneous testing of improved IEQ conditions does not imply any particular order in which IEQ parameters should be improved first or last; this study, first, examined the effect of acoustic conditions. Next, the simultaneous effect of acoustic and lighting conditions was examined. Finally, this study examined the effect of acoustic and lighting conditions at high indoor air quality conditions.

2. Method

2.1. Practical setting

The experiment was performed from September 2020 till January 2021. In this study, 201 first-year students of the Hanze University of Applied Sciences (UAS) School of Future Environments, participated in seven campaigns, while following their regular academic classes during two consecutive academic periods of seven weeks. These first-year students were selected for the study, because they were lay persons and not yet versed in building physics. Due to COVID-19 restrictions, students had to maintain a 1.5-meter distance in the classroom but were not mandated to wear face masks in the classroom.

The study was performed in two identical classrooms of Hanze UAS, the Netherlands during two academic courses of seven weeks. The classrooms were identical in size, height, orientation, and daylight entry (window north-north-west). Fig. 1 shows two pictures of the interior of classroom A, hereafter referred to as the intervention condition and classroom B, hereafter referred to as the control condition.

During the first academic period, the classrooms were equipped with a full recirculation system to maintain a set air temperature of 21 °C. Outdoor air could enter the classrooms though vents, which were located above the double glazing. At the start of the experiment, the reverberation time was adjusted in the classrooms, with the use of Ecophon Master sealing and

Intervention condition　　Control condition

Fig. 1. Visual appearance of the intervention and control condition classrooms interior. The top photos show the classrooms from the lecturer's perspective, the bottom photos show the students' perspective.

wall panels to meet quality class A or B specifications (RVO, 2015). Table 1 presents the reverberation time of both conditions at different frequencies.

The intervention condition was fitted with twelve and the control condition with six ETAP U3352 lighting armatures with a colour temperature of 3000 K and a colour rendering index of 80. Both lighting systems were equipped with a dimmer and the illuminance was adjusted to meet the specified value before the start of every lecture. Lecturers were instructed not to adjust the illuminance level during the lecture. Before the start of the second academic period, the two classrooms were equipped with a heating, ventilation, and air conditioning (HVAC) system. This system consisted of a combined air handling unit, including fixed plate heat exchangers and F7 filters, with a capacity of 3500 m^3/h for both classrooms, which results in a maximum ventilation rate of 14.5 air changes per hour and, at a maximum capacity of 30 persons per classroom, in a ventilation rate of 16 l/s per person. Outside the classrooms, an air-cooled heat pump of 15 kW (for the control condition) and an air-cooled heat pump of 25 kW (for the intervention condition) were installed. The classrooms were equipped with a VLK-60 W multi-sensor, which was placed in the middle of both classrooms at a height of 1.1 m to measure air temperature, CO_2 concentration, relative humidity, particle matter (PM) 2.5, and total volatile organic compounds (TVOC). Fig. 2 shows the classrooms' layout, including the location and technical details of the HVAC system and the position of the multi-sensor.

Table 1
Reverberation times at different frequencies in the intervention and control conditions.

Condition	Quality class	Reverberation time (sec)				
		250 Hz	500 Hz	1000 Hz	2000 Hz	250–2k Hz
Intervention condition	A	0.35	0.53	0.38	0.39	0.4
Control condition	B	0.59	0.6	0.54	0.61	0.6

2.2. Data collection of the actual indoor environmental quality

Before the start of the experiment, the readings of air temperature (t_a), carbon dioxide (CO_2), and indoor relative humidity (RH_i) were compared with the reading of an ATAL ATU-CT sensor, which was calibrated by the manufacturer (calibration nr. 2020273092 006). Based on these readings, the readings of the multi-sensor were adjusted. In addition, readings with ATAL ATU-CT sensors were collected at different places, i.e., at the back and at the front of both classrooms. These readings were also compared with the readings of the VLK-60 multi- sensor. To determine if measured t_a differed from the mean radiant temperature (t_r) and the black globe temperature (t_g), the t_r and the t_g were measured with a Delta Ohm HD32.3TCA Thermal Microclimate sensor. During the experimental period, the VLK-60 sent all readings to an online platform (www.onlinesensor.nl) every 5 min. Next, this data was exported to EXCEL to determine IEQ conditions which represent the observed value at the time when students answered the questionnaire and performed the tests. Furthermore, the horizontal illuminance level of each student desk was collected with the use of a VOLTCRAFT MS-1300 illuminance measurement device before the start of each lecture. Next, the students had to fill in their desk number when completing the online questionnaire and various tests. The measured horizontal illuminance level on the table was linked to the table number of the student. The desk number was used to determine the row in which the student sat during the lecture. This row number was used for further analysis. Appendix A presents details about the used measuring equipment.

2.3. Data collection of students' perceptions, responses, and short-term academic performance

A previously developed method was used to examine students' perceptions, responses, and short-term academic performance (Brink et al., 2022). To determine the effect of reverberation time on students' perceived acoustic comfort, the related item score to the speech intelligibility was used (Castro-Martínez et al., 2016). Furthermore, to determine the perception of the horizontal illuminance level, the combined scores of five

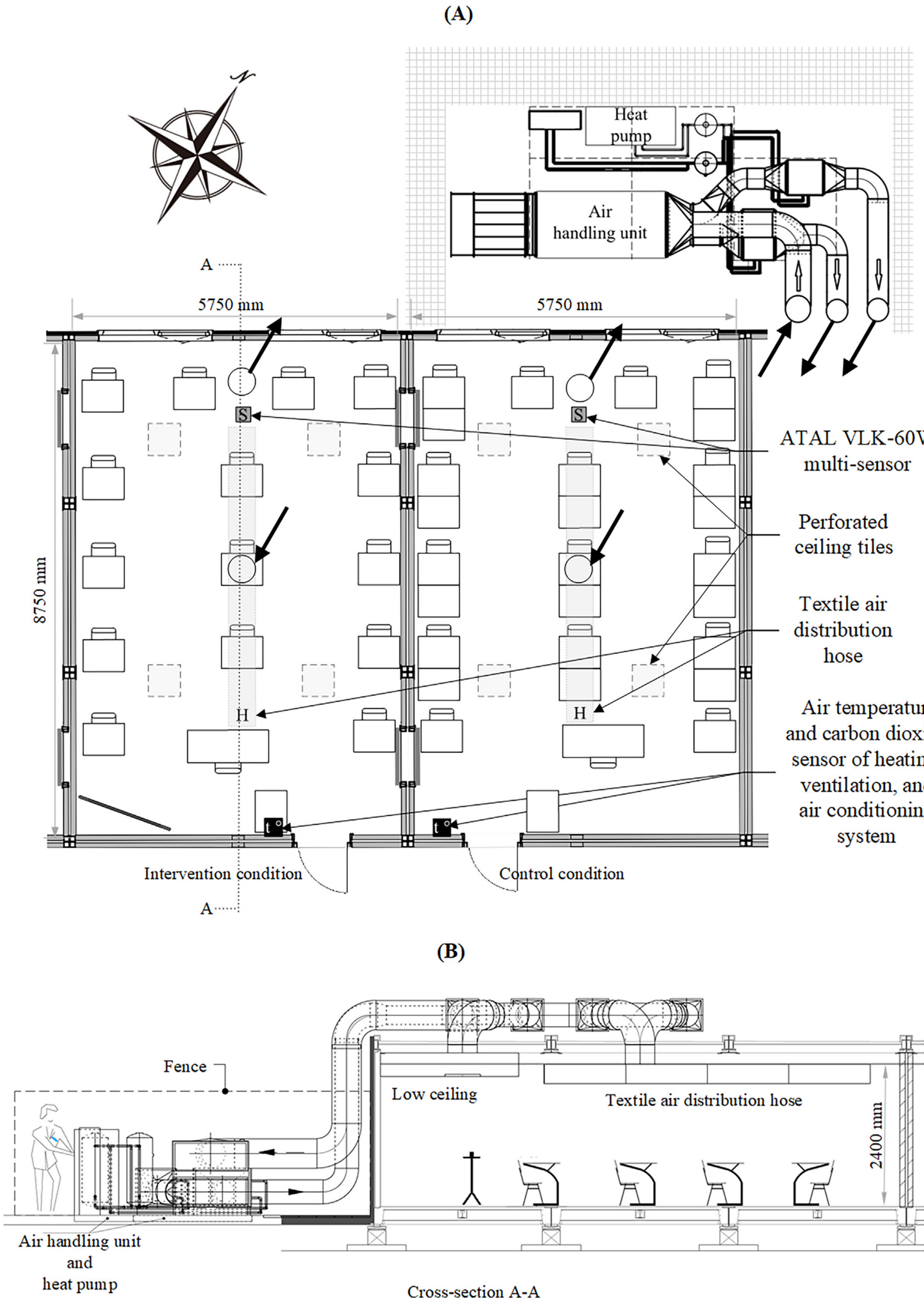

Fig. 2. (A) Layout of the intervention and control conditions, including the orientation and technical details of the HVAC system and (B) cross-section of the intervention condition.

statements covering the topics amount of light, reflections, and glare were used (Castilla et al., 2017, 2018; Gentile et al., 2018; Yang et al., 2013). To determine the effect of the actual indoor air quality conditions on students' perception, the combined scores on eight items which covered the topics air quality, ventilation, odour intensity and character, and moisture were used (Castilla et al., 2017; Corgnati et al., 2007; Mongkolsawat et al., 2014;

Ramprasad and Subbaiyan, 2017; Valavanidis and Vatista, 2006; Yang et al., 2013). Students thermal comfort, as a control variable, was measured with the use of three questions which addressed their thermal acceptance, sensation and preference (Almeida et al., 2016; Corgnati et al., 2007; de Abreu-Harbich et al., 2018; Mishra et al., 2017; Mongkolsawat et al., 2014; Ramprasad and Subbaiyan, 2017). Students' perceived health and self-reported physical health complaints were collected with an answering schedule (Ashrafi and Naeini, 2016; Bidassey-Manilal et al., 2016; Chowdhury et al., 2010; Jaakkola, 2006; Norbäck et al., 2013). To determine if a reported health symptom is building-related, a question was added to reveal if the reported symptom (or symptoms) disappeared after leaving the building. Reported symptoms which disappeared after leaving the building were considered an indicator for perceived physical health complaints. Appendix B presents more details about the questions, statements, and composed scales.

Students' objective cognitive responses were measured with the use of cognitive performance tests. To measure the four main cognitive response categories: attention and concentration, memory, perception, and problem solving (Xiong et al., 2018), four different tests were included. These tests are: (1) the Go-No Go task (Drewe, 1975), the Corsi block task (Corsi, 1972), (3) the Stroop colour-word task (Stroop, 1935), and (4) the Wisconsin Card Sorting test (Ozonoff, 1995) respectively (see Table 2). Appendix C presents more details about these tests and the calculation of the test scores.

Students' perceived cognitive performance was measured with questions addressing the four cognitive response categories (Jonsdottir, 2006; Mongkolsawat et al., 2014; Xiong et al., 2018). Students' emotional responses were measured by the use of the positive and negative affect scales (Gentile et al., 2018; Watson et al., 1988), the basic emotional process scale (Gentile et al., 2018; Kuller, 1991) and the Karolinska Sleepiness Scale (Åkerstedt and Gillberg, 1990; Choi et al., 2019). Appendix D provides detailed information about these applied methods.

The following moderators were identified and accounted for: age, gender, the distance of students to the lecturer expressed in row number, the number of students present in the classroom, the estimated number of hours of sleep before participation, and room temperature at home (Corgnati et al., 2007; Jaber, 2017; Gentile et al., 2018; Madbouly et al., 2016).

To measure the perceived quality of learning, students had to respond to three statements which address students' perceived productivity and ability to read and write (Lee et al., 2012). To measure students' short-term academic performance, a content-related test was composed in collaboration with the involved lecturers (McDonald et al., 2004; Shelton et al., 2009). Before making the content-related test, students had to fill in the questionnaire which evaluated their perceptions regarding the IEQ, internal responses, and quality of learning. By using this order, the time span between the lecture and the content-related test was increased and the students were forced to focus their thoughts on other aspects than those covered during the lecture (McDonald et al., 2004). The content-related test consisted of eight to ten multiple-choice questions relating to the topics covered during the lecture of that week. Each week new topics were discussed and tested, no topics from previous weeks were evaluated. Therefore, the assumption was made that the learning outcomes of each lecture were not affected by the learning outcomes from previous lectures. The academic performance test score equals the percentage of questions answered correctly, and reflects students' short-term academic performance.

The identified statements from the literature that were used to measure students' perceptions and internal responses, consisted of both positively and negatively formulated statements. Following Salazar (2015), the negatively formulated statements were reformulated into their positive counterparts, because a combination of positively and negatively formulated items can seriously affect the internal consistency of the perception scales. For all statements, a seven-point Likert scale, from one (strongly disagree) to seven (strongly agree) was applied. Consequently, the mean perception scores should be interpreted as from 1-very poor to 7-very good. An exception is the mean perceived thermal comfort score: this score should be interpreted as from 1-very uncomfortable to 4-comfortable (see Appendix B for information about composition of this scale). Furthermore, the mean score on students' perceived health should be interpreted as from 1-very bad to 5-very good.

As a final step to enable the application of the questionnaire and tests, all questions and statements were translated into Dutch by the authors. These questions and statements were then translated back into English by a professional translator. This translation was compared to the original English approach, differences were discussed with the translator and, if necessary, the Dutch translation of the question or statement was adjusted.

2.4. Data collection procedure

The final study design was approved by the Hanze UAS' Ethical Committee (No. 2019.026). Prior to their participation, the students were provided with a general outline of the study and its objective, which was to assess the quality of the classroom. All students who participated in this study signed an informed consent form. The students could end their participation in the study without any consequences and at any time. However, none of the students made a request to do so or to have their data removed. During the two academic courses, the lectures were the same and equally distributed among involved lecturers and between the intervention and control condition. The type of lecture was a tutorial, in which the lecturer gave a presentation about basic management principles. Students did not carry out assignments nor did they participate in group discussions. Intervention and control conditions were measured in similar time frames; the difference between the starting time of the lectures in both conditions was not more than 1 h per lecturer. For example, an involved lecturer gave a lecture on Wednesday from 8:30 a.m. till 9:30 a.m. in the intervention condition. Immediately following this first lecture, the same lecturer gave a lecture in the control condition from 9:30 a.m. to 10:30 a.m. The lecturers were instructed to give the same lecture in both conditions and were not informed which classroom was the control condition.

Before the experiment, students were randomly assigned to one of two groups, initially with 15 students each, following the academic course in the experimental or control condition. Students were not allowed to join a lecture in another classroom than pre-assigned. All lectures were given from Tuesday till Friday and always on the same day and time for each group. All participants spent >20 min in the classroom; therefore, the assumption was made that all individuals were fully acclimatised to the thermal environment (Mishra et al., 2017). After the lecture, the lecturer left the classroom and the researcher entered asking the students to participate in the pilot study. The degree of participation was high, reaching approximately 91 % of all students present. After each lecture, a short 5-minute break, were students remained in the classroom, was reserved before the

Table 2
Applied cognitive performance tests, the original reference of test, and performance indicators.

Category	Test	Performance indicator	Link to test
Attention and concentration	Go-No Go task	D-prime score, from −1 (very low) to +6 (very high)	[link]
Memory	Corsi block task	Score, score from 0 (very low) to 9 (very high)	[link]
Perception	Stroop colour-word task	Average score from 0 (very low) to 135 (very high)	[link]
			[link]
Problem-solving	Wisconsin Card Sorting test	Correct responses (C) score from 0 (very low) to 64 (very high) Attempts (A), score 0 (very low) to 64 (very high) Matching rules (R), score 0 (very low) to 6 (very high)	[link]

questionnaires were filled in. Within a week, students who took the in-class academic performance test received an e-mail to inform them about their personal score on this test.

2.5. Data and statistical analysis

In the first academic period, students, first had to get familiar with the questionnaires and the cognitive performance tests. After three weeks, all students had filled in at least one questionnaire and completed all cognitive performance tests. Therefore, from week four onwards, the collected data were used for further analysis. Due to practical reasons, only the data collected during weeks 12 till 14 of the second academic period was used for further analysis. In total, seven campaigns were conducted during the two academic periods. The data, collected in week 4–7 and week 12–14, were checked for errors. Furthermore, Cronbach's alpha values of all composed perception scales were calculated, and the scales were acceptable if the values were >0.70 (Tavakol and Dennick, 2011). Next, the following three research questions were analysed:

1. Do students in a high-quality classroom, with a reverberation time of 0.4 s, a horizontal illuminance level of 500 lx, a moderate indoor air quality with a carbon dioxide concentration of ~1100 ppm, and an air temperature of 21 °C score higher on perceived speech intelligibility, physical, emotional, and cognitive responses, and short-term academic performance when compared to students in a low-quality classroom (Model 1: RT 0.4–0.6 s, E_{hor} 500 lx, CO_2 ~ 1100 ppm, t_a 21 °C)?
2. Do students in a high-quality classroom, with a reverberation time of 0.4 s, a horizontal illuminance level of 750 lx, a moderate indoor air quality with a carbon dioxide concentration of ~1100 ppm, and an air temperature of 21 °C score higher on perceived speech intelligibility and perceived lighting comfort, physical, emotional, and cognitive responses, and short-term academic performance when compared to students in a low-quality classroom (Model 2: RT 0.4–0.6 s, E_{hor} 750–500 lx, CO_2 ~ 1100 ppm, t_a 21 °C)?
3. Do students in a high-quality classroom, with a reverberation time of 0.4 s, a horizontal illuminance level of 750 lx, a high indoor air quality with a maximum carbon dioxide concentration of 800 ppm, and an air temperature of 21 °C score higher on perceived speech intelligibility and perceived lighting comfort, physical, emotional and cognitive responses, and short term academic performance when compared to students in a low-quality classroom with high indoor air quality (Model 3: RT 0.4–0.6 s, E_{hor} 750–500 lx, CO_2 < 800 ppm, t_a 21 °C)?

Fig. 3 shows an overview of all examined direct and indirect associations and moderation effects, which were derived from a previously performed literature review (Brink et al., 2021). Furthermore, this figure shows all studied categories and variables related to students' perceptions, physical, emotional, and cognitive responses, and short-term academic performance.

To analyse the assumed associations, first, mean scale values were calculated. Next, mixed-effects linear models (LMMs) were computed to explore the assumed direct and indirect associations and moderation effects. These models include the main effects of IEQ conditions in the intervention condition, compared to those in the control condition. Multiple LMMs were conducted to test the students' perceptions, their internal responses, and their academic performance under varying conditions of the factors reverberation time, horizontal illuminance level, and ventilation rate. Student responses were statistically corrected for the moderators' age, gender, the distance of students to the lecturer, the estimated number of hours of sleep before participation, and room temperature at home. In addition, the LMMs were controlled for individual student level by random intercept. The models were computed with a general unstructured covariance matrix dealing with the repeated measurements in the design. The main effects were considered statistically significant at a p-value < .05.

The classroom in which the student attended the lecture (the control or intervention condition) was considered as the independent variable in all LMMs that analysed direct associations, see Fig. 3. Significant indirect

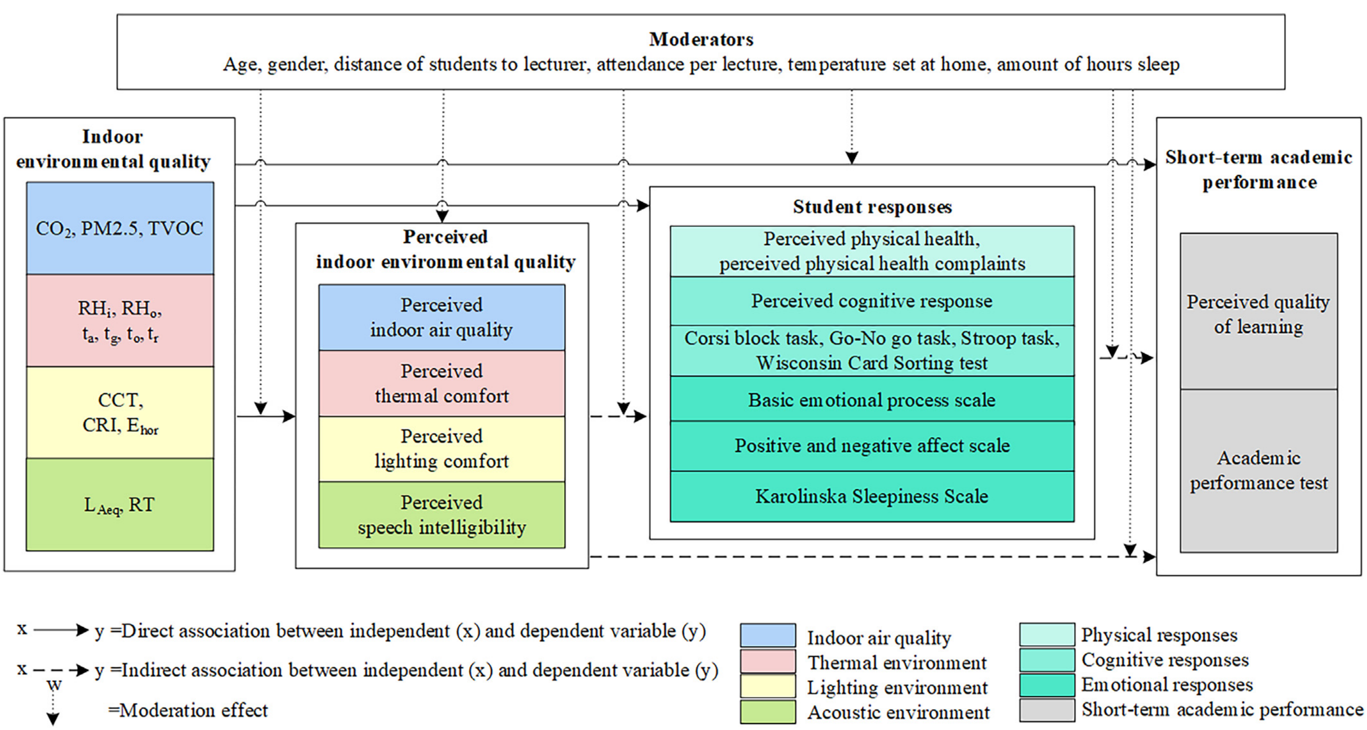

Fig. 3. Overview of studied categories and variables, including the examined direct and indirect associations and moderation effects (Brink et al., 2021).
Note: CCT = correlated colour temperature; CO_2 = carbon dioxide; CRI = colour rendering index E_{hor} = horizontal illuminance; L_{Aeq} = A-weighted background noise or ambient noise; PM2.5 = particles < 2.5 μm; RH_i = indoor relative humidity; RH_o = outdoor relative humidity; RT = reverberation time; t_a = air temperature; t_g = globe temperature; t_o = outdoor temperature; t_r = radiant temperature; TVOC = total volatile organic compounds.

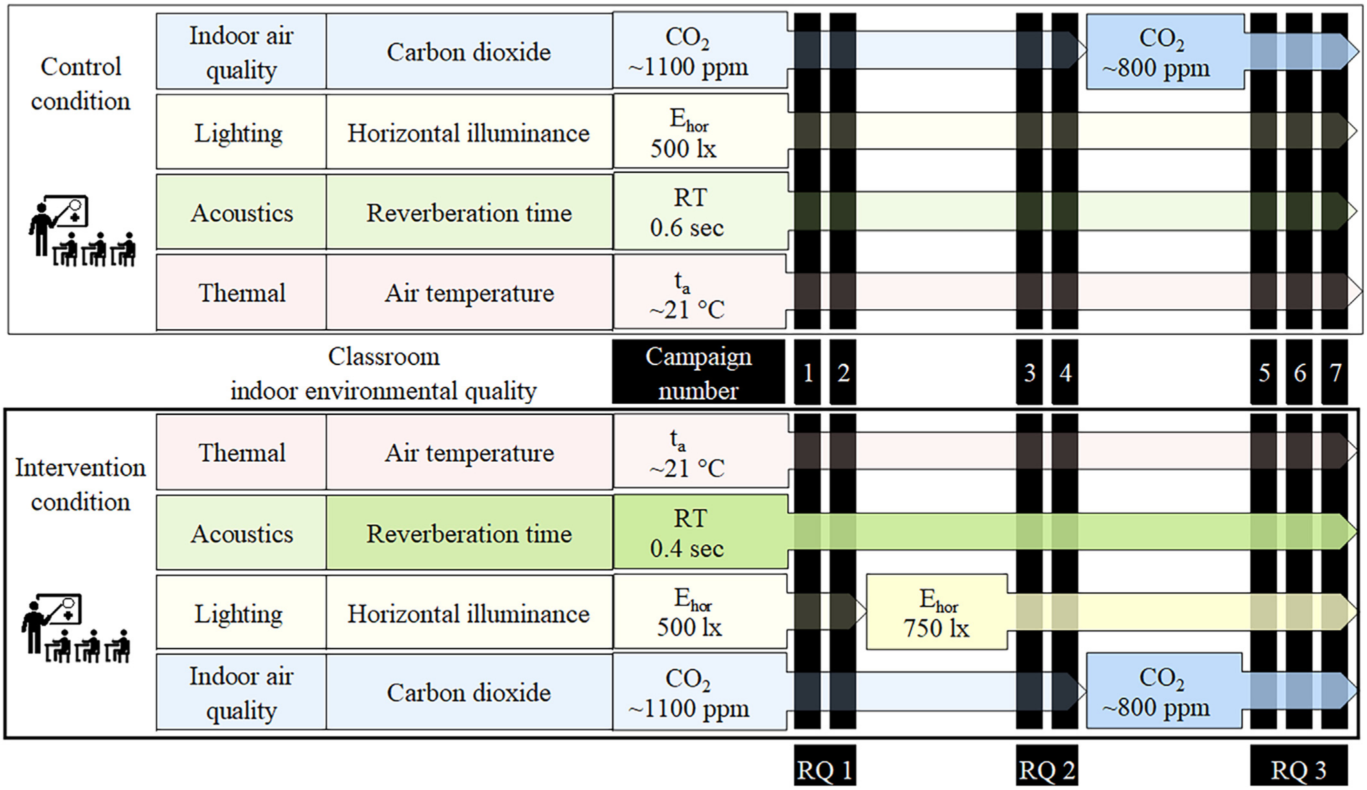

Fig. 4. Overview of interventions during the experiment, including the intended indoor environmental quality in the intervention and control conditions, the campaigns numbers, and of the data of which campaigns were used to answer the three research questions (RQ). See footnote to Fig. 3 for explanation of shading.

effects were only reported when this effect was triggered by a significant direct association. Those LLMs which revealed significant effects were checked by Cook's diagnostic measure. The latter gives a distance measure per respondent over which the maximum was evaluated. In case of values larger than the cut-off value 4/n (Van der Meer et al., 2010), the significance of the LMM parameters' estimates were compared with those from robust LMM (Yohai et al., 1991). When these robust analyses led to a different conclusion regarding the estimate coefficient (β) beyond the first decimal, this is reported.

The LMM function in the linear mixed effects models package (lme4) in R version 3.5.0 (R Foundation for Statistical Computing, 192 Vienna, Austria) and IBM SPSS Statistics Version 28.0.0.0 (190) were used for statistical analyses. In line with the research questions, Fig. 4 shows a schematic overview to summarize the IEQ interventions and in which academic weeks the campaigns were conducted.

3. Results

In this paragraph, first, the number of students which participated during the campaigns and the average scores of all moderators are presented. Next, the observed actual IEQ conditions in the intervention and control conditions are presented, which specifically address the effect of the interventions. Finally, the observed direct and indirect associations and moderation effects of the three interventions on students are presented, derived from LMMs.

Table 3
Overview student participation and moderators.

Week	Period 2020–2021	CP	CO	n	♀ (%)	Age	Row	Attendance per lecture	Desk occupancy (%)	t_a set at home (°C)	Estimated amount of hours sleep
4	29–9/30–9	1[a]	I	51	68	20 ± 2	3 ± 1	10 ± 4	67	20 ± 1	7 ± 1
			C	63	61	19 ± 2	3 ± 1	13 ± 3	87	20 ± 1	7 ± 1
5	6–10/7–10	2[a]	I	40	55	19 ± 2	4 ± 1	9 ± 3	60	20 ± 1	7 ± 2
			C	38	68	19 ± 2	4 ± 1	11 ± 2	73	20 ± 1	7 ± 1
6	20–10/22–10	3[a]	I	64	63	19 ± 2	3 ± 1	13 ± 2	87	20 ± 1	8 ± 1
			C	62	63	19 ± 2	4 ± 1	11 ± 2	73	20 ± 1	7 ± 1
7	27–10/29–10	4[a]	I	47	56	19 ± 2	4 ± 1	9 ± 1	60	20 ± 1	8 ± 1
			C	48	60	19 ± 2	4 ± 1	10 ± 3	67	20 ± 1	8 ± 1
12	15–12/16–12	5[b]	I	14	57	20 ± 2	4 ± 1	2 ± 2	13[c]	21 ± 1	7 ± 2
			C	15	53	19 ± 2	3 ± 1	2 ± 2	13[c]	20 ± 1	7 ± 2
13	5–1/8–1	6[b]	I	15	60	19 ± 3	3 ± 1	10 ± 0	67	20 ± 1	7 ± 1
			C	30	63	19 ± 2	4 ± 1	6 ± 1	40	20 ± 1	6 ± 2
14	12–1/15–1	7[b]	I	16	63	19 ± 2	4 ± 1	7 ± 2	47	20 ± 1	7 ± 2
			C	24	71	19 ± 2	4 ± 0	5 ± 2	33	20 ± 1	6 ± 1

Note: CO = condition; CP = campaign; n = number of participants; t_a = air temperature.
[a] During partial lockdown to bring down COVID-19 infections in the Netherlands.
[b] During full lockdown to bring down COVID-19 infections in the Netherlands.
[c] First week in which the Netherlands were in full lockdown.

3.1. Participation and moderators

Table 3 presents an overview of the number of students which participated during all campaigns and all moderators. The experiment was performed from September 2020 till January 2021. Travel and lecturing restrictions, due to the outbreak of the coronavirus in the Netherlands may have affected student attendance (Government of the Netherlands, 2020b), especially during the last three campaigns, although the Hanze UAS gave permission to continue the experiment (Government of the Netherlands, 2020a). It was not mandatory, due to government regulations, to wear a mask inside the class room. As a result, all participating students did not wear a mask. During all campaigns, students had to keep a distance of at least 1.5 m from each other within the classrooms. The self-reported evaluations of students' emotions, see Appendix E, gave no reason to assume that during the experiment emotions differed greatly for both students in the control and in the experimental groups. Therefore, these results do not provide any indication that the ongoing pandemic, although in general it may have caused mental stress among the students who participated in the experiment influenced the results as presented.

3.2. Actual indoor environmental quality

With reference to Fig. 4, the difference between the reverberation time of the intervention and the control conditions was −0.2 s (0.4–0.6 s). As intended, the horizontal illuminance level at the lecturer's desk was manually manipulated during campaigns 1–2 to ~500 lx. As a result, no significant difference in the horizontal illuminance level at the students' desks was observed during these campaigns. From campaign 3 onwards, the horizontal illuminance level at the lecturer's desk was raised in the intervention condition to ~750 lx, and as a result, the mean horizontal illuminance level at the students' desks was on average 192 lx higher in the intervention condition, compared to those of the control condition. Bear in mind that besides the artificial lighting also daylight entered the classrooms through the windows. However, the classrooms' orientation prevented direct sunlight entry. The average cloud coverage during the campaigns (in octants) was 7.5, 7.5, and 7.2 (9 = sky invisible) and the global radiation (hourly division) was 51.0, 37.3 and 20.4 J/cm^2 for campaigns 1–2, 3–4, and 5–7, respectively (The Royal Netherlands Meteorological Institute, 2022). Fig. 5 shows the average horizontal illuminance levels at lecturer's and students' desks and how the light was distributed in the classroom during the campaigns.

The air temperature setpoint was 21.0 °C during all campaigns. The globe (−0.2 °C) and radiant temperatures (−0.3 °C) did not differ beyond accuracy specification from the air temperature at 21.4 °C, presumably due to the low thermal mass of the building in which the classrooms are located. After the new HVAC system was installed, the CO_2 concentration was reduced with ~490 ppm CO_2. The concentration TVOC and PM2.5 was also lower during the last three campaigns. However, during the fifth campaign the PM2.5 concentration was higher than during the sixth and seventh campaigns, due to a higher PM2.5 concentration in the outdoor air (National Institute for Public Health and the Environment, 2022). Table 4 shows all obtained measurements of the indoor air quality and thermal conditions in the intervention and control conditions during the seven campaigns of the experiment.

3.3. Students perceptions, internal responses, and academic performance

Regarding Table 4, the air temperature setpoint was not adjusted during all campaigns. Although small differences in air temperature and indoor humidity were observed between the intervention and control condition, LMMs revealed no statistically significant difference in students' perceived thermal comfort between the intervention and control condition and between campaigns three and four (before the instalment of the new HVAC system) and campaigns five, six and seven (when the new HVAC system was operational). However, students' perceived indoor air quality (α-value of this scale is 0.92) was expected to improve during campaigns five, six and seven, compared to those of campaigns three and four. This effect was expected in both the control and the intervention condition, as a result of an improved ventilation rate. LMMs revealed that students' perceived indoor air quality average score was in fact significantly higher during the last three campaigns (p = .020; β = 0.33). Unexpectedly, during the fifth campaign, a difference was observed in the mean score of perceived indoor air quality between the intervention and control conditions, which may have influenced other students' perceptions. This has been taken into account when the results of this campaign were interpreted. Appendix E presents all scores of students' perceptions of the indoor environment, their internal responses, and their academic performance in the control and intervention conditions during all seven campaigns.

3.4. Analysis of direct, indirect, and moderation effects

With regard to all research questions, average scores for related items and scales were computed. Next, LMMs were computed to analyse all direct

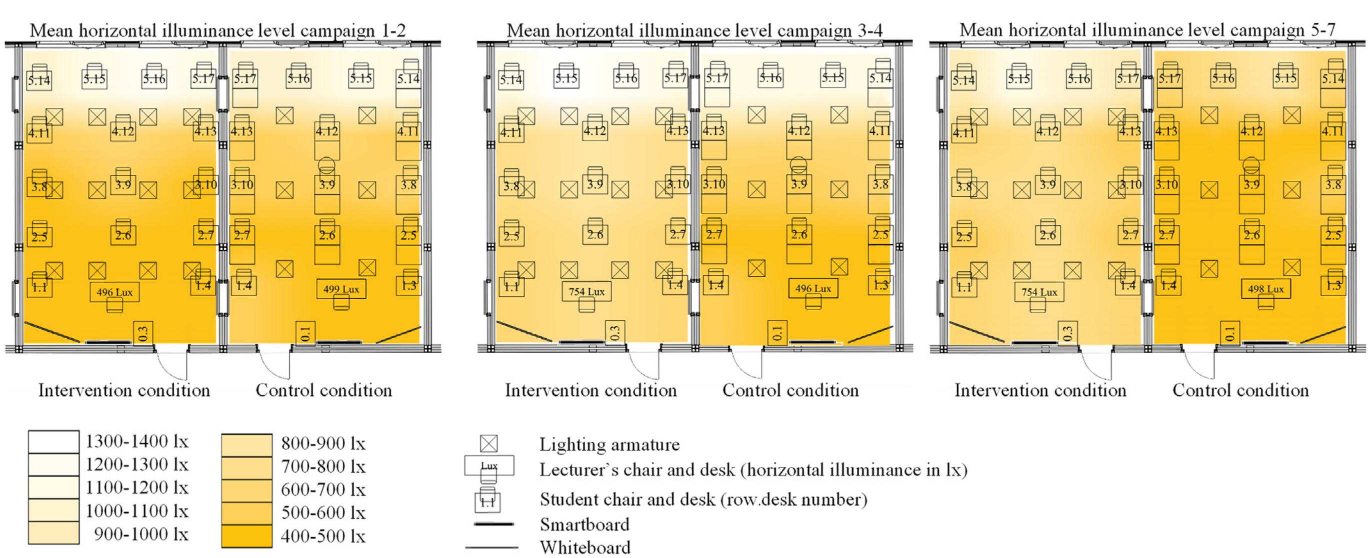

Fig. 5. Average horizontal illuminance level in the classrooms during all campaigns, average horizontal illuminance level at lecturer's desk, the row and desk numbers of students' desks, and the location of the lighting armatures, smartboard, and whiteboard.

Table 4
Average observations and standard deviations of outside and inside relative humidity and air temperature, carbon dioxide concentration, particles < 2.5 μm and total volatile organic compounds of the intervention and control conditions during the experiment.

CP	CO	RH_o (%)	RH_i (%)	t_o (°C)	t_a (°C)	CO_2 (ppm)	PM2.5 (μg/m^3)	TVOC (mg/m^3)
1[a]	CC	90 ± 11	59 ± 2	15.2 ± 2.5	20.9 ± 1.4	1239 ± 128	3.8 ± 2.9	0.5 ± 0.7
	IC	86 ± 11	52 ± 1	16.0 ± 2.1	20.8 ± 1.1	994 ± 208	3.7 ± 2.8	0.2 ± 0.1
2[a]	CC	86 ± 7	57 ± 1	13.5 ± 1.3	19.2 ± 1.3	938 ± 316	1.8 ± 0.4	0.4 ± 0.3
	IC	82 ± 7	50 ± 1	13.8 ± 1.0	20.2 ± 1.1	959 ± 323	1.7 ± 0.4	0.3 ± 0.2
3[a]	CC	80 ± 8	52 ± 2	14.0 ± 2.2	21.9 ± 0.5	1140 ± 125	3.4 ± 1.5	1.4 ± 1.0
	IC	79 ± 7	44 ± 2	14.0 ± 2.4	22.6 ± 0.6	1022 ± 179	3.5 ± 1.8	0.6 ± 0.3
4[a]	CC	78 ± 4	47 ± 2	11.2 ± 0.9	21.8 ± 0.5	1062 ± 172	3.5 ± 3.3	1.3 ± 1.2
	IC	80 ± 5	41 ± 1	10.8 ± 0.8	22.3 ± 0.4	986 ± 164	1.9 ± 0.3	1.2 ± 1.0
5[b]	CC	96 ± 1	41 ± 1	8.0 ± 0.8	21.5 ± 0.3	571 ± 43	3.1 ± 1.0	0.0 ± 0.0
	IC	96 ± 1	36 ± 1	8.0 ± 0.8	21.5 ± 0.1	649 ± 49	3.2 ± 1.2	0.0 ± 0.0
6[b]	CC	91 ± 6	34 ± 1	2.6 ± 0.3	21.2 ± 0.3	630 ± 91	0.9 ± 0.2	0.0 ± 0.0
	IC	93 ± 6	28 ± 2	1.8 ± 1.1	21.5 ± 0.3	757 ± 160	0.8 ± 0.1	0.0 ± 0.0
7[b]	CC	83 ± 6	35 ± 2	4.7 ± 1.1	21.2 ± 0.4	654 ± 48	0.9 ± 0.1	0.0 ± 0.1
	IC	77 ± 7	27 ± 2	4.7 ± 2.3	21.7 ± 0.4	632 ± 66	1.1 ± 0.3	0.0 ± 0.0

Note: CC = control condition; CO = condition; CO_2 = carbon dioxide; CP = campaign number; IC = intervention condition; PM2.5 = particles < 2.5 μm; RH_i = indoor relative humidity; RH_o = outdoor relative humidity; t_a = air temperature; t_o = outdoor temperature; TVOC = total volatile organic compounds.

[a] Full recirculation system was operational.

[b] Heating, ventilation, and air conditioning (HVAC) system was operational.

and indirect associations and moderation effects of campaign one and two (model 1), campaign three and four (model 2), and campaign five, six, and seven (model 3), as shown in Fig. 4. In the LMMs, perception values were used to determine speech intelligibility, mean lighting comfort, mean cognitive performance, and quality of learning. Cook's distance of the LMMs exceeded the cut-off value in all significant LMMs. However, the robust LMMs which were subsequently calculated showed estimates which did not differ beyond the first decimal, except the estimates of one LMM. The robust values of this LMM are also reported.

3.4.1. Model 1 Delta reverberation time (−0.2 s) at low horizontal illuminance conditions (500 lx) and moderate indoor air quality (~1100 ppm CO_2)

With regard to the first research question, whether a reduced reverberation time had a positive effect on students' perceived IEQ, responses and academic performance, LMMs were computed with all related items and scales of the first two campaigns. The difference in reverberation time between the intervention and control conditions did not lead to a significant difference in students' ability to hear the lecturer's voice and students' short-term academic performance. However, the difference in reverberation time did lead to a higher score on students' perceived cognitive performance (α scale 0.88; $\beta = 0.34$; $t(157) = -2.05$; $p = .042$). There was a gender effect: male students on average scored higher on their perceived cognitive performance than female students ($\beta = 0.38$; $t(115) = -2.40$; $p < .018$). Also, an indirect association was observed between students' perceived cognitive performance and perceived quality of learning ($\beta = 0.62$; $t(144) = 10.70$; $p = .000$).

3.4.2. Model 2 Delta reverberation time (−0.2 s) and delta horizontal illuminance level (+250 lx) at moderate indoor air quality (~1100 ppm CO_2)

With regard to the second research question, whether a reduced reverberation time and enhanced horizontal illuminance level had a positive effect on students' perceived IEQ, responses, and academic performance, LMMs were computed with all related items and scales of the third and fourth campaigns. The influence of reduced reverberation time and enhanced horizontal illuminance level led to a significant improvement of the perceived lighting conditions ($\beta = 0.37$; $t(143) = -2.78$; $p = .006$). Furthermore, the perceived lighting comfort was negatively influenced when the number of students present was higher ($\beta = -0.06$; $t(129) = -2.81$, $p = .006$).

The influence of reduced reverberation time and enhanced horizontal illuminance level led to an unexpected decline in the intervention condition on the Wisconsin Card Sorting test, a cognitive performance test to measure students' ability to solve problems on the indicator correct responses ($\beta = -2.10$; $t(127) = 2.04$; $p = .043$), although the robust LMM showed a lower estimate ($\beta = -0.59$; $t(138) = -1.35$). This score was also associated with the row the student sat during the lecture ($\beta = 0.68$; $t(165) = 2.20$; $p = .029$). The direct association between the improved acoustic and lighting conditions and students' perceived lighting comfort initiated multiple indirect associations between this perceived comfort and students' responses. When the perceived lighting comfort increased, this improved students' perceived physical health ($\beta = 0.17$; $t(202) = 2.96$; $p = .003$). A significant effect of gender was observed: female students rated their health on average lower ($\beta = -0.23$; $t(123) = -2.34$; $p = .003$). Students' perceived cognitive performance was positively influenced when the perceived lighting comfort increased ($\beta = 0.39$; $t(203) = 3.98$; $p = .000$). Students' ability to hear the lecturers' voice was not significantly associated anymore with students' perceived cognitive performance ($\beta = 0.04$; $t(197) = 0.45$; $p = .65$). An improvement in perceived lighting comfort positively influenced the performance indicator matching rules of the Wisconsin Card Sorting test ($\beta = 0.23$; $t(187) = 2.30$; $p = .022$). Furthermore, an improvement in perceived lighting comfort positively influenced multiple emotional responses. Students' basic emotional status score was positively influenced ($\beta = 0.10$; $t(194) = 3.04$; $p = .003$). A significant association was observed between students' basic emotional status and students' number of hours sleep, the amount of sleep the night before the students participated in the research project. The observed effect indicates that when students had slept longer, their basic emotional status increased ($\beta = 0.04$; $t(196) = 2.01$; $p = .046$). Students' emotional positive affect scale score was positively influenced by an improved perceived lighting comfort ($\beta = 1.47$; $t(210) = 2.33$; $p = .021$). Students' perceived level of sleepiness was positively influenced by an improved perceived lighting comfort ($\beta = -0.41$, $t(185) = 2.56$; $p = .011$).

Students' perceived quality of learning score was also positively influenced by the perceived lighting comfort ($\beta = 0.18$; $t(159) = 3.20$; $p = .002$) and by the perceived cognitive performance ($\beta = 0.60$; $t(185) = 11.42$; $p = .007$). Also, the perceived quality of learning score is positively influenced by students' ability to hear the lecturer's voice ($\beta = 0.12$; $t(141) = 2.72$; $p = .007$). However, no difference was observed between the intervention and control conditions in the ability to hear the lecturers' voice and students' short-term academic performance.

3.4.3. Model 3 Delta reverberation time (−0.2 s) and horizontal illuminance level (+250 lx) at high indoor air quality (<800 ppm CO_2)

With regard to the third research question, whether under improved indoor air quality conditions, compared to those in the third and fourth campaigns, a reduced reverberation time and enhanced horizontal illuminance level had a positive effect on students' perceived IEQ responses and academic performance, LMMs were computed with all related items and scales of the fifth, sixth, and seventh campaigns. LMMs did not reveal any significant differences in students' perceptions, responses, or short-term academic performance.

3.5. Visualization of direct and indirect associations and moderation effects

Fig. 6 shows all direct and indirect observed associations of model 1 and model 2, including all estimated fixed effect sizes and levels of significance. To improve the readability of these models, a variable is present with its original shading, when a direct or an indirect association was observed. The shading of the variable was removed when no association was observed.

4. Discussion

The main objective of this study was to analyse the effect of multiple IEQ parameters on students' academic performance in higher education. The following hypothesis was examined: indoor environmental conditions meeting quality class A of the Dutch guidelines, have a positive effect on students' perceptions, responses, and performance. To analyse the effect of these improved conditions, a between-groups experimental design was performed where students were randomly assigned to either the control or the intervention group. This group was then taught in either the intervention condition, with improved IEQ conditions, or the control condition, with standard IEQ conditions. Lecturers taught in both conditions consecutively on the same day. In this paragraph, the results related to three research questions, see Section 2.5, are discussed.

4.1. Effect of reduced reverberation time

First, the research question that addressed the effect of an improved reverberation time (−0.2 s) at low lighting environmental and moderate

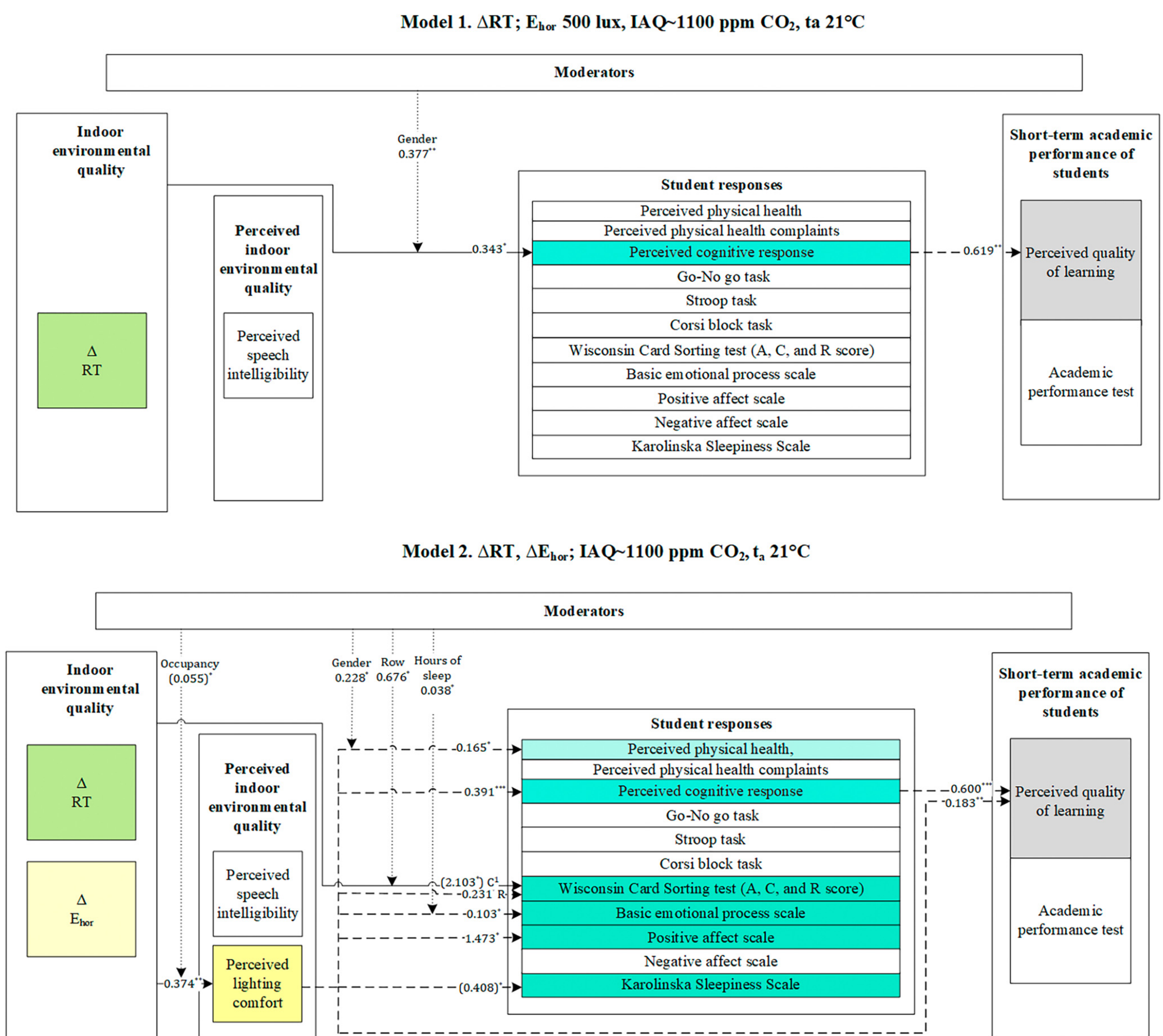

Fig. 6. Estimate values of significant associations between the improvement of indoor environmental parameters and students' perceptions, responses, short-term academic performance, and moderators. See Fig. 3 for explanation of shading.
Note: * = correlation is significant at the 0.05 level; ** = correlation is significant at the 0.01 level; *** = correlation is significant at the 0.001 level.
E_{hor} = horizontal illuminance; RT = reverberation time; Wisconsin Card sorting test A score = attempts score;
Wisconsin Card Sorting test C score = correct responses score; Wisconsin Card Sorting test R score = matching rules score.
[1] = estimate of robust LMM was lower.

indoor air quality conditions on students' perceived acoustic comfort, internal responses, and short-term academic performance will be discussed. Except for the reverberation time, the acoustic conditions in the intervention and control conditions were similar, indicating that the perceived speech intelligibility of the lecturer is particularly influenced by the difference in reverberation time (Madbouly et al., 2016). The relatively small improvement of the reverberation time of −0.2 s, as prescribed by Dutch guidelines (RVO, 2015), did not lead to a significant difference in students' perceived ability to hear the lecturer's voice nor did it influence students' actual cognitive performance test scores. The absence of this effect was also observed by Braat-Eggen et al. (2019). However, at the same time the improved reverberation time positively influenced students' perceived cognitive performance and a higher perceived cognitive performance positively influenced students' perceived quality of learning. This positive effect of reverberation time on students' cognitive and short-term academic performances was also reported by Castro-Martínez et al. (2016), although they examined classrooms with higher reverberation times, i.e., 1.2 versus 2.0 s.

As observed, lowering the reverberation time, from 0.6 to 0.4 s, did not lead to a significant difference in students' perceived ability to hear the lecturer's voice. Comparing this result with Kim and de Dear (2012) IEQ classification, it seems apparent that the reverberation time can be classified as a basic factor. Kim and de Dear (2012) describe basic factors as "minimum requirements". Basic factors do not necessarily enhance overall satisfaction, but they can cause dissatisfaction when they are not fulfilled. In our experiment, students did not notice the reduction of reverberation time and in the control condition students did not underperform on cognitive performance and short-term academic performance, indicating that base line conditions at a reverberation time of 0.6 s were met in the control condition. Furthermore, although previous work revealed a relation between students' perceived cognitive performance and content-related test scores (Brink et al., 2022), the presented results in Sections 3.4.1, 3.4.2, and 3.4.3 do not confirm this relation.

4.2. Effect of reduced reverberation time and enhanced horizontal illuminance level at moderate indoor air quality

Second, the research question that addressed the effect of an improved reverberation time (−0.2 s) and an improvement of the lighting environment (horizontal illuminance level at lecturer's desk + ~250 lx) at moderate indoor air quality conditions (~1100 ppm CO_2) on students' perceived acoustic and lighting comfort, internal responses, and short-term academic performance will be discussed. The improved lighting environment, defined as quality class A (RVO, 2015), positively influenced students' perceptions of it. Regarding cognitive performance test scores, a small direct negative effect of the higher horizontal illuminance level in the intervention condition was observed with regard to students' ability to solve problems, measured with the Wisconsin Card Sorting test (Ozonoff, 1995).

Our findings confirm those of Xiong et al. (2018). In that study, students also scored lower on a problem-solving task under a high illuminance level, compared with their score under a low illuminance level at similar conditions of indoor air temperature (22 °C) and background noise (40 dB(A)). In the study of Xiong et al. (2018), a full factorial experiment was analysed on multiple cognitive responses of students, i.e., perception, memory, problem-solving, and attention. However, the number of subjects was 10 in a within groups experiment and instead of being exposed to 500 and 750 lx, subjects were exposed to 300 and 2200 lx, which imposed a much larger effect (Xiong et al., 2018). However, the direction of the observed effect is similar in these different but related experiments, strongly suggesting that higher illuminance levels do not improve students' problem-solving ability.

A higher perceived lighting comfort, at a horizontal illuminance level of 750 lx, directly influenced students' emotional process scale positively. This positive effect on students' emotions in combination with no observed effect on cognitive performance was also observed by Tanabe and Nishihara (2004). They evaluated students' level of fatigue when they had to perform several cognitive performance tests at low and high illuminance conditions. Although the students did not perform significantly better under 800 lx, compared to those at 3 lx, students self-reported level of fatigue was significantly lower when tasks were performed under 800 lx. In the current study, improved lighting conditions also decreased students' self-reported level of sleepiness, measured with the Karolinska Sleepiness Scale (Shahid et al., 2011), in favour of the level of alertness. This positive effect on sleepiness was also reported by van Duijnhoven et al. (2018) in an office environment. Furthermore, the perceived lighting conditions were positively, though indirectly, associated with students' ability to solve problems, perceived cognitive performance, and quality of learning; however, students' ability to hear the lecturer's voice was not significantly associated with these perceptions anymore.

The presented results in Section 3.4.2 confirm Kim and de Dear's (2012) classification of visual comfort as a proportional factor. These researchers describe proportional factors as factors that have a predominantly linear relationship with overall satisfaction (Kim and de Dear, 2012). The observed effects during the third and fourth campaigns, point in the same direction. When students' perceived lighting comfort increased, so did their perceived internal responses and perceived quality of learning. However, it should be noted that raising horizontal illuminance levels can also negatively influence humans' perceived visual comfort. For example, applying the regression equation of Cao et al. (2012) revealed that human satisfaction with the luminous environment declines when illuminance levels exceed ~1100 lx. Furthermore, the work of Xiong et al. (2018) showed that there is no 'one-size fits all' illuminance level for students in higher education. Students perform at their best in different lighting conditions, depending on the type of task they have to perform. Furthermore, although students report a higher level of lighting comfort, and this improved comfort also positively influenced perceived internal responses and quality of learning, again no main effect of a reduced reverberation time and raised horizontal illuminance level on students' short-term academic performance was observed.

4.3. Effect of reduced reverberation time and enhanced horizontal illuminance level at high indoor air quality

Third, the research question on the effect of an improved reverberation time (−0.2 s) and an improvement of the lighting environment (horizontal illuminance level at lecturer's desk + ~250 lx) at high indoor air quality conditions (<800 ppm CO_2) on students' perceived acoustic and lighting comfort, internal responses, and short-term academic performance will be discussed. Due to an improved ventilation rate, the CO_2 concentration (~610 vs ~1100 ppm) and the perceived indoor air quality improved in the intervention and control conditions. However, in this case no significant differences in students' perceived speech intelligibility and perceived lighting comfort were observed between both conditions. Consequently, these findings suggest that the benefits of improved indoor air quality conditions may outweigh the benefits of improved acoustic and lighting conditions. However, in this study, students' participation, and consequently classroom occupancy, was lower during the last three campaigns, compared to the first four campaigns, see Table 3.

To the best of our knowledge, no evidence is available that examined a combination of acoustic, lighting, and IAQ conditions on students in higher education (Brink et al., 2021). Furthermore, Torresin et al. (2018) performed a systematic literature study to examine interaction effects of IEQ parameters. These researchers also did not find any studies dealing with the effects of IAQ and lighting conditions. Although is it well documented that poor IAQ affect students' cognitive performance, studies that examine IAQ conditions with CO_2 concentrations between 600 and 1100 ppm do not provide unequivocal evidence (Du et al., 2020). Therefore, combinations of reduced reverberation times, horizontal illuminance levels, and ventilation rates are worthwhile to examine further, for example, by using a full-factor design. However, applying complete experimental designs may affect the feasibility of examining these effects in 'real life' settings.

5. Strength and limitations

This study focused on how improved IEQ conditions simultaneously influenced students' perceptions, responses, and short-term academic performance. Studying multiple factors simultaneously has a higher ecological validity than studying only one factor, as in daily facility management practices in higher education many parameters change frequently and simultaneously when (re)designing classrooms.

The experimental design of this study focused on specific differences in outcomes between students in experimental and control conditions when attending lectures on the same day, in a similar time frame, and given by the same lecturer. Due to the incompleteness of the experimental design, no interaction effects could be examined. However, the observed effects of reduced reverberation time and raised illuminance level, in the order as investigated, were found to be significant in contributing to improved comfort and perceived performance.

Student responses were statistically corrected for age, gender, the distance of students to the lecturer (expressed in row number), the number of students present in the classroom, the self-perceived number of hours of sleep before participation, and room temperature at home. In addition, the LMMs controlled for the individual student level by random intercept. Therefore, the presented evidence is highly suggestive for the validity of the observed effects.

Due to low student attendance and participation during the last three campaigns compared to the first four campaigns of this study, most likely caused by COVID-19 restrictions during this period (Government of the Netherlands, 2020a), no conclusions should be drawn based on the results of these last three campaigns.

In this study, a relatively young population was examined, with an average age of 19 ± 2 years. A different population, for example, older students, may yield different results. Another point is that the academic context was a tutorial. Different academic contexts, such as a workshop or a seminar, may show different results. Furthermore, the effect size of horizontal illuminance level cannot be determined individually, because only the simultaneous effect of improved acoustic and lighting conditions was examined.

6. Conclusion

Studies which examine the simultaneous effect of improved indoor environmental factors are rare. To some extent, this study revealed the influence of improved acoustic, lighting, and indoor air quality conditions on classroom occupants. Our results suggest that adoption of Dutch IEQ guidelines for school buildings for reverberation time (0.4 s vs 0.6 s) positively influences students' perceived cognitive performance, which in return positively influences students' perceived quality of learning. Moreover, the raised horizontal illuminance at the lecturer's desk (750 lx vs 500 lx) contributed positively to students' perceived lighting comfort, which in return positively influenced students' perceived health, cognitive performance, emotional status, and quality of learning. However, this experimental condition of reduced reverberation time and raised horizontal illuminance level negatively influenced students' ability to solve problems. Furthermore, the experimental condition did not influence other cognitive performance and the content-related test scores. In none of the intervention studies was the short-term academic performance affected. Therefore, adapting quality class A conditions for reverberation time and horizontal illuminance improved students' perceptions, but it did not influence their cognitive and short-term academic performance. In this study, self-reported comfort and cognitive performance was proven not to be a valid predictor for students' actual ability to solve problems, as a function of cognitive performance. Furthermore, no valid significance was observed for the effects of improved air quality because of low student occupancy rates in classrooms (COVID 19 restrictions) which unintendedly may have influenced students' perceptions and performance. Notwithstanding these limited occupancy rates, our findings do suggest the relevance of further research into the effects of two or more indoor environmental factors, with higher occupancy rates and other study designs, such as a full factorial experiment. The applied measurement procedure showed to be a useful approach to support studies on the topic.

CRediT authorship contribution statement

H.W. Brink: Conceptualization, Data curation, Methodology, Visualization, Writing – original draft. **W.P. Krijnen:** Methodology, Software, Writing – review & editing. **M.G.L.C. Loomans:** Supervision, Writing – review & editing. **M.P. Mobach:** Supervision, Writing – review & editing. **H.S.M. Kort:** Supervision, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.161813.

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