Examining in-class activities to facilitate academic achievement in higher education

Citation for published version (APA):
Brink, H. W. (2023). *Examining in-class activities to facilitate academic achievement in higher education: A framework for optimal indoor environmental conditions*. [Phd Thesis 1 (Research TU/e / Graduation TU/e), Built Environment]. Eindhoven University of Technology.

Document status and date:
Published: 07/03/2023

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

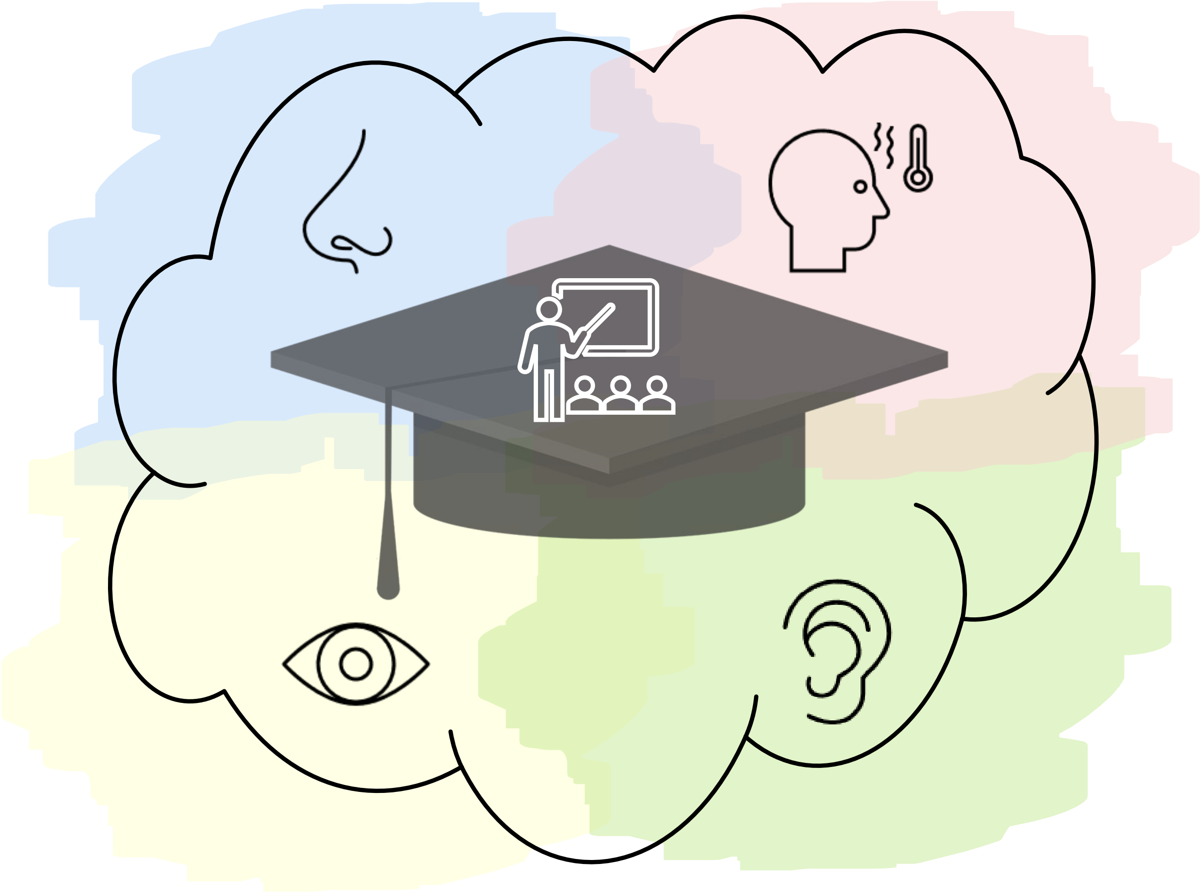
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 08. Feb. 2024



Examining in-class activities to facilitate academic achievement in higher education

A FRAMEWORK FOR OPTIMAL INDOOR ENVIRONMENTAL CONDITIONS

Henk W. Brink

Bouwstenen 345

Examining in-class activities to facilitate academic achievement in higher education

A framework for optimal indoor environmental conditions

Henk W. Brink

The work described in this thesis has been carried out in the Unit Building Physics and Services, Building Performance group, chair Building Healthy Environments for Future Users at the Eindhoven University of Technology, Department of the Built Environment.

A catalogue record is available from the Eindhoven University of Technology Library.
ISBN: 978-90-386-5687-8
NUR: 955

Published as issue 345 in the Bouwstenen series of the Department of the Built Environment of the Eindhoven University of Technology.

This research is supported by the Facility Management Department, the Institute of Future Environments, the Research Centre for Built Environment NoorderRuimte, and the Executive Board of Hanze University of Applied Sciences, Groningen, The Netherlands.

© Henk W. Brink, 2023

All rights reserved. No part of this publication may be reproduced, distributed, or transmitted in any form or by any means, including photocopying, recording, or any other electronic or mechanical methods without permission of the author.

Examining in-class activities to facilitate academic achievement in higher education: A framework for optimal indoor environmental conditions

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de rector magnificus prof.dr.ir. F.P.T. Baaijens, voor een commissie aangewezen door het College voor Promoties, in het openbaar te verdedigen op dinsdag 7 maart 2023 om 13:30 uur

door

Henk W. Brink

geboren te Groningen

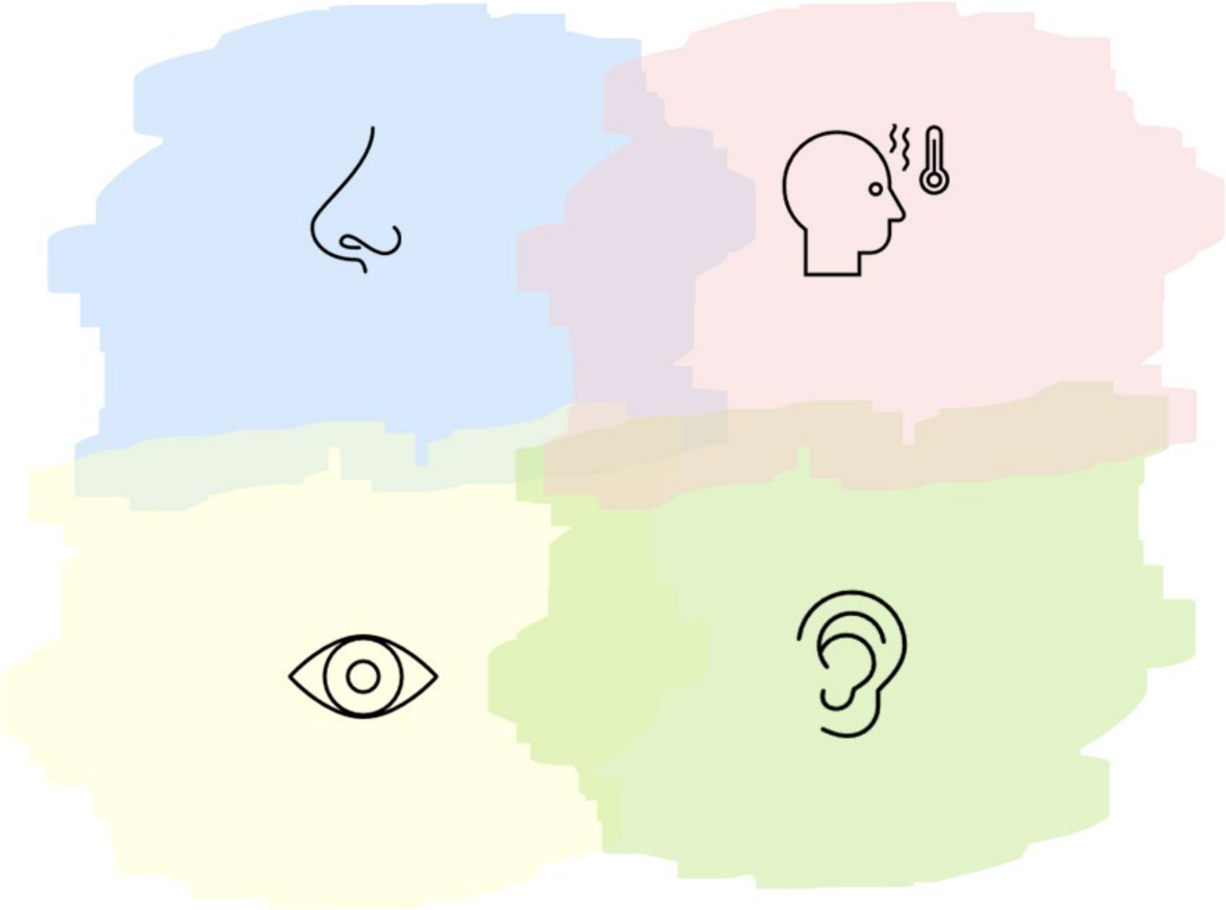
Dit proefschrift is goedgekeurd door de promotor en de samenstelling van de promotiecommissie is als volgt:

voorzitter:	prof.dr.ir. P.J.V. van Wesemael	
1e promotor:	prof.dr. H.S.M. Kort	
copromotor(en):	dr.ir. M.G.L.C. Loomans	
	dr. M.P. Mobach	(Hanzehogeschool Groningen)
leden:	prof.dr.ir. A.C. Boerstra	(Technische Universiteit Delft)
	prof.dr. P.M. Le Blanc	
	prof.dr. M. Pitt	(University College London)
	univ.-prof.dr. M. Schweiker	(RWTH Aachen University)

Het onderzoek dat in dit proefschrift wordt beschreven is uitgevoerd in overeenstemming met de TU/e Gedragscode Wetenschapsbeoefening.

Contents

Summary



There is an increasing interest in how to create an effective and comfortable indoor environment for lecturers and students in higher education. To achieve evidence-based improvements in the indoor environmental quality (IEQ) of higher education learning environments, this research aimed to gain new knowledge for creating optimal indoor environmental conditions that best facilitate in-class activities, i.e. teaching and learning, and foster academic achievement. The academic performance of lecturers and students is subdivided into short-term academic performance, for example, during a lecture and long-term academic performance, during an academic course or year, for example. First, a **systematic literature review** was conducted to reveal the effect of indoor environmental quality in classrooms in higher education on the quality of teaching, the quality of learning, and students' academic achievement. With the information gathered on the applied methods during the literature review, a **systematic approach** was developed and validated to capture the effect of the IEQ on the main outcomes. This approach enables research that aims to examine the effect of all four IEQ parameters, indoor air quality, thermal conditions, lighting conditions, and acoustic conditions on students' perceptions, responses, and short-term academic performance in the context of higher education classrooms. Next, a **field experiment** was conducted, applying the validated systematic approach, to explore the effect of multiple indoor environmental parameters on students and their short-term academic performance in higher education. Finally, a **qualitative case study** gathered lecturers' and students' perceptions related to the IEQ. Furthermore, how these users interact with the environment to maintain an acceptable IEQ was studied.

During the **systematic literature review,** multiple scientific databases were searched to identify relevant scientific evidence. After the screening process, 21 publications were included. The collected evidence showed that IEQ can contribute positively to students' academic achievement. However, it can also affect the performance of students negatively, even if the IEQ meets current standards for classrooms' IEQ conditions. Not one optimal IEQ was identified after studying the evidence. Indoor environmental conditions in which students perform at their best differ and are task depended, indicating that classrooms should facilitate multiple indoor environmental conditions. Furthermore, the evidence provides practical information for improving the design of experimental studies, helps researchers in identifying relevant parameters, and lists methods to examine the influence of the IEQ on users.

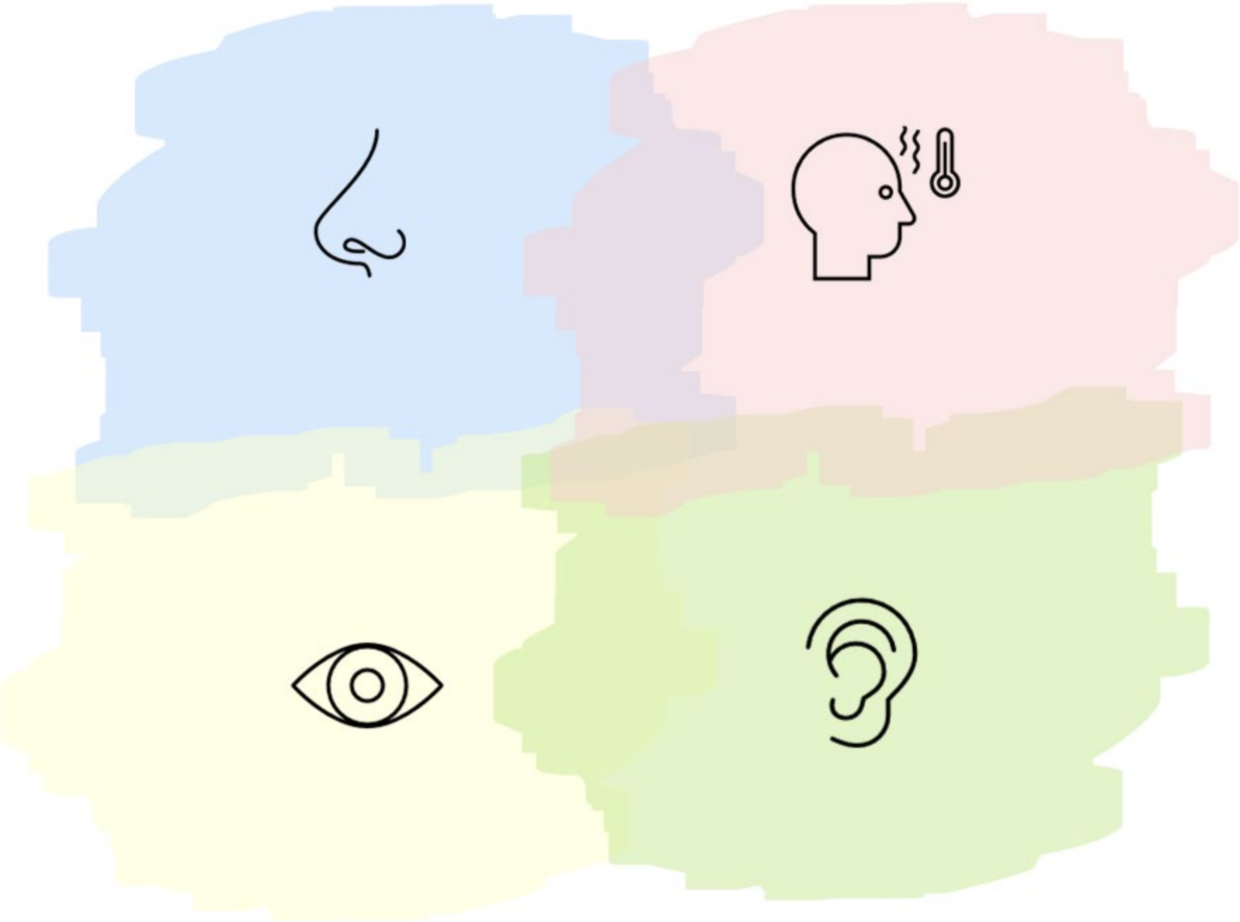
The measurement methods deduced from the included studies of the literature review, were used for the development of a **systematic approach** measuring classroom IEQ and students' perceived IEQ, internal responses, and short-term academic performance. This approach allowed studying the effect of multiple IEQ parameters simultaneously and was tested in a pilot study during a regular academic course. The perceptions, internal responses, and short-term academic performance of participating students were measured. The results show associations between natural variations of the IEQ and students' perceptions. These perceptions were associated with their physiological and cognitive responses. Furthermore, students' perceived cognitive responses were associated with their short-term academic performance. These observed associations confirm the construct validity of the composed systematic approach.

This systematic approach was then applied in a **field experiment**, to explore the effect of multiple indoor environmental parameters on students and their short-term academic performance in higher education. A field study, with a between-groups experimental design, was conducted during a regular academic course in 2020-2021 to analyze the effect of different acoustic, lighting, and indoor air quality (IAQ) conditions. First, the reverberation time was manipulated to 0.4 s in the intervention condition (control condition 0.6 s). Second, the horizontal illuminance level was raised from 500 to 750 lx in the intervention condition (control condition 500 lx). These conditions correspond with quality class A (intervention condition) and B (control condition), specified in Dutch IEQ guidelines for school buildings (2015). Third, the IAQ, which was ~1100 ppm carbon dioxide (CO_2), as a proxy for IAQ, was improved to CO_2 concentrations under 800 ppm, meeting quality class A in both conditions. Students' perceptions were measured during seven campaigns with a questionnaire; their actual cognitive and short-term academic performances were evaluated with validated tests and an academic test, composed by the lecturer, as a subject-matter-expert on the taught topic, covered subjects discussed during the lecture. From 201 students 527 responses were collected and analyzed. 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. 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

Finally, a **qualitative case study** explored lecturers' and students' perceptions of the IEQ of classrooms, which are suitable to give tutorials with a maximum capacity of about 30 students. Furthermore, how lecturers and students interact with this indoor environment to maintain an acceptable IEQ was examined. Eleven lecturers of the Hanze University of Applied Sciences (UAS), located in the northern part of the Netherlands, and twenty-four of its students participated in three focus group discussions. The findings show that lecturers and students experience poor thermal, lighting, acoustic, and IAQ conditions which may influence teaching and learning performance. Furthermore, maintaining acceptable thermal and IAQ conditions was difficult for lecturers as opening windows or doors caused noise disturbances. In uncomfortable conditions, lecturers may decide to pause earlier or shorten a lecture. When students experienced discomfort, it may affect their ability to concentrate, their emotional status, and their quality of learning. Acceptable air and thermal conditions in classrooms will mitigate the need to open windows and doors. This allows lecturers to keep doors and windows closed, combining better classroom conditions with neither noise disturbances nor related distractions. Designers and engineers should take these end users' perceptions into account, often monitored by facility management (FM), during the renovation or construction of university buildings to achieve optimal IEQ conditions in higher education classrooms.

The results of these four studies indicate that there is not a one-size fits all indoor environmental quality to facilitate optimal in-class activities. Classrooms' thermal environment should be effectively controlled with the option of a local (manual) intervention. Classrooms' lighting conditions should also be adjustable, both in light color and light intensity. This enables lecturers to adjust the indoor environment to facilitate in-class activities optimally. Lecturers must be informed by the building operator, for example, professionals of the Facility Department, how to change classrooms' IEQ settings. And this may differ per classroom because each building, in which the classroom is located, is operated differently apart from the classroom location in the building, exposure to the environment, and its use. The knowledge that has come available from this study, shows that optimal indoor environmental conditions can positively influence lecturers' and students' comfort, health, emotional balance, and performance. These outcomes have the capacity to contribute to an improved school climate and thus academic achievement.

Samenvatting



In Nederland en daarbuiten is sprake van een toenemende belangstelling voor het creëren van een gezond en effectief binnenmilieu voor docenten en studenten in het hoger onderwijs. Binnen dit onderzoek is bewijs verzameld van interventies die leiden tot verbetering van de leeromgeving in het hoger onderwijs. Het onderzoek had tot doel nieuwe kennis te verwerven voor het creëren van optimale binnenmilieucondities die de activiteiten in de klas, d.w.z. het lesgeven en leren, het beste faciliteren en die de academische prestaties daarmee bevorderen. Met binnenmilieucondities wordt de binnenluchtkwaliteit, de thermische omgeving, het licht en de akoestische condities bedoeld. Met de academische prestatie van docenten en studenten wordt de prestaties op korte termijn, bijvoorbeeld tijdens een college, en de academische prestaties op lange termijn, bijvoorbeeld durende een cursus of een academisch jaar bedoeld.

Het onderzoek is gestart met het uitvoeren van een **systematisch literatuuronderzoek**. Dit onderzoek richtte zich met name op het verzamelen van bewijs met betrekking tot het effect dat het binnenmilieu in klaslokalen voor het hoger onderwijs heeft op de kwaliteit van lesgeven, de kwaliteit van leren en de academische prestaties van studenten. Op basis van de uit de geïncludeerde studies afgeleide meetmethoden is vervolgens ook een **systematische aanpak** ontwikkeld en gevalideerd. Deze aanpak maakt onderzoek mogelijk naar het effect dat alle vier de binnenmilieu parameters in klaslokalen in het hoger onderwijs gelijktijdig hebben op het ervaren comfort, de lichamelijke, emotionele en cognitieve reacties en de academische prestaties van studenten. Vervolgens werd een **veldexperiment** uitgevoerd waarin met behulp van de gevalideerde systematische aanpak mogelijke positieve effecten van meerdere binnenmilieu parameters op studenten en hun academische prestaties zijn onderzocht. Ten slotte werd in een **kwalitatieve casestudy** de perceptie van docenten en studenten onderzocht met betrekking tot het binnenmilieu, hun interactie met deze omgeving en de wijze waarop zij een acceptabele kwaliteit van het binnenmilieu creëren of handhaven.

Tijdens de **systematische literatuurstudie** werden meerdere wetenschappelijke databases doorzocht om relevant wetenschappelijk bewijs te identificeren. Na de screening werden 21 publicaties opgenomen. Deze publicaties toonden aan dat het binnenmilieu positief kan bijdragen aan de academische prestaties van studenten. Echter, het binnenmilieu kan de prestaties van de studenten ook negatief beïnvloeden, zelfs als het binnenmilieu nog voldoet aan de huidige normen voor de binnenmilieu kwaliteit in klaslokalen. Op basis van het verzamelde bewijs kon worden vastgesteld dat er niet één bepaald binnenmilieu optimaal is voor het faciliteren van de verschillende activiteiten. De binnenmilieucondities waarin studenten het beste presteren, verschillen en zijn taakafhankelijk. Dit wijst erop dat in klaslokalen verschillende binnenmilieucondities moeten kunnen worden gecreëerd. Verder leverde het verzamelde bewijsmateriaal praktische informatie op voor het verbeteren van de opzet van experimentele studies, Verder kan het bewijsmateriaal onderzoekers helpen bij het vaststellen van relevante parameters. Tot slot geeft het bewijsmateriaal een overzicht van de verschillende methoden om de invloed van het binnenmilieu op studenten te onderzoeken.

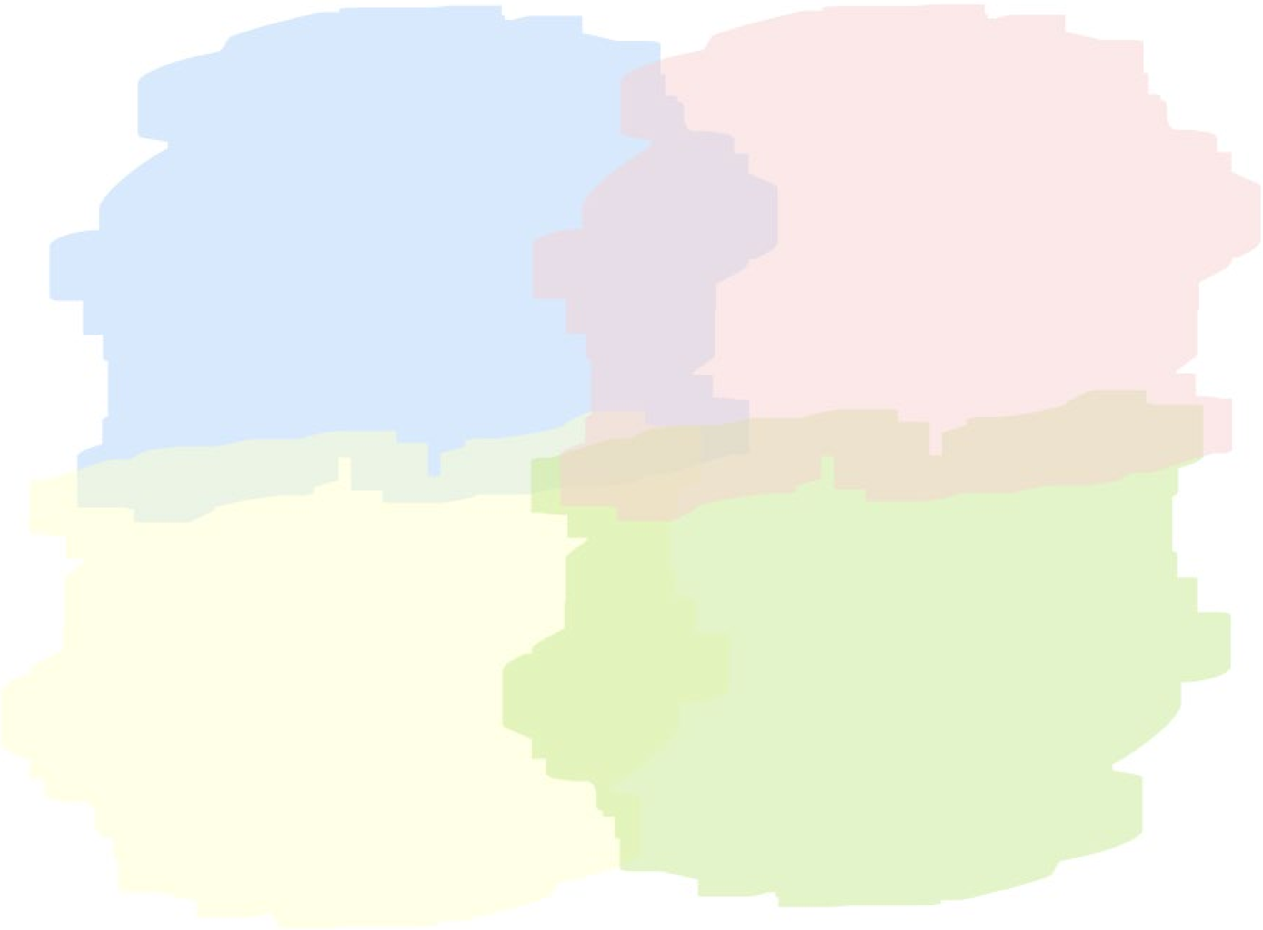
De meetmethoden, welke zijn afgeleid uit het verzamelde wetenschappelijke bewijs tijdens de systematische literatuurstudie, zijn vervolgens gebruikt voor de ontwikkeling van een **systematische aanpak** om de invloed van het binnenmilieu op het ervaren comfort, de fysieke gezondheid, de emotionele balans en de cognitieve en academische prestatie van studenten te meten. Deze aanpak maakt het mogelijk om het effect van alle vier de binnenmilieu parameters tegelijkertijd te bestuderen. Vervolgens is deze aanpak getest in een pilotstudie. Het testen vond plaats tijdens een reguliere academische cursus. Het ervaren binnenmilieu comfort van studenten werd gemeten met een vragenlijst. Ook de interne reacties, waarmee studenten hun ervaren fysieke gezondheid, emotionele balans en cognitieve vermogen wordt bedoeld, werd gemeten met een vragenlijst. Ook is de academische prestatie van studenten gemeten door middel van een test. In deze test kwamen onderwerpen aan de orde die tijdens de les waren behandeld. De resultaten van deze pilotstudie lieten verbanden zien tussen natuurlijke variaties van de binnenmilieu kwaliteit en het door de studenten ervaren binnenmilieu. Het ervaren binnenmilieu hield ook verband met de ervaren gezondheid en het cognitieve vermogen van studenten. Bovendien werd een relatie vastgesteld tussen enerzijds het ervaren cognitieve vermogen van studenten en de score op de academische prestatie test anderzijds. Deze relaties bevestigden de constructvaliditeit van de ontwikkelde systematische aanpak.

Deze systematische aanpak werd vervolgens toegepast in een **veldexperiment** om het effect van meerdere binnenmilieuparameters op studenten en hun academische prestaties in het hoger onderwijs te onderzoeken. Dit experiment had een ‘between-subjects’ design, waarbij de student elke keer slechts één conditie ervaarde en vervolgens de verschillen tussen de gemiddelden van twee groepen studenten kon worden geanalyseerd. Dit experiment is uitgevoerd tijdens een reguliere academische cursus in 2020-2021 om het effect van verschillende akoestische, verlichtings- en binnenluchtcondities te analyseren. Als eerste werd de nagalmtijd in een leslokaal gemanipuleerd tot 0,4 s in de interventieconditie en in de controleconditie tot 0,6 s. Na twee weken werd vervolgens de horizontale verlichtingssterkte verhoogd van 500 tot 750 lx in de interventieconditie en in de controleconditie bleef deze 500 lx. Deze condities komen overeen met kwaliteitsklasse A voor de interventieconditie en met kwaliteitsklasse B voor de controle conditie. Deze kwaliteitsklassen zijn gespecificeerd in Nederlandse richtlijnen voor schoolgebouwen, het programma van eisen “Frisse Scholen” (2015). Tenslotte werd na twee weken ook de binnenluchtkwaliteit verbeterd. Deze binnenluchtkwaliteit was circa 1100 parts per million (ppm) kooldioxide (CO_2). De CO_2-concentratie moet in dit kader worden gezien als een indicator voor de binnenluchtkwaliteit. In beide leslokalen werd deze binnenluchtkwaliteit verbeterd tot een CO_2-concentratie lager dan 800 ppm CO_2, waarmee in beide condities aan kwaliteitsklasse A van het programma van eisen “Frisse Scholen” werd voldaan. Percepties van de studenten werden gedurende deze zeven weken gemeten met een vragenlijst, ontleend aan de systematische aanpak. De feitelijke cognitieve en academische prestaties van de studenten op de korte termijn werden geëvalueerd met verschillende gevalideerde cognitieve testen en een academische test. Deze test behandelde onderwerpen die behandeld waren in de les. Van 201 studenten werden 527 responses verzameld en geanalyseerd. Uit de resultaten bleek dat de verkorting van de nagalmtijd een positieve invloed had op de gepercipieerde cognitieve prestatie van de studenten. Een kortere nagalmtijd in combinatie met verbeterde lichtcondities beïnvloedde ook positief het gepercipieerde lichtcomfort van de studenten. Deze combinatie van factoren werd ook positief geassocieerd met de ervaren gezondheid van de studenten, hun cognitieve vermogen, hun emotionele balans en de kwaliteit van het leren. Deze combinatie van factoren had echter een negatieve invloed op het vermogen van de studenten om problemen op te lossen, terwijl de academische testscore van de studenten niet werd beïnvloed. In de laatste drie weken, toen de luchtkwaliteit in zowel de interventie- als controlecondities was verbeterd, werden deze effecten echter niet waargenomen, terwijl er nog wel een verschil was tussen deze condities met betrekking tot de nagalmtijd en lichtcondities. Onbekend is of de opeenvolgende volgorde van de veranderingen van het binnenmilieu relevant is voor het teweegbrengen van deze effecten en of het verbeteren van twee binnenmilieu aspecten al gunstig is. Toekomstige studies zijn nodig om dit verder te onderzoeken.

Ten slotte werd in een **kwalitatieve casestudy** de percepties van docenten en studenten onderzocht met betrekking tot het binnenmilieu in leslokalen, die geschikt zijn voor het geven van colleges met een maximale capaciteit van ongeveer 30 studenten. Verder is onderzocht hoe docenten en studenten een aanvaardbare kwaliteit van het binnenmilieu realiseren en handhaven in deze leslokalen. Voor deze studie werd een kwalitatieve onderzoeksaanpak toegepast om de ervaringen van docenten en studenten, gerelateerd aan het binnenmilieu in klaslokalen, te verzamelen. Elf docenten van de Hanzehogeschool Groningen werden individueel geïnterviewd en vierentwintig studenten van deze hogeschool namen deel aan drie focusgroep discussies. Op basis van de bevindingen van deze studie kon worden geconcludeerd dat docenten en studenten onacceptabele binnenluchtkwaliteit, thermische, licht en akoestische condities ervaarden, die vervolgens hun vermogen om les te geven en te leren negatief beïnvloedden. Bovendien was het voor docenten moeilijk om een acceptabele omgevingstemperatuur en binnenluchtkwaliteit te handhaven zonder ramen of deuren te openen. Het openen van ramen en deuren leidde vervolgens tot ervaren geluidsoverlast. In oncomfortabele binnenmilieu condities konden docenten besluiten om eerder dan gepland een pauze in te lassen of om de les eerder te laten eindigen. Wanneer studenten oncomfortabele condities ervaarden had dit een negatieve invloed op het concentratievermogen, de emotionele balans en het vermogen om te leren. Uit deze studie kwam ook naar voren dat het belangrijk is om aanvaardbare lucht- en omgevingstemperatuur condities in klaslokalen te realiseren. Dit vermindert de noodzaak om ramen en deuren te openen waardoor geluidsoverlast en daarmee samenhangende afleiding wordt voorkomen. Ontwerpers en ingenieurs kunnen zich laten inspireren door deze percepties van eindgebruikers, welke vaak worden verwoord door facility managers, te integreren tijdens renovatie- of nieuwbouwprojecten, met als doel om betere binnenmilieucondities te realiseren in klaslokalen voor het hoger onderwijs.

De resultaten van deze vier studies geven aan dat er niet één standaard binnenmilieuconditie bestaat om optimaal verschillende activiteiten in leslokalen te faciliteren. De omgevingstemperatuur moet effectief worden geregeld, met daarnaast de mogelijkheid om deze (handmatig) aan te kunnen passen. Ook de verlichting moet kunnen worden aangepast, zowel in lichtkleur als in lichtintensiteit. Dit maakt het mogelijk voor docenten om het binnenmilieu aan te passen op de activiteit in het leslokaal, waarmee deze activiteit optimaal wordt gefaciliteerd. Verder moeten docenten door de beheerder van het gebouw, bijvoorbeeld het Facilitair Bedrijf, worden geïnformeerd over hoe lesactiviteiten optimaal kunnen worden gefaciliteerd en in het lokaal kunnen worden gecreëerd. En dit kan per klaslokaal verschillen omdat tussen gebouw en lokalen verschillen zijn in de wijze waarop het binnenmilieu wordt geconditioneerd. De onderbouwing voor het creëren van verschillende binnenmilieucondities in klaslokalen wordt gegeven door de kennis die beschikbaar is gekomen uit dit onderzoek, wat heeft aangetoond dat optimale binnenmilieucondities een positieve invloed hebben op het comfort, de gezondheid, de emotionele balans en de academische prestaties van de docenten en studenten. Daarmee dragen deze uitkomsten bij aan het creëren van een beter schoolklimaat.

1. General introduction



1.1 Introduction

From a historical perspective, the environmental setting was carefully considered when lecturers and students met. For example, more than 2000 years ago, the school of Epicurus was founded and located in the ancient Greek city Melite. Although the school's garden was located in the suburbs, Epicurus and his fellow philosophers spent their time preferably in the garden to study and discuss philosophy (Wycherley, 1959). Although after the rise of Christianity more and more school buildings were built in big cities, which were attached to churches and monasteries, these cities did not provide a healthy and comfortable climate for the students at all (Zeiler, 2022). From the beginning of the nineteenth century, schools for primary and secondary education had only one classroom with sometimes hundreds of children. The IEQ conditions in these classrooms were poor and children became ill. At that time in America and England "fresh-air-room" schools became popular. In these schools, teaching took place while the windows in the classrooms remained open and without heating of the classroom, even during cold days. Therefore, the indoor air quality remained "fresh" and "clean" (Kingsley & Dresslar, 1917). When designing school buildings in the early 20th century, the benefits of outside conditions were also acknowledged, due to health problems of pupils caused by the then-prevailing tuberculosis. With the introduction of open-air schools, teaching outside was facilitated, like Epicurus did in ancient times. In the Netherlands, open-air schools were built, usually close to the sea or in the forest, where education was provided in the open air as much as possible to promote the health of pupils in primary education (Broekhuizen, 2005). Although these schools were, first, designed for delicate children, around 1950 open-air schools were also built to educate healthy children in rural areas. Outside conditions, in comparison to indoor conditions, improved not only students' health, students' ability to concentrate also improved (Broekhuizen, 2005). An example of how an architect in 1961 integrated outdoor conditions into a school design by building a permanent open-air classroom with a retractable roof is shown in Figure 1-1, which can be found in Leeuwarden, the Netherlands. The retractable roof prevented moving and covering of furniture and thus avoided turmoil while pupils and teachers could benefit from outside conditions (Broekhuizen, 2005).

Figure 1-1 Classroom with a retractable roof. The left picture shows the roof covering the classroom. The right picture shows the roof in the rejected position (Photography: Mark P. Mobach).

To the best of our knowledge, no initiatives were deployed in the Netherlands to facilitate higher education with open-air schools in the Netherlands. However, the importance of the ability to concentrate in relation to student learning performance was at the beginning of the 20th century already characterized by Kingsley and Dresslar (1917, p. 259) as follows: “There is, perhaps, no better index of mental overwork than that furnished by lack of attention and failure of concentration. A teacher who is able to perceive the presence of either of these factors is possessed of the key to both successful teaching and the maintenance of healthful child development.” In 2018, at the start of this study, there were still concerns about the IEQ in schools. Although it was known for more than a decade that the IEQ should be improved (Haverinen-Shaughnessy et al., 2004; Heschong, 2002), major problems were still identified in Europe regarding the IEQ in classrooms, which negatively affected the general well-being and comfort of users (European Commission's Directorates General for Health and Consumers & Joint Research Centre, 2014). In practice, facility managers of schools in higher education reported complaints from staff and students, such as poor air quality, too low or too high indoor temperatures, classroom noise, and light intensity. Furthermore, research in the Netherlands revealed that the IAQ in schools for secondary education was even worse, compared to the IAQ in primary schools (Meijer & Duijm, 2010); and there was no reason to assume that IEQ conditions in classrooms for higher education were better. Kok et al. (2015), for example, revealed that the IEQ of classrooms and buildings of 18 Dutch universities of applied sciences was rated the lowest of all facility aspects.

To improve the IEQ in schools, the Dutch government issued a program of requirements (PoR) “Fresh Schools” (in Dutch “Frisse Scholen”) in 2008 (RVO, 2008), which was updated in 2015 and 2021 (RVO, 2021). These requirements for energy consumption and the IEQ have been formulated on the basis of consensus between the parties concerned and strive for a higher level of ambition than the minimum requirements, as listed in the Dutch national building code (“Building decree”), for school buildings to be built or renovated (BZK, 2012). Many of the contemporary and newly built school buildings, which apply these PoR “Fresh Schools”, are highly insulated and aim for net zero energy consumption. However, there is a danger that the focus on energy reduction leads to less attention towards the IEQ (Zeiler, 2022). Recently, and induced by the COVID-19 pandemic, research revealed again that the IEQ, and more specific the IAQ, in many schools is still insufficient (Ruimte-OK, 2021). The suggestion of a possible reduced attention and undeserved neglect towards the indoor environment is also confirmed in a recent publication, which covers 88 recent Dutch examples of inspirational learning environments for secondary and higher education, but not including the IEQ as one of the characteristics of a meaningful learning and working environment (Schooldomein, 2021). It is therefore relevant to renew attention to the IEQ conditions in schools and more specifically to those of classrooms for higher education.

1.2 Importance of classrooms' environment

We shape our school buildings, and afterwards our school buildings shape us

Inspired by Winston Churchill (1945)

In this study, it is pre-supposed that the environmental setting of classrooms is an important facilitator of the educational process. Ideally, school buildings in general and classrooms in particular should influence the educational process positively by providing a healthy and comfortable built environment, which in return will contribute to a positive school climate (Wang & Degol, 2016).

This study focusses on the indoor environment in higher education classrooms, as part of the schools' built environment. The following four conditions define the indoor environment of classrooms: (1) acoustics conditions, (2) indoor air quality (IAQ) conditions, (3) thermal conditions, and (4) visual conditions (Frontczak & Wargocki, 2011). Optimal indoor environmental quality (IEQ) conditions in school buildings foster students' development and learning (Cohen, J. et al., 2009). However, the opposite is also true; uncomfortable and unhealthy IEQ conditions can affect students' performance (Mendell & Heath, 2005). When students cannot perform to the best of their ability, it can have adverse effects on students and society (Wargocki et al., 2005). Mendell & Heat (2005, p. 1) concluded that: "overall, evidence suggests that poor IEQ in schools is common and adversely influences the performance and attendance of students, primarily through health effects from indoor pollutants".

The built environment of schools refers to the whole range of physical properties of a classroom, where teaching and learning activities take place. It includes the physical characteristics of learning materials or tools (e.g., texture, color, size, shape, weight, and sound), the physical presence of other people, and the physical attributes of the built environment (e.g., volume, density, arrangement, indoor environment) (Choi, H. et al., 2014). The indoor environment, as part of the school's built environment, is accepted as being an independent variable that can positively influence academic outcomes (Choi et al., 2014). This leads to the assumption that this environment can be designed in such a way that it may improve the quality of in-class activities, which in turn may have a positive effect on the quality of learning, teaching, and academic achievement (Choi et al., 2014). Extensive empirical research has revealed a relation between features of school climate, e.g., the indoor environment, and student outcomes across academic, behavioral, and psychosocial domains (Wang & Degol, 2016). This relation between the indoor environment, in-class activities, and academic outcomes can be explained with the framework developed by Donabedian (1988). This framework defines a three-part approach to assess the quality of outcome, i.e., a good structure increases the likelihood of a good process, and a good process increases the likelihood of a good outcome. Figure 1-2 shows this three-part approach to assess the quality of academic outcomes, when the indoor environment is treated as an independent variable of structure and when academic outcomes are related to students' short and long-term academic performance.

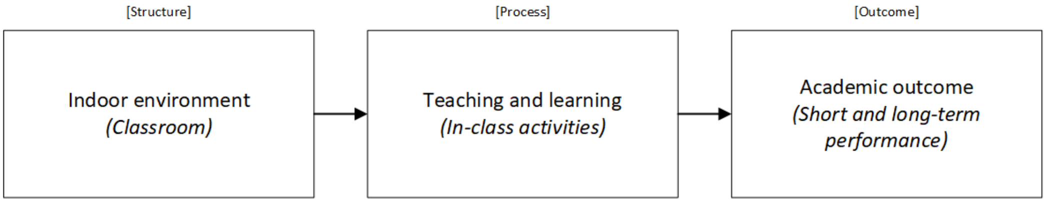


Figure 1-2 Conceptual framework to understand relations between classrooms' indoor environment, teaching and learning, and academic outcome, adapted from Donabedian (1988).

The assumed relations between classrooms' indoor environment, as part of schools' built environment, and classroom users, are elaborated in the next paragraph.

1.3 Relations between classrooms' indoor environment and users

No matter what happens in the world of human beings, it happens in a spatial setting, and the design of that setting has a deep and persisting influence on the people in that setting

Edward T. Hall (1966)

To understand environment-user relationships, Bitner (1992) developed a framework within the context of service organizations, and identified five categories: (1) environmental dimensions, (2) holistic environment, (3) moderators, (4) internal responses, and (5) behavior. When applying these categories to an educational context, the environmental dimensions include all physical properties of the classroom, see paragraph 1.2. Although the dimensions of the built environment are being defined independently, it is important to recognize that they are perceived by lecturers and students as a holistic pattern of interdependent stimuli (Bitner, 1992).

Lecturers and students receive information about the environment in which they teach and learn through their senses (Hall, 1966). Man's sensors are the eyes, ears and nose (distance receptors) and membranes and muscles (immediate receptors). The last human receptor is the skin, both an immediate and a distance receptor because it is the chief organ of touch and it is sensitive to heat gain and loss (Hall, 1966). The environment, as observed by these human sensors, and the way the information of these sensors is processed by the central nervous system and the brain ultimately determine how students and lecturers experience the environment. Each dimension of the built environment may affect the overall perception independently and/or through its interactions with the other dimensions (Bitner, 1992).

User experiences of the environment may differ individually, due to personal, social, and cultural differences (Bitner, 1992; Hall, 1966). The individual experience of the environment will lead to three types of internal responses: cognitive, emotional, and physiological, and are interdependent (Bitner, 1992; Choi et al., 2014). For example, if a student can concentrate well, which is a cognitive response, this can also lead to a positive emotional response, e.g., feeling pleasant; vice versa.

Environmental psychologists suggest that individuals react to places, e.g., classrooms, with two general and opposite forms of behavior: approach and avoidance (Mehrabian & Russell, 1974). Approach behaviors include all positive behaviors that might be directed at a particular place, such as the desire to stay, explore, work, and affiliate differences (Bitner, 1992). Avoidance behaviors reflect the opposite, in other words, a desire not to stay, explore, work, and affiliate. In addition to its effects on their individual behaviors, the classroom environment influences the nature and quality of the interactions between lecturer and student, such as participation, withdrawal and helping (Holahan, 1982). From an academic perspective, approach behaviors of lecturers and students and good interactions between and among them, increase the likelihood of good user outcomes regarding gained knowledge and developed skills (Wang & Degol, 2016). Figure 1-3 shows how classrooms' indoor environment influences student and lecturer internal responses, behavior, and interactions between and among them.

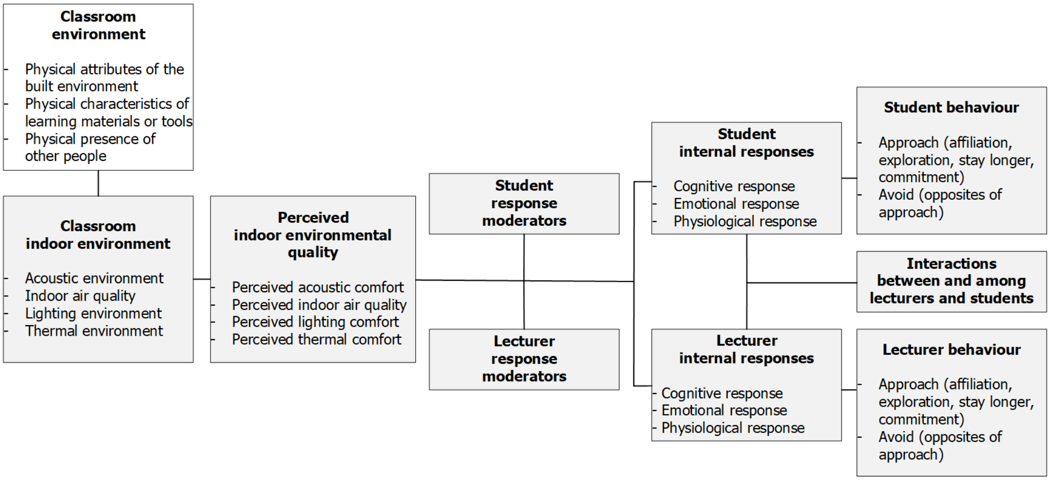


Figure 1-3 Relations between classrooms' indoor environment, as part of classroom environment, student and lecturer responses, behavior, and interactions between and among them, adapted from Bitner (1992).

This study explores the categories, as presented in Figure 1-3, i.e., classroom indoor environment and the perceived IEQ, perception, response, and behavior categories, including the assumed relations between and among them.

1.4 Contribution to science and practice

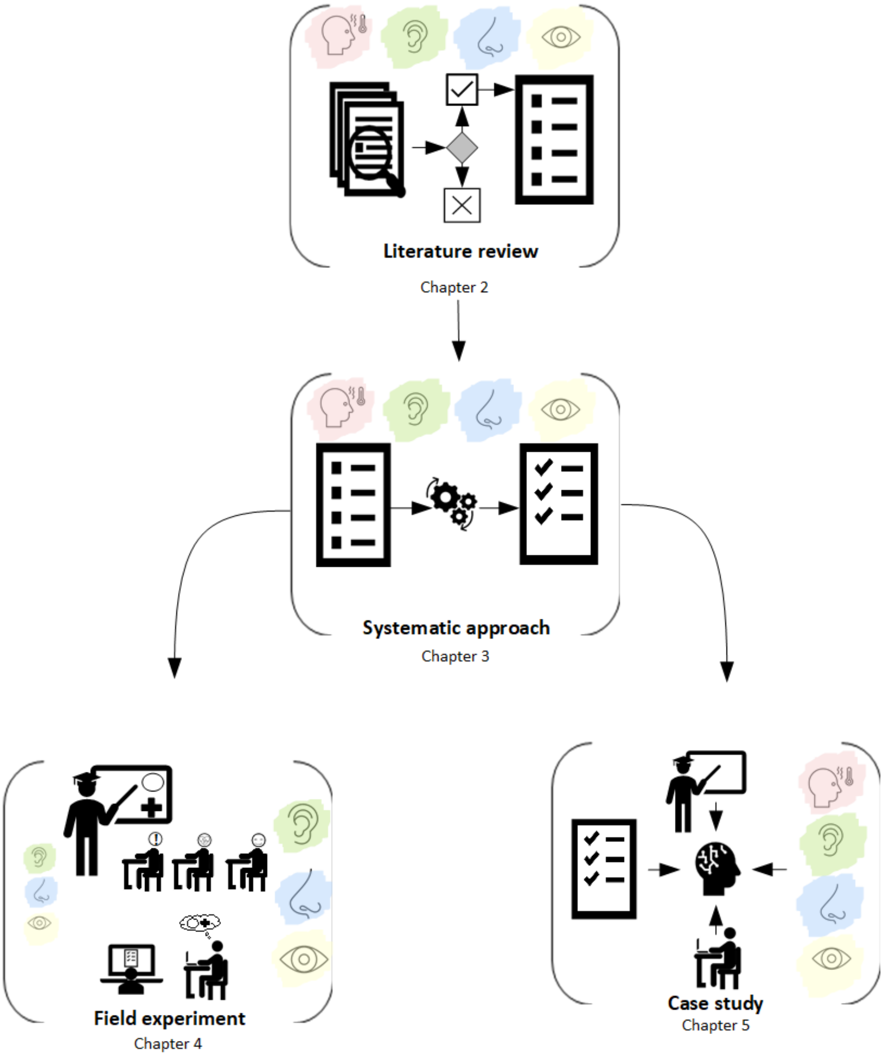
From a scientific perspective, there is a need to understand and quantify the influence of the presented categories in Figure 1-3 on academic achievement. Research over the last decade at schools shows that classroom conditions are far from optimal and in some cases even unhealthy and affect the performance of lecturers and students negatively (Haverinen-Shaughnessy et al., 2004). Although there is sufficient evidence, for example, that thermal conditions and indoor air quality do affect the performance of office work and schoolwork; the evidence is often based on experiments in simulated environments, such as climate chambers (Wargocki & Wyon, 2017). These findings require validation in field intervention experiments in which the performance of real work is monitored quantitatively (Wargocki & Wyon, 2017). Furthermore, research in general does not consider the perception of positive stimuli. Therefore, there is a need for an adapted approach to evaluation of health and comfort of occupants in the indoor environment with real subjects (Bluyssen, 2010).

From a practical perspective, this study provides information about evidence-based improvements for users, interactions between users, and education outcomes. Different IEQ conditions in classrooms are examined and discussed in real-life settings. The examined IEQ conditions are derived from the Dutch program of requirements (PoR) “Fresh Schools” (in Dutch, “Frisse Scholen” (RVO, 2015). The requirements have been formulated on the basis of consensus between the parties concerned and strive for a higher level of ambition than the minimum requirements, as listed in European and Dutch guidelines for school buildings (BZK, 2012). The Dutch Chief Government Architect recommends that every municipality and every school management, when renovating or building a future-proof school, starts from the highest level of ambition, class A, labelled as “excellent”, or at least class B, which is labelled as “good”. The consequence of this recommendation is that school management must make a choice between class A or B requirements for the five listed themes in the PoR. Application of class A requirements will inevitability lead to higher initial building costs; however, what the benefits are for lecturers and students remains unclear. This study aimed to provide information to make a well-considered choice between class A and B requirements. Furthermore, this study provides a thorough and profound understanding of the perceptions of lecturers and students towards classrooms’ actual IEQ conditions and how these conditions influence the perceived quality of teaching and learning. Incorporation of these end-user perceptions in the renovation or construction of school buildings contributes to an improved school climate (Wang & Degol, 2016).

The overall aim of this study is to gain new knowledge about optimal IEQ conditions that best facilitate teaching and learning in higher education, which positively influence the academic achievement of lecturers and students. To provide input, the following four research questions are answered: (1) What is known about how the indoor environment influences students and their academic achievement? (2) How can this influence be measured? (3) How can indoor environmental quality positively contribute to students’ comfort, health and academic achievement? And (4): How do indoor environmental classroom conditions influence teaching and learning in higher education? In total four propositions are examined: (1) the IEQ influences the quality of teaching; (2) the IEQ influences the quality of learning, (3) the IEQ influences the students’ academic achievement, and (4) indoor environmental conditions, meeting quality class A of the Dutch guidelines as compared to class B, have a positive effect on students’ perceptions, responses, and performance. The next paragraph of this chapter presents a brief outline of this thesis.

1.5 Outline of the thesis

This thesis provides information about how the IEQ conditions in higher education classrooms influence students and lecturers in four main sections. **Chapter 2** provides an insight into what is known about the influence of IEQ, based on the information available in scientific literature. Studies that examine the positive or negative effects of the IEQ in classrooms in higher education on the quality of teaching and learning and students' academic achievement were identified, analyzed and summarized. Furthermore, the first, second and third propositions were examined in this study. **Chapter 3** describes the development of a systematic approach, which give guidance to test the second and third propositions in practice. This approach was derived from methods, applied in the identified studies from literature which analyzed the influence of the IEQ on students and lecturers. The presented approach combines existing methods to enable studying the effects of all four IEQ parameters simultaneously on students' perceptions, responses and academic achievement. **Chapter 4** presents a field study that examined the influence of improved acoustic, lighting, and indoor air quality conditions on students' comfort, internal responses, and short-term academic performance. For this study, the developed systematic approach was applied to study the effect of high-quality IEQ conditions, meeting quality class A of the Dutch guidelines, compared to those meeting quality class B of the Dutch guidelines. In addition, the fourth proposition was examined in this chapter. **Chapter 5** provides insight into how lecturers and students perceive IEQ conditions in classrooms. The framework, which was developed during the composition of the systematic approach including all related topics to classrooms' IEQ conditions, was used to identify and analyze the relations between the IEQ conditions and perceived comfort, health and academic achievement. Furthermore, this chapter outlines users' preferences regarding optimal acoustic, indoor air quality, lighting, and thermal conditions in classrooms. Figure 1-4 visualizes the four main sections of this thesis. **Chapter 6** presents the **general discussion** in which the key findings, practical implications, strengths, and limitations of this thesis are discussed and the final conclusions are presented.



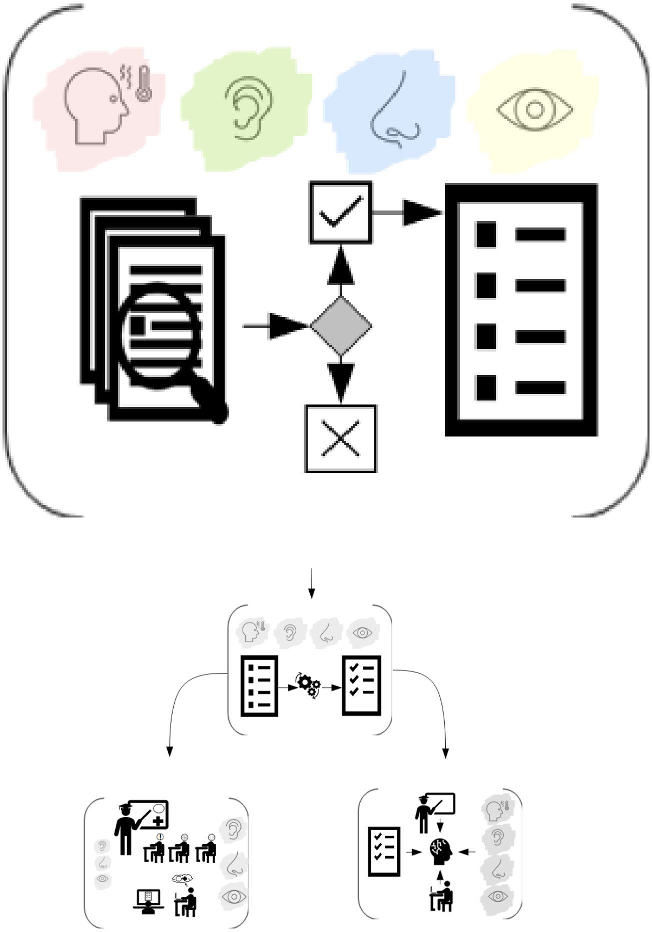
Note:

- The eye which represents the lighting environment
- The ear which represents the acoustic environment
- The nose which represents the indoor air quality
- The skin which represents the thermal environment

- ! visualizes humans' internal cognitive responses
- ♡ visualizes humans' internal physiological responses
- ☺ visualizes humans' internal emotional responses

Figure 1-4 Visualization of the four steps to determine which indoor environmental conditions best facilitate in-class activities and foster academic achievement in classrooms for higher education.

2. Systematic literature review



This subchapter is based on:

Brink, H. W., Loomans, M. G. L. C., Mobach, M. P., & Kort, H. S. M. (2021). Classrooms' indoor environmental conditions affecting the academic achievement of students and teachers in higher education: A systematic literature review. *Indoor Air*, 31(2), 405-425. https://doi.org/10.1111/ina.12745

2.1 Introduction

In schools, students learn to form positive social relationships, gain independence, and develop emotionally, behaviorally, and cognitively (Cohen et al., 2009). The most important role for school management is to provide an optimal school climate that represents virtually every aspect of the school experience. This includes the quality of teaching and learning, school-community relationships, school organization, and the institutional and structural features of the school environment (Wang & Degol, 2016). This is also a challenge in the education at a college or university, hereafter referred to as higher education (Wæraas & Solbakk, 2009). To facilitate the school climate, higher education school management provides buildings, assets, and services for their employees and students. The role of facility management (FM) is to coordinate and maintain these assets and services (NEN-EN-ISO 41011, 2018). By doing so, FM influences a school's ability to act proactively and meet all requirements to create a positive school climate (Wang & Degol, 2016). A positive school climate is associated with students' healthy development and the retention of lecturers, and can even have a predictive value for the academic achievement of students (Cohen et al., 2009).In order to improve the effectiveness of this climate, FM has an active role in creating an optimal learning environment. This requires, among other things, appropriate ventilation, heating and air conditioning, ample forms of lighting, necessary acoustical control, and upkeep of maintenance (Wang & Degol, 2016).

This study focusses on the indoor environment, which is a system of the indoor air quality (IAQ), thermal conditions, acoustic conditions, and lighting conditions (Frontczak & Wargocki, 2011). Many factors may influence the academic achievement of students (Lee, J. & Shute, 2010), but the indoor environmental quality (IEQ) in classrooms can potentially influence teaching and learning positively (Lee & Shute, 2010; Wargocki & Wyon, 2017), which in turn increases the likelihood of a better academic achievement of students, see Figure 2-1 (Wang & Degol, 2016).

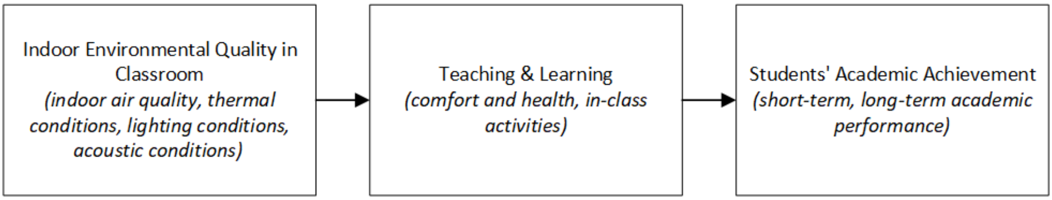


Figure 2-1 Conceptual framework for the influence of indoor environmental conditions on students' academic achievement in schools (Wang & Degol, 2016).

The IEQ addresses the subtle issues that influence how users experience an indoor space, for example, a classroom (Bitner, 1992).The IEQ results from a variety of pollutants or other determinants that can be caused by all four indoor environmental parameters. In this context, occupants' comfort depends on the actual indoor environmental conditions and personal demographic characteristics, such as gender and age (Frontczak & Wargocki, 2011). In addition, it depends on psychobiological processes, such as arousal and stress, and psychological processes, such as perceived control and attention (Veitch, 2001). Moreover, the IEQ to which lecturers and students are exposed, can affect teaching effectiveness and instructional practices (Dawson & Parker, 1998), which in turn can affect students' academic achievement (Wang & Degol, 2016). A study of Kok et al.(2015) showed, for example, a statistically significant positive relationship between lecturers' perceptions of classrooms' lighting and acoustic conditions and study success. Also, the IEQ can influence users' task performance, communication and social interaction, mood, and health and safety at school (Fisk et al., 2019; Frontczak & Wargocki, 2011; Wang & Degol, 2016). This influence has often been examined by analyzing the effect of one parameter (Frontczak & Wargocki, 2011). In 2016, Wargocki and Wyon analyzed the combined effect of thermal comfort and IAQ on humans' short-term cognitive performance (Wargocki & Wyon, 2017). These researchers identified the following human mechanisms which are affected by both thermal and IAQ conditions: distraction and attention, motivation, arousal, neurobehavioral symptoms, and acute health symptoms. Moreover, lighting conditions, for example, can affect mental alertness and cognitive performance (Chellappa et al., 2011); and annoyance and distraction can be caused by poor acoustic conditions (Maxwell, 2009). Furthermore, a poor IEQ can cause adverse health outcomes, which can cause sick leave and impaired academic achievement (Mendell & Heath, 2005). Students' academic achievement also depends on how lecturers use all resources to improve in-class activities (Wang & Degol, 2016). Finally, it depends on the students' ability to concentrate and think clearly, as these aspects together influence the in-class academic performance of students (Wargocki & Wyon, 2017). Therefore, to assess both the individual and the combined influences of all four indoor environmental parameters on the quality of teaching and learning and students' academic achievement is a worthwhile exercise.

At this moment, there are no specific guidelines available for higher education school buildings. The focus of earlier research, for example addressing the IAQ, was mainly on pupils in primary and secondary education (Fisk, 2017). Based on the outcome of this research, specific IEQ guidelines for pupils of primary and secondary schools were developed (RVO, 2008). However, facilitating young adults (aged 18-25 years) and lecturers (aged 25-65 years) in higher education might require a different IEQ in which they can perform optimally. In order to support initiatives, which aim to develop specific IEQ guidelines for higher education school buildings, this review aims to provide an overview of how classroom indoor environmental conditions influence the quality of teaching and learning and students' academic achievement in higher education.

The following research question is explored in this review: What is the effect of IEQ in classrooms in higher education on the quality of teaching and learning, and students' academic achievement? In addition, three propositions will be examined: (a) the IEQ influences the quality of teaching; (b) the IEQ influences the quality of learning, and (c) the IEQ influences the students' academic achievement. In addition, in the context of this study, the quality of teaching and learning is operationalized by how lecturers and students perceive teaching quality, learning quality, and their physical and mental health. Students' academic achievement refers to their short-term and long-term academic performance.[2] Short-term academic performance is often quantified with cognitive performance tests or with the use of school exercises (Wargocki et al., 2002; Wargocki & Wyon, 2017) Long-term academic performance focusses on the performance of students for a course or academic year (Gaihre et al., 2014; Pawlowska et al., 2014).

2.2 Methodology

We applied the Cochrane Collaboration Method to identify relevant literature for review (Alderson et al., 2004). We included laboratory experiments and field experiments; results obtained in both settings can reveal how the IEQ influences the quality of teaching and learning and students' academic achievement. Included were studies that addressed students and lecturers in higher education with no physical disabilities (e.g., diseases, blindness, and under sedation) or mental disabilities (e.g., auditory processing disorder, attention disorders, and dyslexia) and that are written in English. In addition, we included studies that addressed the physical environmental conditions in combination with physiological conditions (e.g., attention, comfort, discomfort, illness, stress, and vitality), affective responses (e.g., perceived mood and emotions), or the influence on teaching, learning, or academic achievement. We did not apply any restrictions with regard to the publication year and searched relevant databases until the 20th of May 2020. We identified potentially relevant literature through computerized searches in the following databases: Web of Science, Scopus, Emerald Insight, Wiley Online Library, Sage, PubMed, and 27 EBSCOhost databases (i.e., Academic Search Premier, ERIC, APA PsycINFO, Teacher Reference Center), which were searched simultaneously. For the search, we used keywords that are related to classrooms in higher education, IEQ, teaching, learning, and students' academic achievement. Appendix 1 presents an overview of the used keywords during the search. The used search strings can be found in Appendix 2.

The search through the selected databases yielded 2501 publications, which were imported in RefWorks. After removing duplicates (n = 608), we analyzed the relevance of the selected publications. When the title, keywords, or abstract did not give any indication that indoor environmental conditions were studied, the publication was excluded (n = 1512). These publications emerged in the primary search because one or more keywords were used in a different context. For instance, a study used the word "light" or "noisy" as an adjective, or the word "illuminate" was used as a synonym for "illustrate" or "embellish." We also excluded publications that addressed only the physical indoor environmental conditions, or other types of building performance (e.g., energy consumption and sustainability) without analyzing the effect on teaching, learning, or academic achievement (n = 135). Finally, we excluded publications that addressed humans with physical or mental disabilities (n = 44), and publications that did not address classrooms in higher education (n = 131). All publications not written in English were excluded (n = 8). In total, 63 publications were included after this selection stage.

As a final selection stage, the relevance and quality of the 63 remaining publications were determined. To assess the relevance of the included publications, the context and scope of the study were assessed. The context of the study was high when the influence of multiple indoor environmental conditions on the quality of teaching, learning, or academic achievement was analyzed. In addition, the scope of the study was high if the study analyzed indoor environmental conditions and assessed the impact of these conditions on the performance of lecturers or students. Moreover, the reliability and the methodological quality of the study were analyzed to assess the quality of the study. The reliability of the study was high when it was published in a peer-reviewed journal and provided detailed information about the sample (e.g., sample size, gender, age, and standard deviation). The methodological quality was high when the methodological section in the study described in detail how the research was conducted and when the applied tests or questionnaires were available. In addition, this quality was high when the study provided detailed information about the accuracy of used measuring equipment and how the measurements were performed in the classroom (e.g., position, number of measurements, and measuring height). Finally, the methodological relevance was high when three or more key performance indicators of the targeted four indoor environmental parameters were measured, because these studies may reveal, in particular, the combined influence of the indoor environment.

Independently, the authors scored publications, compared the individual scores, and adjusted the rubrics of the assessment tool. Appendix 3 presents the authors' final version of the assessment procedure, which was used for scoring the relevance and quality of all publications. The context, scope, reliability, and methodological quality scores were expressed in a percentage of the maximum score (100 percent). Studies with a relevance and quality (RQ) score lower than 60 percent were excluded (n = 44). Through hand-searching, using the title of the study in Google Scholar, two additional studies have been identified. These studies addressed the same research as the, through the systematic search, identified publication; however, they contain additional and relevant information. The first study added is the doctoral thesis of and complements the study of Ahmed et al.(2017). The second study is of Mishra et al.(2017) and complements the study of Kooi et al.(2017). Figure 2-2 summarizes all different selection stages during the screening process, which eventually led to the identification of the 21 included studies. If an included study examined students' and lecturers' comfort and health, this is linked to the quality of teaching or learning. Examined students' cognitive performance, for example, attention or concentration tests, and students' score on school tests, for example, calculation and reading tests, was classified as short-term academic performance. Students' grades of a course or academic year were classified as long-term academic performance. Reported statistical significant effects of different IEQ conditions on students' academic achievement were quantified by calculating the increase or loss of the reported performance, based on the scores presented.

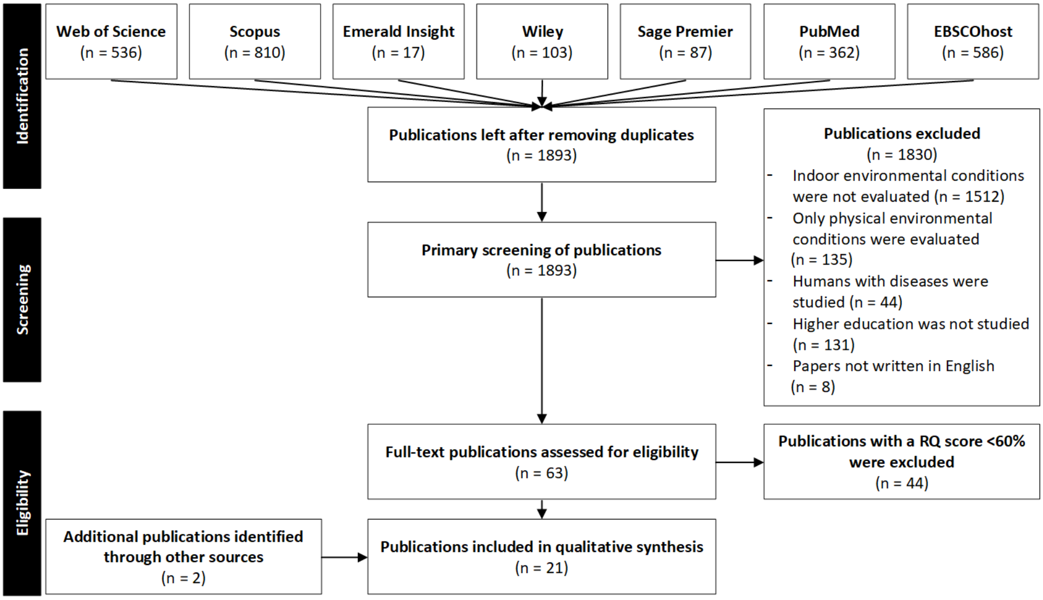


Figure 2-2 Flowchart of the screening process of the literature.

2.3 Results

Figure 2-3 shows the development in time of the distribution of the 63 identified studies, before the final selection stage and the distribution with respect to the studied indoor environmental parameters. The number of identified publications in relation to the year of publication indicates a growing interest in the influence of the IEQ on learning and academic achievement. Three studies addressed all four environmental parameters on the quality of teaching, learning, or academic achievement. The results of this review were derived from 19 identified and two additional studies of high quality and relevance with a RQ-score of 60 % of higher.

Table 2-1 and Table 2-2 describe key features of the 21 included studies. We derived the table layout of Table 2-1 from the way Mendell and Heath (2005) and presented their results. Table 2-1 presents the direct associations between indoor environmental conditions and students' academic performance. Table 2-2 presents direct associations between actual or perceived indoor environmental conditions and perceived academic performance, physical health, or comfort.

The results are presented on the basis of the RQ-score, beginning with the study with the highest score, and include the main findings of the influence of the IEQ on lecturers' and students' health and comfort and students' academic performance. Appendix 4 provides additional details on these studies, including information about the age of participants, measured indoor environmental performance indicators, and studied outcomes.

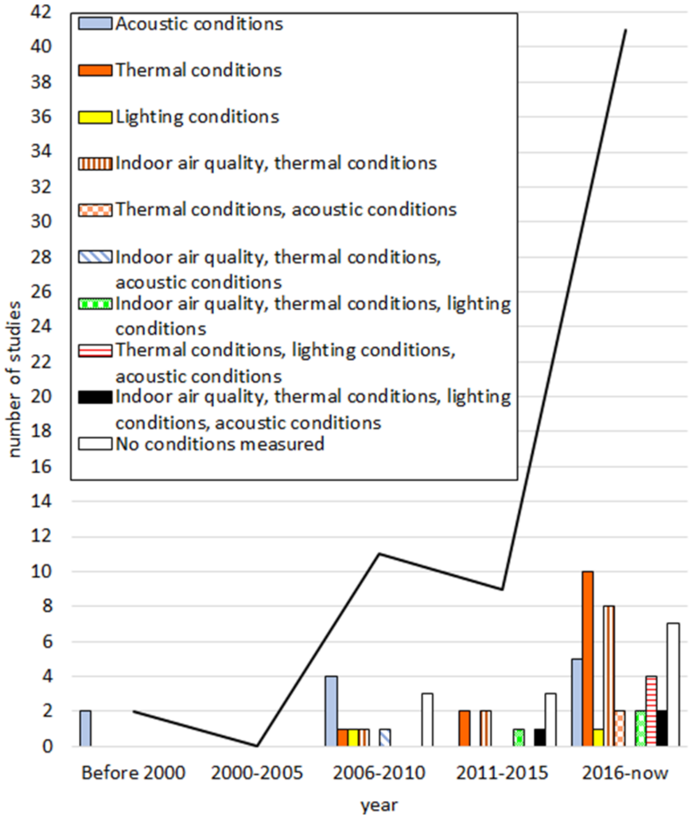


Figure 2-3 The number of studies addressing the IEQ in classrooms in higher education, the distribution over the indoor environmental parameters, and the distribution over the years.

Table 2-1 Findings from research on direct associations between indoor environmental conditions and students' academic performance. See footnote to table for the explanation of all variables and symbols used.

	Study features							Effect of indoor environmental parameter								Reference
								TC		IAQ		AC		LC		
Outcome	Geographic location	Setting	Subject	N	Design	Key	RQ	High	Low	High quality	Low quality	High quality	Low quality	High quality	Low quality	Author
Accuracy in complex, and vigilance tasks	Saudi Arabia, (Jeddah)	cc	♀ S	499	C	@	92	↓			↓					Ahmed et al. (2017)
Accuracy in memory tasks								↓	↑		↓					

Table 2-1 continued.

	Study features							Effect of indoor environmental parameter								Reference
								TC		IAQ		AC		LC		
Outcome	Geographic location	Setting	Subject	N	Design	Key	RQ	High	Low	High quality	Low quality	High quality	Low quality	High quality	Low quality	Author
Concentrated and distributive attention test	Romania (Timisoara)	cc	♀♂ S	18	qE	@	85	↓	↑		↓					Sarbu and Pacurar (2015)
Distributive attention test								↓	↑		↓					
Number of hits in performance test	Brazil	cc	♀♂ S	84	qE	@	85	↕								Siqueira et al. (2017)
Time spent on performance test								🟩 ↑								
Perception test	China	cc	♀♂ S	10	qE	@	85	🟥 ↓	🟥 ↓				🟥 ↓	🟩 ↑		Xiong et al. (2018)
Memory test								🟩 ↑					🟥 ↓			
Problem-solving test								🟥 ↓	🟥 ↓				🟥 ↓	🟩 ↑		
Attention-oriented test									🟩 ↑				🟥 ↓	🟩 ↑		
Recognition rate	China	I	♀♂ S	8	qE	@	85							↓		Yan et al. (2012)
Short-term memory and verbal ability test	Italy (Lombardia)	cc	♀♂ S	20	qE	@	81	🟥 ↓								Barbic et al. (2019)
Reasoning test								↕								
Knowledge test (exam score)	USA (Amherst)	c	♀♂ S	409	C	@	79	🟥 ↓	🟥 ↓							Hoque et al. (2016)
Perception test	Saudi Arabia (Riyadh)	I	S	40	qE	@	79	🟥 ↓	🟥 ↓							Almaqra et al. (2019)
Lexical decision test	USA	cc	♀♂ S	158	E		69						🟥 ↓			Shelton et al. (2009)
Knowledge test													🟥 ↓			
Knowledge test	USA	cc	♀♂ S	71	E		66						↓			End et al. (2010)

Table 2-1 continued.

	Study features							Effect of indoor environmental parameter								Reference
								TC		IAQ		AC		LC		
Outcome	Geographic location	Setting	Subject	N	Design	Key	RQ	High	Low	High quality	Low quality	High quality	Low quality	High quality	Low quality	Author
Attention test	Colombia (Bogotá)	cc	♀♂ S	141	qE		60						🟥↓			Castro-Martínez et al. (2016)

Note: Geographic location: country (place or region if reported).
Setting: c = classroom; cc = controlled classroom; l = laboratory or climate chamber.
Subject: ♀ = female participants; ♂ = male participants; S = students; T = lecturers.
Design: E = experiment, qE = quasi-experiment, C = cohort.
RQ: relevance and quality score in %.
Key confounders: @ = key confounders are controlled.
Effect of indoor environmental parameter: ↓ = negative effect; ↑ = positive effect; ↕ = no effect; red marking = negative effect ($p \leq 0.05$); green marking = positive effect ($p \leq 0.05$); no marking = no statistical significant effect ($p > 0.05$ or not reported).
Correlation: + = positive correlation; - = negative correlation green signifies included and measured; $^{*} = p \leq 0.05$; $^{**} = p \leq 0.01$; $^{***} = p \leq 0.001$; $^{\circ} = p > 0.05$; ^{x} = not reported or no correlation.

Table 2-2 Findings from research on direct associations between actual or perceived indoor environmental conditions and perceived academic performance, physical health or comfort. See footnote to Table 1 for the explanation of all variables and symbols used.

	Study Features							Association		Reference
Outcomes	Geographic location	Setting	Subject	N	Design	Key confounders	RQ-score in %	Effect	Correlation	Author
Accuracy in cognitive performance tasks	Saudi Arabia, (Jeddah)	cc	♀ S	499	C	@	92	Thermal sensation slightly warm, cool and slightly cool have a positive effect on the outcome compared to thermal neutral sensation	$+^{***}$	Ahmed et al. (2017)
								Thermal sensation cold and thermal discomfort that attributes to inability to focus and numbness in fingers have a negative effect on the outcome compared to thermal neutral sensation	$-^{***}$	
								Reported symptoms of headache, dizziness, heaviness on head, confusion, difficulty thinking, difficulty concentrating and fatigue have a negative effect on the outcome compared to no reported symptoms	$-^{***}$	

Table 2-2 continued.

	Study Features							Association		Reference
Outcomes	Geographic location	Setting	Subject	N	Design	Key confounders	RQ-score in %	Effect	Correlation	Author
Heart rate	Brazil	cc	♀♂ S	84	qE	@	85	An air temperature of 27.95°C (globe temperature 25.50°C) increases the heart rate compared to an air temperature of 22.60°C (globe temperature 23.11°C)	+*	Siqueira et al. (2017)
Error rate and cognitive performance								Thermal discomfort has a negative effect on the outcome compared to a thermal neutral sensation	-*	
Blood pressure								Thermal discomfort has a negative effect on the outcome compared to a thermal neutral sensation	-*	
Saliva cortisol concentration	Sweden (Helsingborg)	cc	♀♂ S	72	qE	@	83	The effect of a LED lighting system compared to a T5 lighting system on saliva cortisol concentration	+*/ x	Gentile et al. (2018)
Perceived mood and light perception								The effect of a LED lighting system compared to a T5 lighting system on perceived strength and quality of lighting conditions	+***	
Heart rate	Italy (Lombardia)	cc	♀♂ S	20	qE	@	81	Thermal discomfort has a negative effect on the outcome compared to a thermal neutral sensation	-***	Barbic et al. (2019)

Table 2-2 continued.

	Study Features							Association		Reference
Outcomes	Geographic location	Setting	Subject	N	Design	Key confounders	RQ-score in %	Effect	Correlation	Author
Melatonin concentration in blood and subjective perception of sleepiness	Republic of Korea (Daejeon)	cc	♀♂ S	15	qE	@	79	The effect of exposure to blue-enriched white light with a color temperature of 6,500 K at an illuminance level of 500 lx causes a decline of the outcome compared to exposure to warm white light with a color temperature of 3,500 K at an illuminance level of 500 lx	-*	Choi et al. (2019)
Perceived alertness, mood, and visual comfort								The effect of exposure to blue-enriched white light with a color temperature of 6,500 K at an illuminance level of 500 lx has a positive effect on the outcome compared to exposure to warm white light with a color temperature of 3,500 K at an illuminance level of 500 lx	+*	
Cortisol concentration in blood								No effect was observed on the outcome if participants were exposed to blue-enriched white light with a color temperature of 6,500 K at an illuminance level of 500 lx compared to when they were exposed to warm white light with a color temperature of 3,500 K at an illuminance level of 500 lx	-	
Actual thermal sensation	The Netherlands (Eindhoven)	c	♀♂ S	384	C	@	71	Even when thermal conditions during class did not change much, thermal perception was different at class entry compared to thermal perception after the first 45 min	*	Mishra et al. (2017)

Table 2-2 continued.

	Study Features							Association		Reference
Outcomes	Geographic location	Setting	Subject	N	Design	Key confounders	RQ-score in %	Effect	Correlation	Author
Perceived IAQ	Sweden (Lund)	cc	♀♂ S	232	qE	@	70	A carbon dioxide demand-controlled variable air flow ventilation system has a positive effect on the outcome compared to a ventilation system with a constant air flow	$+^{*}$	Norbäck et al. (2013)
Self-reported headache and tiredness									$+^{**}$	
Satisfaction with IAQ	China (Xi'an)	c	♀♂ S	992	C		66	There was no relation observed between actual CO_2 concentration and perceived IAQ	^{x}	Liu et al. (2008)
Actual thermal sensation								A relationship was observed between actual thermal sensation and perceived IAQ	$+^{*}$	
Fundamental frequency, vocal intensity, percentage of phonation, cycle dose	Brazil (Belo Horizonte)	cc	♀ T	27	qE		65	Noisy conditions of 76.0 dB have a negative influence on the outcomes compared to more quiet conditions at 43.92 dB	$-^{***}$	Rabelo et al. (2019)
Self-reported academic performance	China (Hong Kong)	cc	♀♂ S	312	C		62	Increasing numbers of complains about the IEQ have a negative effect on the self-reported academic performance	$-^{*}$	Lee et al. (2012)

Note: See footnote to Table 2-1 for the explanation of all variables and symbols used.

Ahmed et al. (2017) studied the individual and combined effect of different air temperatures, carbon dioxide concentrations (CO_2), and perceived thermal sensation on the cognitive performance of 499 female students in Saudi Arabia. Participants were exposed to different indoor environmental conditions in two identical university classrooms. This exposure revealed that air temperature affects the accuracy of tasks differently according to the type of task while cognitive performance in all tasks improved significantly ($p < 0.001$) when CO_2 levels decreased from 1800 to 600 ppm and from 1000 to 600 ppm. Although students' accuracy in complex and vigilance tasks was the highest at an air temperature of 20°, the highest accuracy for memory tasks was observed at an air temperature of 23°C, compared to 20 and 25°C ($p < 0.001$).

Sarbu and Pacurar (2015) analyzed students' concentrated and distributive attention test scores in relation to air temperature, relative humidity, and CO_2 concentration. Students' cognitive performance peaked at temperatures between 24 and 26°C, a relative humidity of approximately 60 %, and a CO_2 level of approximately 500 ppm. Although the sample size of this experiment was relatively small ($n = 18$), the researchers report correlations between the observed indoor environmental parameters and students' cognitive performance.

Siqueira et al. (2017) tested the cognitive performance of 84 students by means of five different tests in a computer classroom. In addition, the impact on students' health was analyzed by measuring their heart rate. An average score was calculated for the number of hits and the time required. The results showed that the number of hits was similarly distributed over the 3 days of testing and an average air temperature of 22.60°C (Day 1), 23.24°C (Day 2), and 27.95°C (Day 3). The total time spent decreased significantly ($p < 0.05$) over the experimental period. The researchers reported that this effect could have been caused by the students wanting to leave the uncomfortable warm environment more quickly. The thermal conditions of the environment are factors that may affect cardiovascular parameters. The heart rate of the students increased with 8% ($p < 0.05$) at the end of the cognitive activity at Day 3 compared to Day 1 and with 7% ($p < 0.05$) compared to Day 2. An air temperature of 23.3°C was associated with thermal neutral sensation.

Xiong et al.(2018) explored the impact of three indoor environmental parameters, that is, thermal, acoustic, and visual conditions, on learning efficiency in an environment-controlled university classroom. Five female and five male students were exposed to three different air temperatures, three different desk illuminance levels, and three different noise levels. Students' cognitive performance was measured for each condition with four different cognitive function tests. For the perception-oriented task, students scored highest at a temperature of 22°C, an illuminance level of 2200 lx, and a background noise level of 50 dB(A). The scores of a memory-oriented task were the highest at 27°C, 300 lx, and 50 dB(A). At 22°C, 300 lx, and 40 dB(A) students scored the highest for a problem-solving task. The final task, the attention-solving task, was performed the best at 17°C, 2200 lx, and 40 dB(A). The memory-oriented task was the only experiment in which students' cognitive performance was affected by all three indoor environmental parameters ($p < 0.05$). Analyses of the results showed that cognitive performance can decline with as much as 52 %, when conditions were the worst. Table 3 presents an overview of the quantified combined effect, of an intervention IEQ condition compared with the optimal IEQ condition, on cognitive performance tasks.

Yan et al. (2012) used students' recognition rate, as an indicator for cognitive performance, to determine possible differences between different fluorescent lighting (color temperatures of 2700, 4000, and 6500K) with the same color rendering index (≥80) and luminous values, which were kept constant between 4050 lumen and 4450 lumen. Although the experiment was not conducted in a classroom and with a relative small sample size ($n = 8$), the results indicated that of the three color temperature lamps used, the fluorescent lamp of 4000K was the most suitable classroom light source. The best color temperature combination was 4000K for classroom light, matched to 2700K for chalkboard light and compared with the worst combination the average recognition rate was 23 % higher.

Table 2-3 Overview of combined effects of two or more indoor environmental parameters on cognitive performance. See footnote to Table for the explanation of all variables and symbols used.

	Optimal IEQ condition				Intervention IEQ condition					Reference
Task	IAQ [ppm CO2]	TC [°C]	LC [lx]	AC [dB(A)]	IAQ [ppm CO2]	TC [°C]	LC [lx]	AC [dB(A)]	Effect [%]	Author
Average score cognitive performance tasks	600	20			1000	23			12	Ahmed et al. (2017)
Average score cognitive performance tasks	600	20			1800	25			23	
Memory-oriented task		27	300	50		22	60	70	47	Xiong et al. (2018)
Perception-oriented task		22	2200	50		27	2200	40	32	
Problem-solving-oriented task		22	300	40		22	60	70	42	

Note: Condition: IAQ = indoor air quality; TC = thermal conditions; LC = lighting conditions; AC = acoustic conditions. Effect: red marking: negative effect ($p < 0.05$).

Gentile et al. (2018) compared a direct/indirect T5 lighting system to a new completely indirect LED lighting system, which was installed in four identical school classrooms. Besides the electricity consumption, saliva cortisol concentration, as an indicator of students' health, and mood and light perception, as indicators for students' comfort, of 83 students were analyzed. The perceived strength of lighting of the experimental LED lighting conditions was significantly higher ($p < 0.001$) than that of the control lighting conditions, although the maintained horizontal illuminance level was the same in both lighting conditions. Furthermore, no general effects on the level of the stress hormones, that is, cortisol, were observed over the whole observation period. However, during the dark months, the experimental LED system better-supported students' stress hormones suppression ($p < 0.05$), but it was not clear whether this effect was caused by the different light source, the light distribution, or a combination of both.

Barbic et al. (2019) analyzed the impact of thermal conditions on students' health, comfort, and cognitive performance. Twenty students underwent a continuous single-lead electrocardiogram recording during a two-hour lecture, on two different days with different classroom temperatures, respectively, 22.4 and 26.2°C. On the second day, most students experienced thermal discomfort, the difference between Day 1 and Day 2 was significant ($p < 0.0001$). This difference in thermal discomfort on Day 2 led to a decline of cognitive functions short-term memory (−12 %, $p = 0.007$) and verbal ability (−24 %, $p < 0.001$). There was no decline of the cognitive function reasoning, on the contrary, there was an improvement of 1 %, but this effect was not significant ($p = 0.92$). The researchers did not report any health risks, caused by the experienced thermal discomfort on Day 2. However, this discomfort on Day 2 was associated with a higher cardiac sympathetic modulation, as indicated by higher values of heart rate (+10 %, $p < 0.001$), which may have adversely influenced the cognitive performance of the students.

Choi et al. (2019) analyzed the impact of different lighting conditions on students' health, by analyzing students' melatonin concentration in blood and their perceived health, by analyzing their mood and sleepiness. In addition, students' perceived visual comfort and cognitive performance, by analyzing their perceived alertness, were collected of 15 students, who participated in this research. The researchers found that blue-enriched LED light exposure might be an effective potential countermeasure for morning drowsiness and dozing off in class, particularly in schools with insufficient daylight. The researchers reported correlations between blue-enriched LED light exposure and melatonin concentration in blood, subjective perception of sleepiness, perceived alertness, mood, and visual comfort ($p < 0.05$). From an educational standpoint, however, warm white light has been reported to provide a relaxing environment and support communication. Therefore, the application of blue-enriched white light requires careful consideration and the authors' advice is to incorporate this light appropriately according to learning activities or to apply an auto-dimming feature in which the warm white light gradually changes to blue-enriched white light after its prolonged use during the morning.

Hoque and Weil (2016) examined the thermal environment, thermal comfort, and test scores of 409 students. The aim of this study was to quantify the relationship between the air temperature, humidity, air speed, and perceived comfort and students' test score, as an indicator of their short-term academic performance. The researchers found that students who felt thermal discomfort performed worse on tests than those with no thermal discomfort ($p < 0.001$). Table 2-4 presents a summary of the effect of thermal sensation on different tasks and academic test scores.

Table 2-4 Effect of thermal sensation on different tasks and academic test scores. See footnote to the table for the explanation of symbols used.

	Thermal sensation							Reference
Task	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	Author
Accuracy on vigilance tasks	🟥 10 %	🟩 1.5 %	🟩 2 %	^{1}	🟥 7 %	🟥 12 %	🟥 16 %	Ahmed et al. (2017)
Memory-oriented tasks/learning tasks	🟥 11 %	🟩 1 %	🟩 2 %	^{1}	🟩 0.5 %	🟥 14 %	🟥 22 %	
Academic test scores	🟥 16 %	🟥 9 %	🟥		🟥 9 %	🟥	🟥 16 %	Hoque et al. (2016)

Note: ^{1} = reference score; red marking = negative effect ($p < 0.001$); green marking = positive effect ($p < 0.001$).

Almaqra et al. (2019) analyzed thermal conditions and caffeine intake on students' cognitive performance, by analyzing students' score on a Stroop test, which is a perception-orientated test. The researchers concluded that an increase of caffeine intake did not significantly improve the cognitive performance of the 40 students, who participated in this study. However, the relationship between air temperature and performance appeared to be nonlinear. Students' cognitive performance peaked at 23°C and declined with 48 % at a higher temperature of 30°C, and with 29 % at a lower temperature of 16°C ($p < 0.001$).

Bajc et al. (2018) measured the short-term academic performance of 240 students and related this performance to their perceived thermal comfort. To determine possible performance loss, students had to perform a listening exercise. The results indicated that personal feelings regarding thermal comfort in buildings are strongly subjective. In addition, the results indicated that performance and performance loss are not just a function of the predicted mean vote (PMV) index, and no simple relation in real conditions can link productivity loss of students with the PMV index alone.

Mishra et al. (2017) and Kooi et al. (2017) studied the effect of temporal transitions on the perceived thermal comfort of 384 students. They observed that students' thermal perceptions changed significantly ($p < 0.05$) as the class progressed. In addition, they observed gender differences in thermal sensation. After the transition period of about 20 min, the correlation between operative temperature and thermal sensation receded and individual thermal preferences evened out.

Norbäck et al. (2013) examined the effect of two different ventilation systems on the perceived comfort and physical health of 232 students. Statistically significant differences, in favour of the variable flow conditions, were observed for immediate perception of air quality ($p = 0.02$), headache ($p = 0.003$), and tiredness ($p = 0.007$) and concluded that the critical level of CO_2 in classrooms is 800 ppm and the critical operational indoor temperature is 22°C.

Shelton et al. (2009) and End et al. (2010) investigated the effect of a disturbing noise from within a classroom on students' short-term academic performance with a knowledge test, covering topics presented in the lecture. The results revealed a significant ($p < 0.05$) decline of as much as 37 % of students' performance.

Liu et al. (2019) examined students' comfort in naturally ventilated university classrooms, in the north-west of China. A total of 992 responses were collected during days when the mean outdoor air temperature was about 10°C. The results showed that the thermal neutral temperature was 20.6°C and revealed that only thermal sensation has a significant correlation ($p < 0.05$) with air quality perception.

Rabelo et al. (2019) analyzed the impact of noisy classroom conditions on the voice of 27 lecturers. Observed was that an increase in background noise of 32 dB causes an increase of the fundamental frequency of lecturers' voice of 12 % ($p < 0.001$), an increase of vocal intensity of 8 % ($p <0.001$), an increase of the percentage of phonation of 16 % ($p < 0.001$), and an increase of the number of vibration cycles of 31 % ($p < 0.001$). These results indicate that an increase of background noise increases vocal health risks of lecturers.

Lee et al. (2012) investigated the relationship between the actual IEQ in university teaching rooms, the perceived indoor environmental comfort, and the perceived short-term academic performance of 321 students. Correlations were found between the self-reported academic performance and the number of IEQ complaints of students ($p < 0.05$). Compared to the contribution of the thermal and lighting conditions and IAQ, which contribute similar to the overall perceived IEQ, the acoustic conditions were found to be a relatively sensitive contributor to the overall indoor environmental satisfaction with an almost twice as high coefficient value ($p < 0.0001$).

Castro-Martínez et al. (2016) indicated that noise levels have an important effect on the students' attention processes, and that specific changes, aimed at decreasing reverberation values in classrooms (with at least 0.7-0.9 s) affect positively the levels of attention and students' short-term academic performance. They found that the 141 students, who participated in this study, scored significantly better ($p < 0.01$) on mathematics (+59 %), statistics (+18 %), and attention (+14 %) in a classroom with an average reverberation time of 1.2 s compared to students in a classroom with an average reverberation time of 2.0 s.

Figure 2-4 presents the relation between the studied variables, presented in the included studies, and the quality of teaching, learning, and students' academic performance.

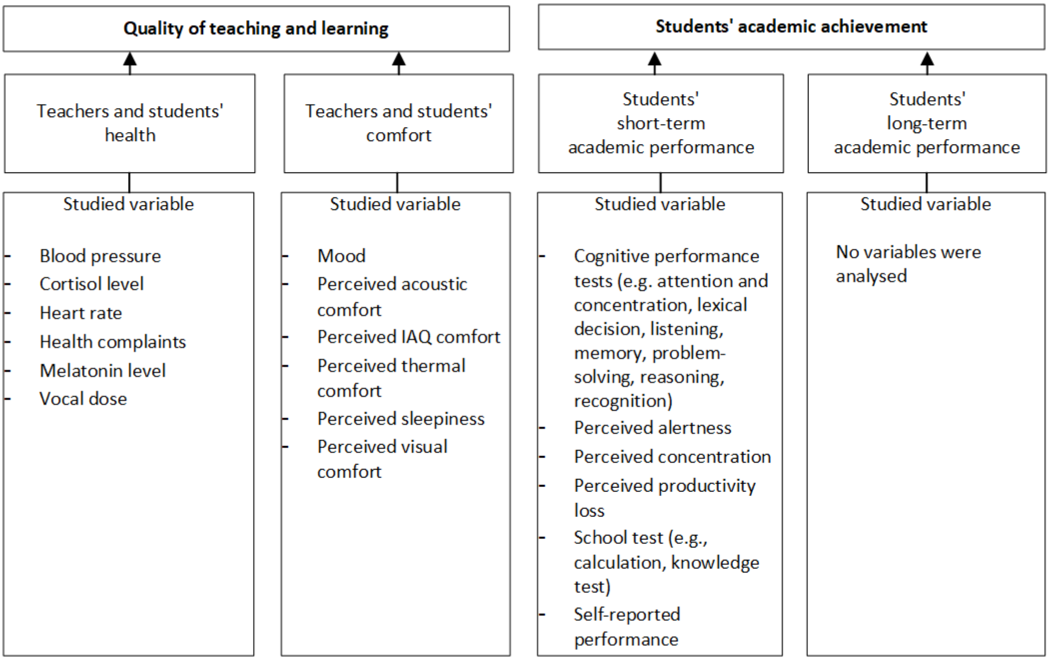


Figure 2-4 Relation between the studied variables and the quality of teaching, learning, and academic performance.

2.4 Discussion

This review aims to give an overview of 21 studies of high quality and relevance on the influence of the IEQ—as a system of the IAQ, thermal conditions, acoustic conditions, and lighting conditions— on the quality of teaching and learning and students' academic achievement in higher education. Figure 3 shows that in the last decade the IEQ conditions have been examined more holistically and have been conducted in both controlled and free-running conditions. Only three studies addressed all four indoor environmental parameters (Ahmed et al., 2017; Jamaludin et al., 2016; Lee et al., 2012). However, none of these studies analyzed the combined influence of these parameters on the quality of teaching, learning, or academic achievement. Therefore, the emergent properties of all four indoor environmental parameters cannot be determined yet. However, the evidence does illuminate the influence of one or multiple indoor environmental parameters on the quality of teaching, learning, and students' short-term academic performance. First, we reflect on the influence of the IEQ on the quality of teaching. Secondly, we will discuss the influence of the IEQ on learning. Finally, we will discuss the influence of the IEQ on students' academic achievement.

2.4.1 The influence of the IEQ on the quality of teaching

As explained in the introduction, the quality of teaching is determined by the level of comfort, mental health, and physical health of lecturers. Mendell and Heath (2005) relate a poor IEQ to adverse health outcomes and discomfort, which can impair teaching effectiveness and instructional practices (Dawson & Parker, 1998), which in return affect students' academic achievement (Wang & Degol, 2016). Two publications were identified which addressed the quality of teaching. Therefore, the evidence for the influence of the IEQ on teaching is limited and focusses on one parameter, that is, acoustic conditions. High noise levels in classrooms can cause heavy strain on female lecturers' vocal cords and increase lecturers' health risks (Rabelo et al., 2019). However, the intelligibility of a teacher's voice is an essential element in the transfer of knowledge from teacher to student. This is supported by the findings of Castro-Martínez et al. (2016) that acoustics in classrooms could affect the ability of students to hear the teacher. In addition, this ability to hear decreases substantially when the distance between teacher and student increases (Leavitt & Flexer, 1991). According to Jonsdottir (2006), voice amplification can improve the intelligibility of a teacher's voice. This researcher reported evidence that voice amplification can positively influence the perceived quality of teaching by lecturers, reduce lecturers' experienced voice fatigue, and improve student attention. Although this evidence indicates that the acoustic conditions influence the quality of teaching, the amount of evidence is limited to one IEQ parameter, and based on this evidence, the exact influence of all IEQ parameters on the quality of teaching cannot be determined or quantified.

2.4.2 The influence of the IEQ on the quality of learning

The quality of learning, like the quality of teaching, is determined by the level of comfort, mental health, and physical health of students. Mendell and Heath (2005) relate a poor IEQ to adverse health outcomes, discomfort, and distraction of students; the latter negatively influencing students' achievement. The actual and perceived IAQ can be positively influenced by applying a CO_2 demand-controlled ventilation system (Norbäck et al., 2013). Sufficient ventilation will contribute to maintaining good air quality during the use of classrooms and will positively influence the perceived overall IEQ (Lee et al., 2012). One study could not find a relationship between the actual CO_2 concentration and perceived IAQ (Liu et al., 2019). However, a significant correlation was observed between the actual thermal sensation of students and the perceived IAQ, indicating a mutual interdependence between the perceptions of these two indoor environmental parameters (Liu et al., 2019).

Thermal neutral sensation varies per individual and depends also on many factors, for example, climate, cooling or heating season, adaptation period, and room temperature at home (Hoque & Weil, 2016). When the thermal environment is assessed, there is evidence that indicates gender differences. Female students tend to feel cold more than male students (Hoque & Weil, 2016; Lee et al., 2012; Mishra et al., 2017; Norbäck et al., 2013).

High indoor temperatures increase students' heart rate (Barbic et al., 2019; Siqueira et al., 2017). Liu et al. (2008) also observed this effect. They concluded that these high temperatures strongly stimulate the sympathetic nervous system, causing thermal discomfort. Furthermore, a heart rate that exceeds the normal heart rate at rest may affect students' cognitive performance negatively (Siqueira et al., 2017).

The included studies indicate that a thermal neutral sensation will occur at different indoor temperatures, between 19.5 and 23.3°C (Liu et al., 2019; Norbäck et al., 2013; Siqueira et al., 2017) and depends on outdoor temperature and transition period (Liu et al., 2019; Mishra et al., 2017). However, De Abreu-Harbich et al.(2018), for example, observed a thermal neutral sensation at an even higher indoor temperature of 25.9°C, among students in a high-altitude tropical climate. Furthermore, thermal neutrality is influenced by more factors, besides indoor and outdoor temperature, transition period and climate. For example, indoor air humidity and the clothing insulation (clo) value, metabolic rate, gender, and age of students will influence their thermal sensation vote (Fanger, 1970). Even students' socio-economic and socio-cultural background will influence their thermal sensation vote (Singh et al., 2019). This explains why students' thermal sensation will differ, even among students in the same classroom and in the same indoor environment. In line with the findings of Singh et al. (2019), students in university classrooms report feeling comfortable on the cooler side of the thermal sensation scale. In order to assess thermal sensation, combined thermal sensation scales (e.g., a combined scale for the thermal sensations "slightly warm" and "warm") should be avoided because all descriptors of human thermal sensation can cause a different effect on perceived or measured short-term academic performance (Xiong et al., 2018).

Perceived visual comfort can be positively influenced with different correlated color temperatures. Warm white light provides a relaxing environment and supports communication, and should gradually change to blue-enriched white light after its prolonged use during the morning to prevent drowsiness and dozing off in class (Choi et al., 2019). Application of these different correlated color temperatures imitates the natural change of daylight during the day and therefore supports lecturers' and students' circadian rhythm (Gentile et al., 2018). Application of a lighting system with a color temperature of 4000K in classrooms can also influence the ability to concentrate positively (Yan et al., 2012). Although artificial lighting systems are necessary for creating optimal lighting conditions for facilitating in-class activities, students should be always provided with access to daylight in order to regulate students' circadian rhythm and level of stress hormones, that is, cortisol (Gentile et al., 2018). And according to Reid and Zee (2011), regulation of students' circadian rhythm is important because it influences students' alert state and cognitive performance.

Acoustic comfort is an important factor, which might play a dominant role in how the overall IEQ is perceived by students (Lee et al., 2012). Creating acceptable acoustic conditions in classrooms is important. Poor acoustic conditions can affect students' ability to hear the teacher (Castro-Martínez et al., 2016). Furthermore, Persinger et al. (1999) pointed out that poor acoustic conditions can cause mental health effects such as fatigue and concentration problems among students. In addition to what we have elaborated before, it is essential for students to hear the voice of lecturers clearly in order to be able to learn effectively.

The evidence presented suggests that the IEQ influences the quality of learning. By providing conditions in which students feel comfortable, they will be able to concentrate better and keep their attention for a longer period of time. However, poor IEQ can cause negative health effects, such as fatigue and sleepiness in students. These effects can lead to sick leave, which in turn can affect students' achievement (Mendell & Heath, 2005).

2.4.3 The influence of the IEQ on students' academic achievement

The focus of all included studies, which examined the effect of IEQ on students' academic achievement, was on students' short-term academic performance. Therefore, the impact of the IEQ on students' long-term academic performance could not be determined yet. Further research is needed to determine the possible relation between the short-term and long-term academic performance of students.

Nine of the included IAQ-studies (Bajc et al., 2018; Barbic et al., 2019; Gentile et al., 2018; Ahmed et al., 2017; Lee et al., 2012; Liu et al., 2019; Sarbu & Pacurar, 2015; Yan et al., 2012) used CO_2 concentration in ambient air as the performance indicator of the IAQ. One may assume, however, as humans (generally) are the single source of CO_2, both CO_2 concentration and other bio-effluents are correlated. None of the included studies analyzed the effect of pure elevated CO_2. Therefore, the observed effect of CO_2 on improved or impaired short-term academic performance is caused by a combination of CO_2 and other pollutants. The reported CO_2 concentration in the identified studies should be considered as an indicator of ventilation adequacy, which can be related to human bio-effluents, but also to material emissions, chemicals used indoors, as well as other indoor sources of pollutants. The negative effect of elevated concentrations of bio-effluents, but not pure CO_2, and other constituents on cognitive performance is also confirmed by Zhang et al. (2017). The cognitive performance of students can decline by as much as 13 % ($p < 0.001$) when the CO_2 concentration increases from 600 to 1000 ppm (Ahmed et al., 2017). However, this concentration of CO_2 still meets prevailing guidelines (NEN-EN 16798, 2019). High CO_2 concentrations of 1800 ppm might affect cognitive performance with 24 % ($p < 0.001$) (Ahmed et al., 2017). The influence of high CO_2 concentrations, as proxy for the IAQ, was higher on complex and memory-oriented than for vigilance tasks. However, the study of Ahmed et al. (2017) is the only study that quantified the effect of IAQ on cognitive performance and examined only female students. Because of these limitations, these results need to be validated with additional field research to confirm the impact and should explore possible gender differences.

Thermal discomfort, caused by high or low temperatures, affects students' cognitive performance (Almaqra et al., 2019; Barbic et al., 2019; Hoque & Weil, 2016; Ahmed et al., 2017). Barbic et al. (2019) observed a decrease of as much as 24% when students experienced thermal discomfort due to high temperature. However, not all thermal discomfort sensations lead to a deterioration of cognitive performance (Siqueira et al., 2017), and the effect is most likely task dependent. Thermal sensations "cool" and "slightly cool" can positively influence cognitive performance (Xiong et al., 2018); thermal sensations "cold," "slightly warm," "warm," and "hot" can affect cognitive performance negatively (Siqueira et al., 2017). The thermal sensation "hot" affects cognitive performance of vigilance tasks and memory and learning tasks more than the thermal sensation "cold (Ahmed et al., 2017)." Nevertheless, Bajc et al. (2018) concluded that students' short-term academic performance is not just a function of PMV index; there is no simple relation in real conditions that can link this performance to the PMV index alone.

The color temperature and light intensity of artificial lighting can affect the cognitive performance of students (Xiong et al., 2018). This effect can be as much as 23 % but this percentage is based on an average recognition rate of objects (Yan et al., 2012). The effect of these conditions on other cognitive tasks of students is not revealed yet.

Two studies investigated the impact of acoustic conditions on short-term academic performance (Lee et al., 2012; Xiong et al., 2018). Xiong et al. (2018) observed that under normal conditions of 22°C and an illumination level of 300-2200 lx, an increase of sound pressure, from 40 to 70 dB(A), affected overall cognitive performance negatively with 3 %-42 % ($p < 0.05$). Hongisto (2005) also confirmed this effect in an office setting. As observed for thermal conditions, the extent of this effect was also task dependent. To quantify students' short-term academic performance, seven of the 11 studies used standard cognitive performance tests (Almaqra et al., 2019; Barbic et al., 2019; Hoque & Weil, 2016; Ahmed et al., 2017; Sarbu & Pacurar, 2015; Siqueira et al., 2017; Xiong et al., 2018). Castro-Martínez et al. (2016) used a different method to quantify students' short-term academic performance. They used students' examination scores on mathematics and statistics and analyzed the attention level with video recording of students' behavior in the classroom. Although an increase of reverberation time does not always lead to a decrease in short-term academic performance, it can affect the intelligibility of background speech and therefore could influence the disturbance and performance of students (Castro-Martínez et al., 2016; Braat-Eggen et al., 2019). Students' short-term academic performance is also affected by unwanted noises in the classroom and may decrease this performance with as much as 34 % (Shelton et al., 2009).

There might be a relation between perceived acoustic comfort and actual thermal conditions but the precise effect remains unclear. Research of Xiong et al. (2018) revealed some relations between thermal comfort and acoustic comfort but not all cognitive tasks were affected due to a combination of these conditions. The combined effect of air temperature and CO_2 seems to increase when air temperature and CO_2 concentration increases according to Ahmed et al. (2017). Other factors, besides temperature, such as stress, sleep deprivation and pre-existing disease or illness, among others, may play a role in health-related symptoms, such as headache and tiredness (Norbäck et al., 2013). Individuals who are fatigued are also more likely to experience increased levels of psychological distress, acute health symptoms, and behavioral problems; these problems affect human performance (Ahmed et al., 2017).

It is well documented that the four individual IEQ parameters do affect the short-term performance of students. Combined effects of thermal conditions and IAQ were observed by Ahmed et al., (2017) among 499 female students. In addition, they controlled the lighting and acoustic conditions. However, they did not analyze the combined influence of these conditions. Xiong (2018) analyzed the combined influence of three IEQ parameters, thermal and lighting conditions and IAQ. None of the studies analyzed the combined influence of all four indoor targeted environmental parameters. Therefore, the magnitude of the combined influence of these four IEQ parameters cannot be quantified yet.

2.5 Future research

This systematic review revealed existing evidence about the influence of the IEQ on the quality of teaching, learning, and students' short-term academic performance. However, the influence of the IEQ on the quality of teaching could be further explored. Not only the influence of the IEQ on lecturers' health, also the effect of the IEQ on the quality of instructional practices, teaching effectiveness, and the motivation of lecturers should be explored. Although the short-term academic performance has been analyzed in different studies, the relation between the IEQ and the long-term academic performance of students was not revealed. Additional research is needed to better understand this possible relation and to quantify the impact on students' academic achievement. For analyzing the actual environmental conditions, different measuring equipment was used and one or more key performance indicators, to determine the IEQ, were applied. Additional research is needed to determine the key performance indicators of the IEQ and how these should be measured in a classroom; in order to (consistently) relate perceptions, health symptoms, and performance to the actual IEQ. Determining key performance indicators can also contribute to making future results more comparable.

Although various standardized tests are available for measuring short-term cognitive performance, few methods were identified for measuring the effect of the IEQ on physical health effects, emotional response, and long-term academic performance. New methods should be developed and could help to reveal the influence of the actual and experienced IEQ on lecturers' and students' health, cognitive performance, emotion, and behavior (Bitner, 1992).

2.6 Strengths and limitations

During the review process, all studies were assessed on quality and reliability. Assessors were the authors of this review. Each assessor examined the exact same studies. The scores of all assessors were compared and discussed and resulted in minimal differences. In addition, this process led to adjustments and fine-tuning of the assessment procedure. This procedure was developed by the assessors and included all rubrics, as no other tool was applicable to this specific domain.

The developed tool can only be applied when studies related to the IEQ need to be assessed for relevance and quality. Cultural or geographical differences between the studies were not analyzed. Therefore, the optimal conditions, as presented in the collected evidence, may not be applicable in every situation and are bound to the specific cultural and geographical cultural backgrounds. However, these conditions can be used as an indication for the development of optimal indoor environment conditions for lecturers and students in a specific setting.

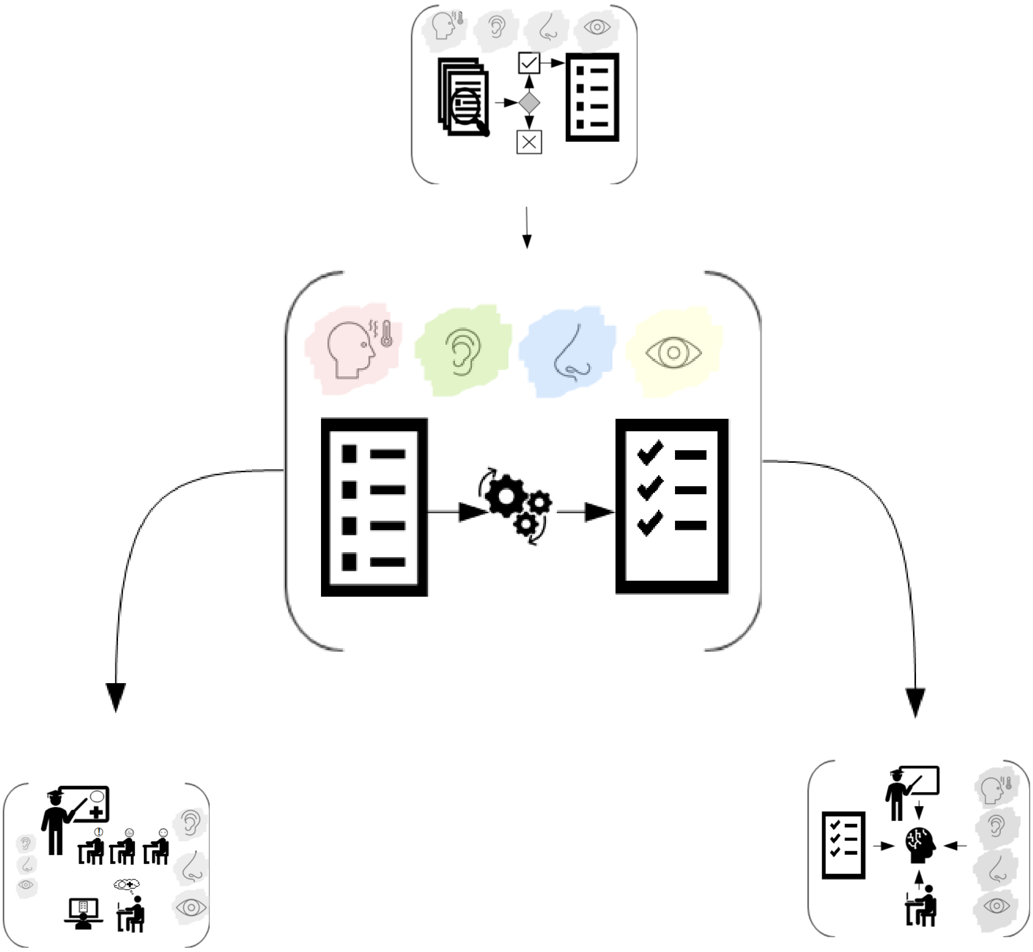
2.7 Conclusion

The primary goal of this systematic literature review was to provide an overview of how classroom indoor environmental conditions influence the quality of teaching and learning and students' academic achievement in higher education. Although a wide range of relevant evidence of high-quality research was identified, the amount of evidence which examined the effect of the IEQ on the quality of teaching is limited to only two studies on acoustics. These studies illuminate how high background noise levels affect students' ability to hear lecturers' voice and increase lecturers' health risks. Evidently, this is insufficient to determine the precise influence of all four IEQ parameters on teaching quality.

In this context, the first proposition—that the IEQ influences the quality of teaching—cannot be confirmed or rejected due to a lack of evidence. However, there is some evidence which suggests the negative impact of impaired acoustic conditions on lecturers' health. The second proposition—that the IEQ influences the quality of learning—is confirmed. Sufficient evidence confirms that a poor IAQ, thermal, acoustic, and lighting conditions negatively influence the quality of learning due to discomfort and impaired mental and physical health of students. Moreover, optimal conditions contribute positively to the quality of learning by creating an environment in which students feel more alert and pay more attention to the information presented in the lecture. Studies showing that the IEQ influences students' academic achievement partially confirm the third proposition. The available evidence that specifies the influence of individual or combined indoor environmental conditions on students' short-term academic performance is sufficient to conclude that these conditions can either influence this performance positively or negatively.

Optimal IEQ conditions, in which the students performed at their best, were task dependent, with a preference for a relatively cool, bright, and quiet environment and in ambient air with low CO_2 concentrations. However, on the other side, the hypothesized influence of all IEQ parameters on students' long-term academic performance cannot be confirmed due to a lack of evidence. Therefore, the overall influence of the IEQ on students' academic achievement cannot be fully determined yet.

3. Development and deployment of a systematic approach



This subchapter is based on:

Brink, H.W., Loomans, M.G.L.C., Mobach, M.P., Kort, H.S.M. (2022). A systematic approach to quantify the influence of indoor environmental parameters on students' academic performance. *Indoor Air*, 32(10), e13116. https://doi.org/10.1111/ina.13116

3.1 Development of a systematic approach

3.1.1 Introduction

This study explores how to measure the influence of the indoor environmental quality (IEQ) parameters on students and their academic performance. It is the primary responsibility of the school management to provide appropriate classrooms for education; which can positively influence students' academic performance, contributing to a sustainable and positive school climate (Cohen et al., 2009). As part of classrooms' environmental quality, this study focusses on four IEQ parameters: (1) indoor air quality, (2) thermal conditions, (3) acoustic conditions, and (4) lighting conditions (Frontczak & Wargocki, 2011). This study examines how to measure the combined influence of all four IEQ parameters on the academic performance of students in higher education. The academic performance of students is acknowledged as an important study outcome, besides behavioral and psychological outcomes (Wang & Degol, 2016).

In the last decade, there has been an increasing interest in developing a more holistic approach for examining the influence of IEQ conditions on students' academic performance (see **Chapter 2**). Previous research on the combined influence of two or more IEQ parameters found that IEQ does influence students' performance (see **Chapter 2**). For example, Wargocki and Wyon (2017) demonstrated how cognitive performance is influenced by thermal conditions and indoor air quality. Other studies have examined the combined influence of thermal conditions and indoor air quality (Ahmed et al., 2017; Sarbu & Pacurar, 2015). These studies show that poor IEQ conditions affects students' cognitive performance in higher education. Xiong et al. (2018), who explored the impacts of three IEQ parameters, namely thermal, acoustic, and visual conditions on students' cognitive performance, concluded that optimal IEQ conditions in which students perform at their best, are task dependent, with students preferring a relatively cool, bright, and quiet environment. However, few studies have examined the combined influence of all four IEQ parameters (see **Chapter 2**).

A holistic assessment of indoor environmental conditions is important because of the mutual interaction of IEQ parameters. This interaction was observed by Kim and De Dear (2012), who developed a model to determine these interaction effects and the existence of a hierarchy among IEQ parameters in another setting. Two basic IEQ factors, namely temperature and noise level, were identified on the basis of data collected in office environments. The negative impact of these factors outweighs their positive effects on the overall experience of IEQ. Air quality, the amount of light in the workplace, visual comfort related to the lighting, and sound privacy were classified as proportional IEQ factors. The overall occupant satisfaction increased or decreased in linear proportion to the building's performance impacting these factors (Kim & de Dear, 2012).

Although previous studies have explored the influence of the above-mentioned parameters, to the best of our knowledge, no study has combined the four separate parameters within a systematic approach to examine the impacts of the IEQ in higher education classrooms. Therefore, there is a need to develop models for assessing the influence of multiple environmental parameters on students' performance (Torresin et al., 2018). To assess this influence, a framework of Bitner (1992) is used. This framework was selected because it addresses the combined influence of different environmental factors, including all four IEQ parameters. To enable its application in higher education classrooms, the relationships described in the work of Wang and Degol (2016) were fitted into this framework. Figure 3-1 presents the framework for understanding IEQ-user relationships in classrooms and outlines the systematic approach.

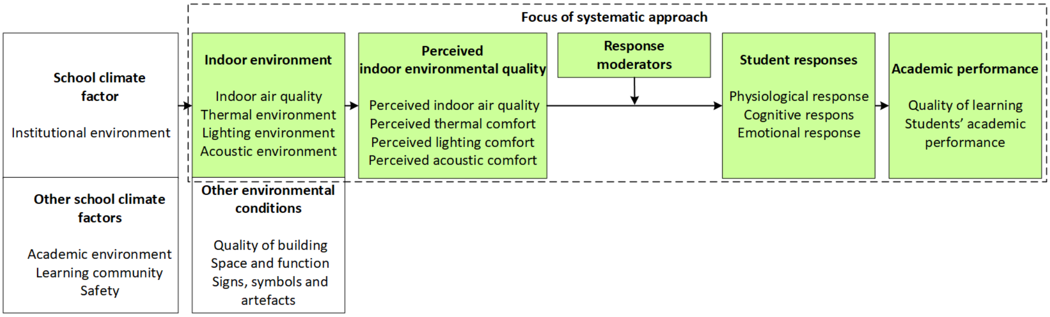


Figure 3-1 The systematic approach, based on Wang and Degol (2016) and Bitner (1992).

The main objective of this study is to develop and validate a systematic approach for measuring the effect of all four IEQ parameters in higher education classroom on students' perceptions, responses and academic performance. The application of this systematic approach benefit future studies seeking to determine the influence of both single and multiple IEQ parameters. Furthermore, it will be possible to determine whether there is a hierarchy between IEQ parameters in assessment of the impacts of IEQ on users in higher education classrooms. In this work, existing methods are used for measuring the influence of IEQ parameters on students and their academic performance. Subsequently, a pilot study is conducted to assess the validity and applicability of the systematic approach in real-life conditions. In the next section, the development of the systematic approach is described, followed by its application in the third section

3.1.2 A systematic approach for assessing the effects of multiple IEQ parameters

3.1.2.1 Method

The development of a systematic approach entailed the following three phases: (1) compilation of available information on how to measure IEQ and higher education students' perceptions, responses and academic performance, (2) categorization of the available information on these methods and (3) adjustments of the identified methods and tests if needed and their incorporation into the systematic approach. This paragraph presents an overview of these three phases. Appendix 5 provides a list of the nomenclature for indicators of the IEQ with abbreviations.

During the first phase, available information on how to measure the IEQ and the influence of the IEQ on students' perceptions, responses and academic performance was collected from literature. Potentially relevant publications were identified through searches in the following databases: Web of Science, Scopus, Emerald Insight, Wiley Online Library, Sage, PubMed, and 27 EBSCOhost databases (e.g. Academic Search Premier, ERIC, APA PsycINFO, Teacher Reference Center). For the search, keywords relating to classrooms' IEQ, teaching and learning, and students' academic performance were used. Publications whose titles, keywords or abstracts did not indicate that indoor environmental conditions were the topic of study were excluded (n = 1,162). These publications emerged in the primary search because one or more keywords were used in different contexts. Publications that only addressed physical indoor environmental conditions or other types of building performance (e.g. energy consumption and sustainability) and did not analyze their effects on teaching, learning or academic performance were excluded (n = 102). Finally, publications were excluded that addressed people with physical or mental disabilities (n = 23), those that did not address classrooms in higher education (n = 54) and those that were not written in English (n = 3).

Following this selection stage, 51 publications were included, to which three additional publications were added of Corgnati and Viazzo (2004), Ricciardi & Buratti (2018), and the NEN-EN-ISO 7730 (2005). These additional publications were cited by resp. Castilla et al. (2018a), Corgnati et al. (2007), and De Abreu-Harbich et al. (2018) and provided relevant additional information about the applied methods. In place of a study by Kooi et al. (2017), the more complete publication by Mishra et al. (2017) on the same study was used. Further details on the applied search string and exclusion criteria can be found in a previous systematic literature review (see **Chapter 2**), which provides an overview of how all four IEQ parameters influence students' perceptions, responses, and academic performance. Figure 3-2 shows the outcome of the selection stages during the screening of the identified publications.

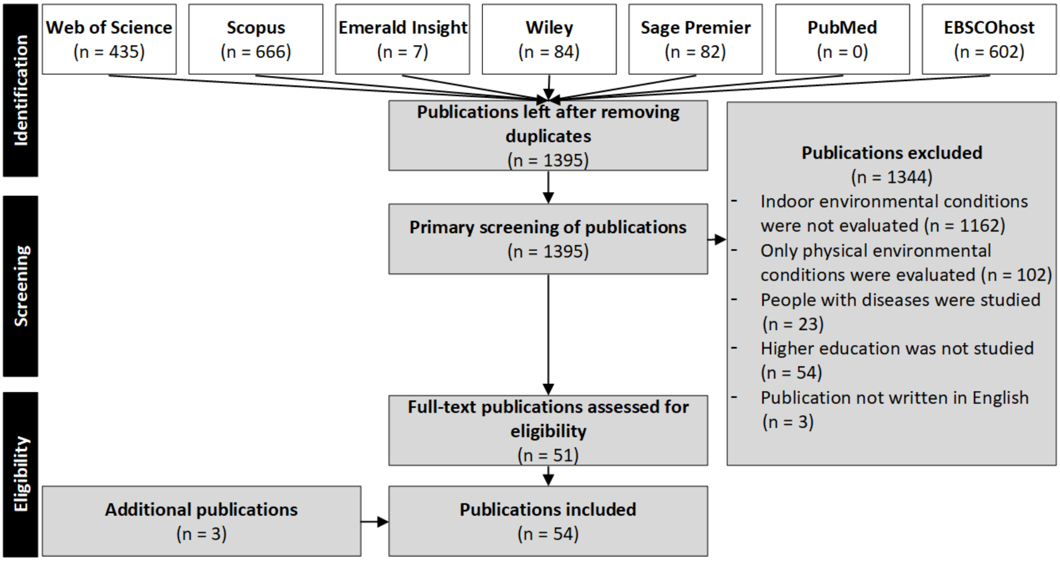


Figure 3-2 Literature screening process for developing a systematic approach.

In the second phase of the systematic approach development, the available information on the applied methods was categorized, according the categories in Figure 3-1. In addition, the available questionnaires in the corresponding manuscripts were arranged by topic, e.g. all items which address the perceived indoor air quality or thermal comfort.

During the third and final phase, constraints were set for applying the systematic approach. Methods and tests were used to compose the approach which showed statistically significant associations between the short-term influence of the IEQ on students' perceptions, responses, and academic performance. If necessary, items, addressing the perceived IEQ, students' perceived cognitive responses to the IEQ, and students' perceived academic performance were reformulated to enable the use of a single, uniform response scale. Three experts from professional and education fields, who deal with indoor environment issues on a daily basis, were consulted to assess the content and face validity of the composed questionnaire. The consulted experts were a senior lecturer and researcher, who specializes in building physics, of The Hague University of Applied Sciences, a consultant focusing on sustainability and health from DGMR Advisors for Construction, Industry, Traffic, and Environment, and an advisor on indoor climate control from Nijeboer-Hage Technical Advisors, all of whom are located in the Netherlands. As a final step to enable the application of the systematic approach in higher education Dutch-language classes, the composed questionnaire was translated into Dutch with the help of a bilingual expert.

3.1.2.2 Outcome of the process of developing a systematic approach

In this sub-section, the results are presented, per category, of all the phases of development of the systematic approach according to the framework shown in Figure 3-1. First, the identified IEQ indicators are presented for determining the actual IEQ, followed by a description of the methods used to measure students' perceptions of the IEQ, their internal responses, and their academic performance. Lastly, the fully composed systematic approach is presented. Appendix 6 presents an overview of all included empirical studies and those used for developing the approach. It also lists all of the indicators used to measure the IEQ and presents detailed information on methods for measuring students' perceptions, responses, and academic performance.

Indoor environment

It is essential to measure specific IEQ parameters to determine the quality of the indoor environment. With reference to the available information in the selected publications, 55 indicators were identified, which reflect the quality of the four indoor environmental parameters. Figure 3-3 presents these indicators, grouped by IEQ parameters.

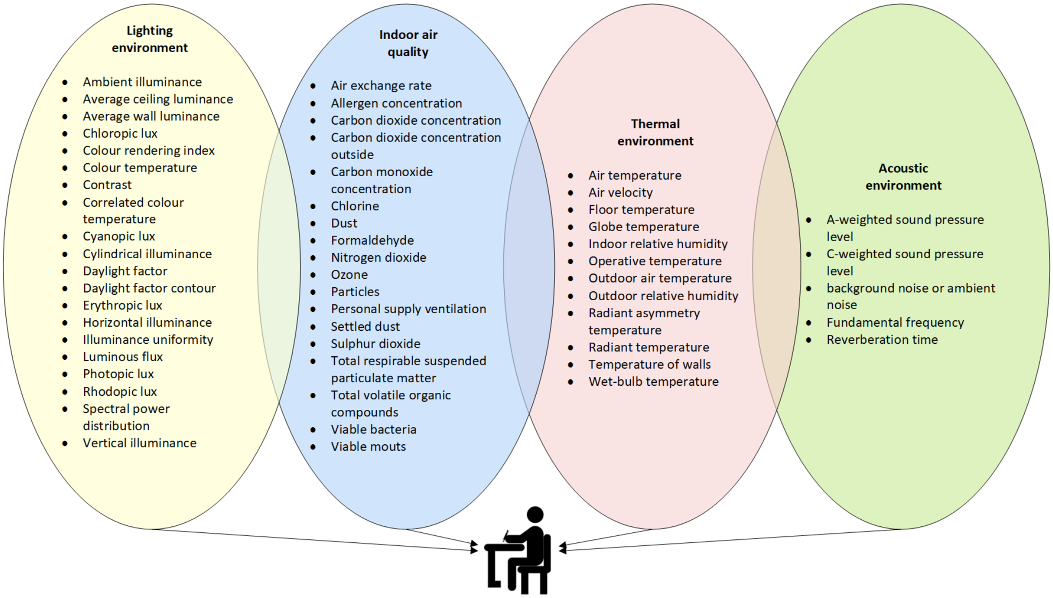
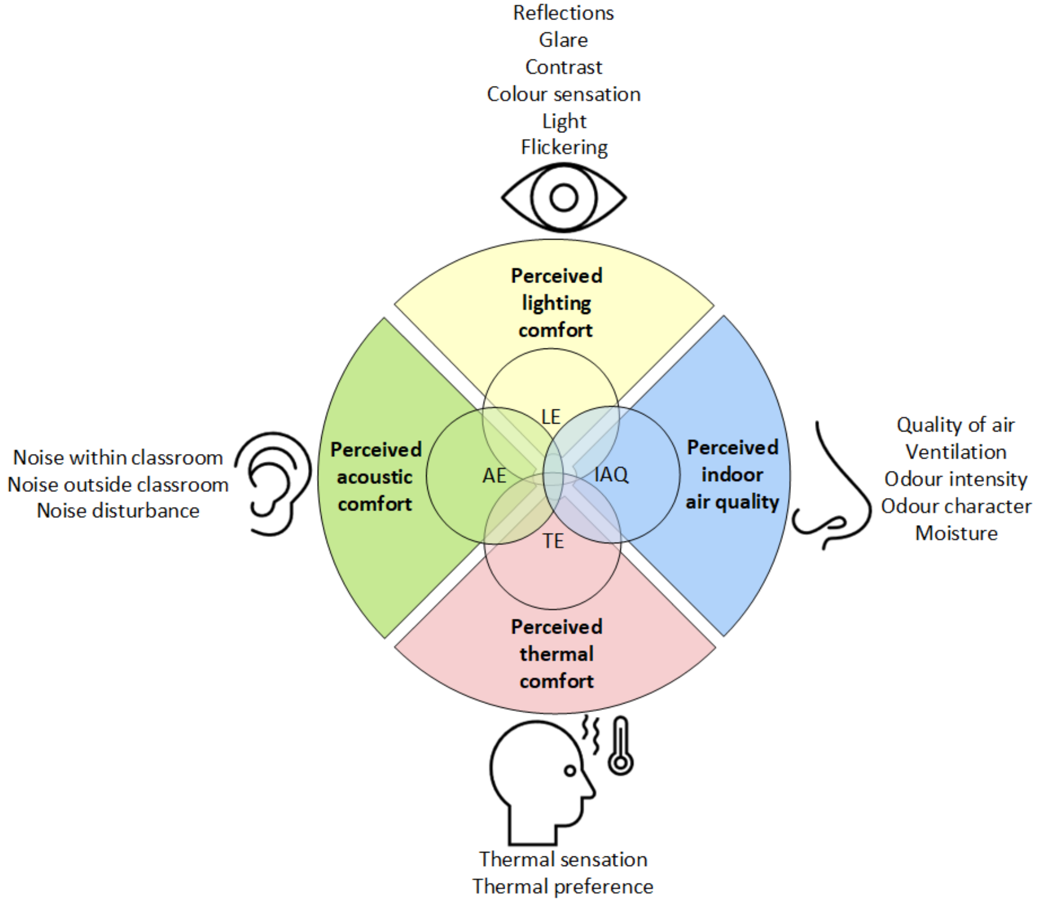


Figure 3-3 Indoor environmental quality indicators grouped by category.

Perceived indoor environmental quality

Respondents in the reviewed studies responded to items for measuring the perceived quality of the indoor environment. Available information on measurement of the perceived IEQ presented in text and questionnaires included in the reviewed studies, were grouped to each specific IEQ parameter. Subsequently, 16 subcategories were identified for measuring the perceived IEQ according to the topics covered by the questionnaire developed for implementing the systematic approach. The questionnaire with these sub-categories was then validated. Figure 3-4 presents the sub-categories and their relations to specific indoor environmental parameters.

The response options applied in the identified studies were analyzed to develop standard response options for use in the systematic approach. The most frequently used scale was a five-point Likert scale, ranging from one (*disagree*) to five (*agree*) (Castilla et al., 2018b; Gentile et al., 2018; Mongkolsawat et al., 2014; Ramprasad & Subbaiyan, 2017; Witkowska & Gladyszewska-Fiedoruk, 2018). Therefore, this scale was adopted for the questionnaire. In some cases, however, items had to be reformulated so they could be answered with this scale. A senior lecturer and researcher of The Hague University of Applied Sciences assisted the authors in this critical process. For example, the topic of dry air was addressed by Yang, Becerik-Gerber and Mino (2013). In one study respondents were asked to assess the air humidity (Kuru & Calis, 2017), and in another study respondents described how they felt about the degree of humidity (Witkowska & Gladyszewska-Fiedoruk, 2018).



Note: LE = lighting environment; IAQ = indoor air quality; TE = thermal environment; AE = acoustic environment.

Figure 3-4 Perceived indoor environmental quality categories and subcategories.

Accordingly, in the questionnaire, the topic of air moisture is addressed with the following reformulated item "The air is dry in here". The questionnaire was then assessed by the above-described experts for relevance and applicability in relation to higher education classrooms. This evaluation process led to the deletion of two items. The first item, "The illumination provided by artificial sources in the classroom compared to the shape of the classroom itself (geometry of the classroom) is inadequate" (Ricciardi & Buratti, 2018), was deleted because an expert on the topic indicated that this question was too difficult to understand. The second item, "The light seeping through windows appears to be inadequate" (Ricciardi & Buratti, 2018), was deleted because an expert on the topic indicated that this question is not valid because there is always a combination of daylight and artificial light in the classroom, so the amount of daylight cannot be assessed by the respondent.

After data-collection, mean scores were calculated for each perceived IEQ scale for further analysis. The lowest average perception score, derived from individuals' scores, was one (very poor); the maximum perception score is five (very good). When assessing perceived thermal comfort, it is necessary to include thermal acclimation, defined as the adaptive changes that occur within individuals (IUPS Thermal Commission, 2001), because it may influence the actual thermal sensation, especially within the first 20 min after entering a classroom (Mishra et al., 2017). In addition, the amount of clothing expressed as an individual's clothing insulation value, could influence their perceived thermal comfort. Therefore, this insulation value was included in the systematic approach and calculated from the garment selected by the individual, according to their thermal insulation value (NEN-EN-ISO 7730, 2005). The level of activity of an individual can also influence their perceived thermal comfort (Fanger, 1970). However, merely attending a lecture, which is a sedentary activity, would not result in a large differences in the metabolic rate among students, although there may be a difference between the metabolic rate of the students (sitting) and that of the lecturer (standing and/or sitting). The mean score for perceived thermal comfort was derived from the students' thermal sensation and preference score. Following Schweiker et al. (2020), the three middle votes of the thermal sensation, slightly cool, neutral, and slightly warm, were selected to represent comfortable conditions[1]. Table 3-1 provides detailed information about how the perceived thermal comfort scale was computed.

Table 3-1 Perceived thermal comfort scale.[1]

Item	**Old value**	**Original classification**	**New value**	**Comfort classification**
PTC_{sens}	1	Cold	1	Very uncomfortable
	2	Cool	2	Uncomfortable
	3	Slightly cool	4	Comfortable
	4	Neutral	4	Comfortable
	5	Slightly warm	4	Comfortable
	6	Warm	2	Uncomfortable
	7	Hot	1	Very uncomfortable
TC_{pref}	1	Much warmer	1	Very uncomfortable
	2	Warmer	2	Uncomfortable
	3	A little warmer	3	Slightly uncomfortable
	4	Neither warmer nor colder	4	Comfortable
	5	A little colder	3	Slightly uncomfortable
	6	Colder	2	Uncomfortable
	7	Much colder	1	Very uncomfortable

Note: PTC_{sens} = thermal sensation; PTC_{pref} = thermal preference.

Response moderators

Different personal, cultural, climatical, social, and contextual factors can explain differences in individual reactions to the same IEQ (De Dear & Brager, 1998). Therefore, all response moderators were listed after reviewing all of the included studies. Accordingly, age and gender were included in the systematic approach as general response moderators (Gentile et al., 2018; Ahmed et al., 2017; Mishra et al., 2017). Furthermore, the classroom positions of students and lecturer, the number of students per classroom, and number of students in the classroom were identified as external-related response moderators (Gentile et al., 2018; Madbouly et al., 2016).

---

[1] Individuals' thermal comfort vote may differ from this classification (Schweiker et al., 2020).

Student responses

In general, people respond physiologically, cognitively, and emotionally to their indoor environments (Bitner, 1992). To determine how these responses should be measured, all studied physiological, emotional, and cognitive responses were listed. To assess physiological responses to the indoor environment, all examined health symptoms and body-related issues were listed. A total of 23 health symptoms were identified. Heart rate, blood pressure, melatonin concentration, saliva cortisol concentration and thirst were identified as body-related issues. The identified health symptoms were divided into five health categories: (1) dermatological symptoms, (2) tympanic, ophthalmological, and vision-related symptoms, (3) upper respiratory symptoms, (4) neural behavioral symptoms, and (5) mucosal symptoms. Table 3-2 shows all IEQ related health symptoms, their corresponding ICD-10 health codes of the World Health Organization(WHO, 2019), and related IEQ parameters. These health symptoms were self-reported.

Table 3-2 Self-reported health symptoms and their relation to the indoor environment

Cat.	**Health symptoms (self-reported)**	**ICD-10 code**	**Relation**			
			IAQ	TE	LE	AE
D	Itchy skin, skin irritation, skin rash, dermatological skin problems	R21		○		
E	Itchy eyes, eye irritation, dry eyes, earache, deafness	H57.8; H92.09; H91.90	○			●
R	Dry throat, throat irritation, nasal dryness, nose irritation, sinus congestion, coughing, sneezing, wheezing, respiratory distress	J39	○	○		●
C	Headaches, nausea, lethargy, dizziness	G44; R11; R53; F44-45	●	●	○	●
M	Mucosal symptoms	R68		○		

Note: Cat. = category; D = dermatological symptoms; E = tympanic ophthalmological vision-related symptoms; R = respiratory tract (upper respiratory symptoms); C = central nervous system (neural behavioral symptoms); M = mucosal symptoms; IAQ = indoor air quality; TE = thermal environment; LE = lighting environment; AE = acoustic environment; ○ = reported relation in study; ● = reported and confirmed relation based on study outcomes.

To identify possible health symptoms, filter questions were added to the systematic approach for each health category and health issues were specified. 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. If this was the case, the reported health issue may be linked to the IEQ of the building. If not, the reported health issue was excluded from the analysis. In the systematic approach, the number of health issues is reported as perceived physiological health complaints.

The most frequently studied emotional responses, which were also related to students' mental health, were fatigue (Ahmed et al., 2017; Jonsdottir, 2006; Persinger et al., 1999), sleepiness (Choi et al., 2019; Mongkolsawat et al., 2014), and tiredness (Chowdhury et al., 2010; Norbäck et al., 2013). Four standardized methods for measuring emotional responses were identified from the literature. The first is the Positive And Negative Affect Scales, which focusses on individual resources, activities, and perceptions of the social environment (Watson et al., 1988). The second is the Basic Emotional Process Scale, which assesses the individual emotions in terms of activation, evaluation, orientation, and control (Kuller, 1991). The third is the Karolinska Sleepiness Scale, which measures perceived sleepiness affecting alertness (Åkerstedt & Gillberg, 1990). The fourth is the Pittsburgh Sleep Quality Index, which measures the reported sleep quality for one month (Buysse et al., 1989). Appendix 7 presents the structure and items of these emotional response methods.

The classification of the items for assessing students' cognitive responses was complex. Studies have reported students' learning performance while addressing students' cognitive responses. In these cases (Sarbu & Pacurar, 2015; Siqueira et al., 2017; Xiong et al., 2018), the framework depicted in Figure 3-1 facilitated the classification of the identified methods. Following Xiong et al. (2018), four main categories were identified, i.e. attention and concentration, memory, perception, and problem-solving performance. The perceived cognitive response can be measured with items focusing on these four categories. The available information in the studies was used to formulate five items that cover these four categories. Objective cognitive responses can be measured with the use of psychometric tests of neurobehavioral functions. For measuring attention and concentration and memory, respectively, the Go-No Go task (Drewe, 1975) and the Corsi block test (Corsi, 1972) were selected. The Stroop test was used to measure students' perception, whereas their ability to solve problems was assessed with the Wisconsin card sorting test (Ozonoff, 1995; Stroop, 1935). These tests were selected as they have been empirically validated and are practically feasible. Feasibility criteria included online availability of the test free of charge and no requirement of special equipment, the ability to perform the test using a mobile phone or laptop, and time-based efficiency for naturally occurring field experiments (5 min or less) (Murre, 2021).

Academic performance

Students' academic performance is the last category which is affected by IEQ, as depicted in the framework shown in Figure 3-1. This performance can be divided into students' long-term and short-term academic performances. Long-term performance relates to students' academic performance during an academic semester. Regrettably, no methods were identified for measuring students' long-term academic performance in the studies. However, we did identify two methods for measuring short-term performance, which relates to students' academic performance during a lecture. The first was the use of questionnaires to measure the perceived quality of learning, including students' academic performance. Following Lee et al. (2012), two items that address students' ability to write (type) and read and an overall statement that addresses students' productivity during the lecture were added to the systematic approach.

The second method entailed administering a content-related test to measure students' academic performance at the end of the lecture and thus assess knowledge transfer between lecturers and students during class. This test focused on logistical principles and practices covered during the lecture. Students' ability to pay attention during the lecture may affect their ability to remember the content presented during the lecture (Cowan, 1998). Therefore, our systematic approach followed the procedure of Shelton (2009) and McDonald (2004). Students would first complete the questionnaire, which evaluated their perceived IEQ, internal responses, and quality of learning. They would subsequently take the academic performance test to measure their ability to recollect the information presented by the lecturer. The above order of implementation increased the time span between the lecture and the content-related test. Therefore, the students were forced to focus their thoughts first on aspects other than those covered during the lecture. For the pilot study, the test was designed in collaboration with the concerned lecturers and consisted of 10 multiple-choice questions. The percentage of questions answered correctly reflected students’ short-term academic performance.

3.1.2.3 Overview of the elements in the composed systematic approach

The developed systematic approach, which measures the influence of all IEQ parameters on students, addresses four main categories: (1) indoor environment, (2) perceived indoor environment, (3) student responses, and (4) academic performance, as presented in Figure 3-1. Figure 3-5 shows how these categories and their mutual relations are covered in the systematic approach, which is based on the information that emerged from the systematic literature review. Because no methods measuring students’ long-term academic performance were identified, the systematic approach only enables assessing the influence of IEQ on students’ short-term academic performance. The Pittsburgh Sleep Quality Index was not included in the approach, because it covers long-term sleep quality and is, therefore, less applicable. Furthermore, measurements of body-related parameters, such as blood pressure or saliva cortisol concentration(Gentile et al., 2018; Siqueira et al., 2017), were not included, as their inclusion would have limited the applicability of the systematic approach. The approach is designed to be applicable in any higher education classroom setting, assuming a steady-state situation (~20 min acclimation) and lecturer-student interactions. There are no restrictions regarding the number and size of classrooms or the number of participants. In the next stage, the systematic approach was tested in practice.

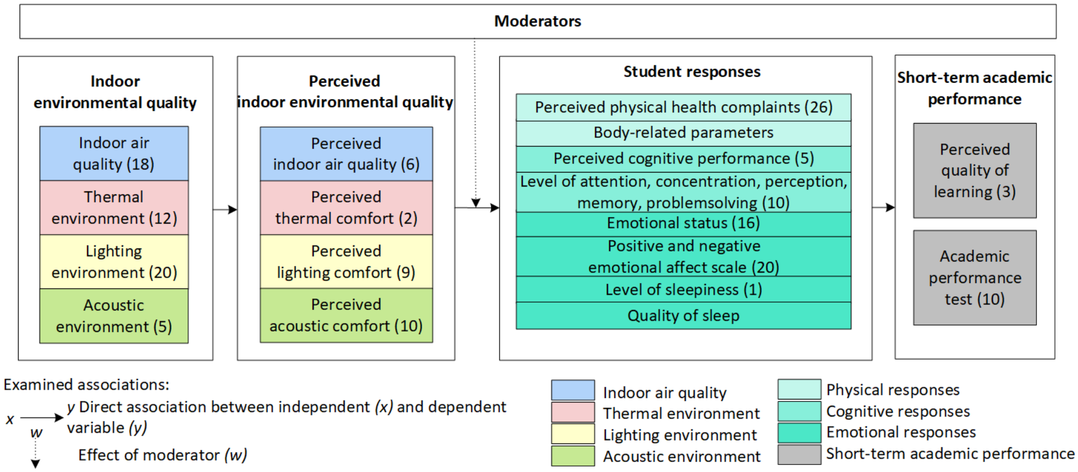


Figure 3-5 Categories covered in the systematic approach and their mutual relations. The figures in the parentheses indicate the number of items in the questionnaire that cover these categories.

3.2 Deployment of a systematic approach

3.2.1 Method

A pilot study was conducted to test the systematic approach in February 2020 during the same week in which the first confirmed case of COVID-19 was reported in the Netherlands. However, the classroom setting and students' attendance were not affected by the pandemic at the time. This pilot study specifically aimed at assessing the applicability and validity of the perception categories relating to thermal comfort, indoor air quality, lighting comfort, acoustic comfort, and cognitive performance, as these categories were modified versions of those referred to in literature. Existing methods and items, namely emotional response methods and cognitive performance tests, were not tested in the pilot study as these methods were not modified during the development of the systematic approach and their applicability has been demonstrated (Choi et al., 2019; Gentile et al., 2018; Ahmed et al., 2017; Xiong et al., 2018).

3.2.2 Design set-up

In this study, first-year students of the Hanze UAS School of Business Management, which is in the northern part of the Netherlands, participated as part of their educational program. These students were selected because they were laypersons who were not versed in building physics. For the pilot study, two heated and naturally ventilated classrooms of the Hanze UAS were selected. These classrooms were equipped with a full air recirculation system to achieve a set air temperature. Outdoor air could enter the classrooms through grilles located above the double glazing. Both classrooms were fitted with nine ETAP U3352 light fittings. Figure 3-6 presents the floorplan of the classrooms, their orientation, the building facility components in the classroom, and its general visual appearance.

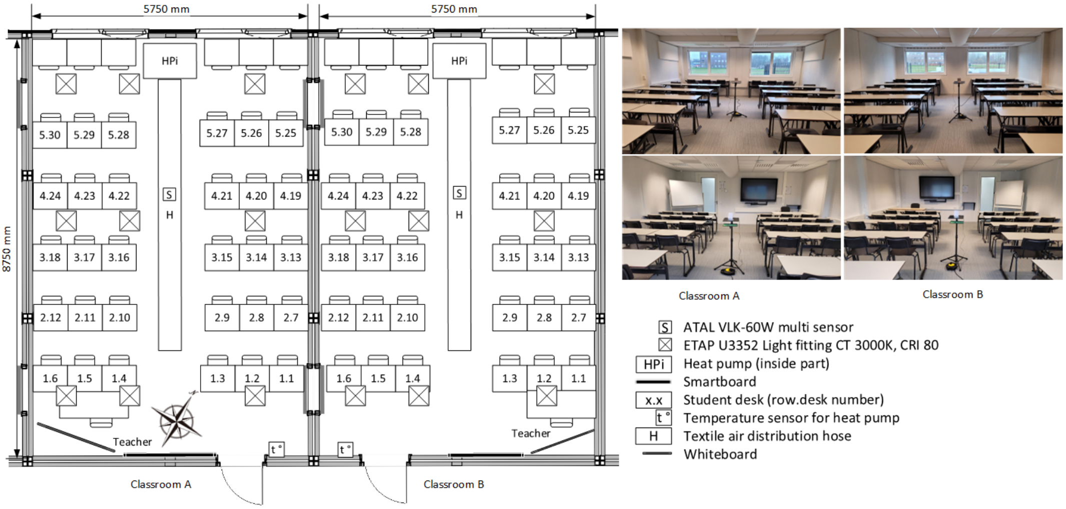


Figure 3-6 Layout of the classrooms A and B along with four photographs of the A and B interiors (left to right respectively).

This pilot study was approved by the ethical committee of the Hanze UAS (approval no.2019.026). Prior to their participation, the students were provided with a general outline of this 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. As a reward for participation, each student received a voucher for a cup of coffee or tea. The students could end their participation in the study without any consequences at any time. However, none of the students requested to do so or to have their data removed.

3.2.3 Procedure

To determine the indoor air quality, carbon dioxide, particulate matter (PM10 and PM2.5), and volatile organic compounds was measured. To determine the thermal environmental quality, air temperature and relative humidity were measured. Because of the low thermal mass of the building in which the classrooms are located, the assumption was made that the globe, radiant, and wall temperatures did not differ beyond accuracy specification from the air temperature, which was confirmed in a follow-up study. The indicators for indoor air quality and thermal environmental quality were measured using an ATAL VLK-60 multi-sensor, which was placed in the middle of the classroom at a height of 1.1 m, see Figure 3-6 (EN ISO 7726, 1998). During the pilot study, this device sent all readings every five min to an online platform (www.onlinesensor.nl). These data were used to determine the test conditions. Before the experiment started, air temperature and carbon dioxide concentration were also measured at the front and in the back of the classroom with an ATAL ENV-MB350NV sensor to determine whether the thermal environmental and indoor air quality in the classroom itself varied. To determine the quality of the lighting environment, the horizontal illuminance level at the desktop of each desk was collected, with the use of a VOLTCRAFT MS-1300 illuminance measurement device, before the start of the lecture. The students were asked to note their position in the classroom (table number) when they filled in the online questionnaire. The horizontal illuminance level of the desk was linked to the table number. Furthermore, the table number was used to determine the row in which the student sat during the lecture. This row number was used for further analysis as an indicator of the physical distance between the student and the teacher. To determine the quality of the acoustic environment, the background noise and the average reverberation time, at frequencies ranging between 250-2000Hz were measured. Because both classrooms were equipped with the same heat pump and the lecturers involved delivered the same number of lectures, the assumption was made that the ambient sound did not influence students' perceived acoustic comfort. Appendix 8 presents the measured indicators and details on the accuracy of the measuring equipment.

During the pilot study, 4 lecturers delivered in total 12 lectures, each lasting approximately two hours on every weekday apart from Monday. Each lecturer delivered the same number of lectures in classrooms A and B. All participants spent more than 20 min in the classroom; therefore, the assumption was made that all individuals were acclimated to the indoor environment (Mishra et al., 2017). After each lecture, the students present were asked to participate in the pilot study. The degree of participation was high, with approximately 90 % of all students taking part in the study. There was a short 10-minute break, during which the students stayed in the room, before they filled in the questionnaires. To obtain their IEQ perceptions and responses and to assess their academic performance, all participants first completed the online questionnaire, which measured their perceived comfort, perceived physiological and cognitive responses, and perceived quality of learning. After completing this questionnaire, they took the academic performance test, which comprised ten questions on topics discussed during the lecture. There was no time limit for the students to complete the questionnaire and test. Those who took the academic performance test received an email the following week with their personal test scores.

3.2.4 Analyses

To determine the validity of the developed systematic approach, all collected data were statistically analyzed. To assess the internal validity of the questionnaire, which addressed the perceived IEQ, cognitive response, and quality of learning, first, the scores on all negative formulated items were reversed. Next, an analysis of Cronbach's alpha (α) values was performed to assess the internal consistency of these scales. To determine the normal distribution of the data, Q-Q plots were computed and Shapiro-Wilk tests were performed. Next, the assumed associations (see Appendix 9) were tested with linear regressions. The assumed associations of the perceived physical health complaints were analyzed by performing a Poisson regression because this dependent variable consists of "count data".

The output of the regression analysis was only taken into consideration when it met the following assumptions. The first was the assumption of normality. To determine the normal distribution of the standardized residuals, a probability plot (P-P) plot was computed. When this plot of the residuals appeared to be approximately linear, the assumption of normal distribution was met. When the outcome appeared not to be linear, the distribution of the standardized residuals and unstandardized residuals was analyzed by performing the Shapiro-Wilk test. When the significance level of this test is >.05, the assumption for normality was met. When the regression model did not meet these assumptions, a one-tailed Spearman test was performed to test an association.

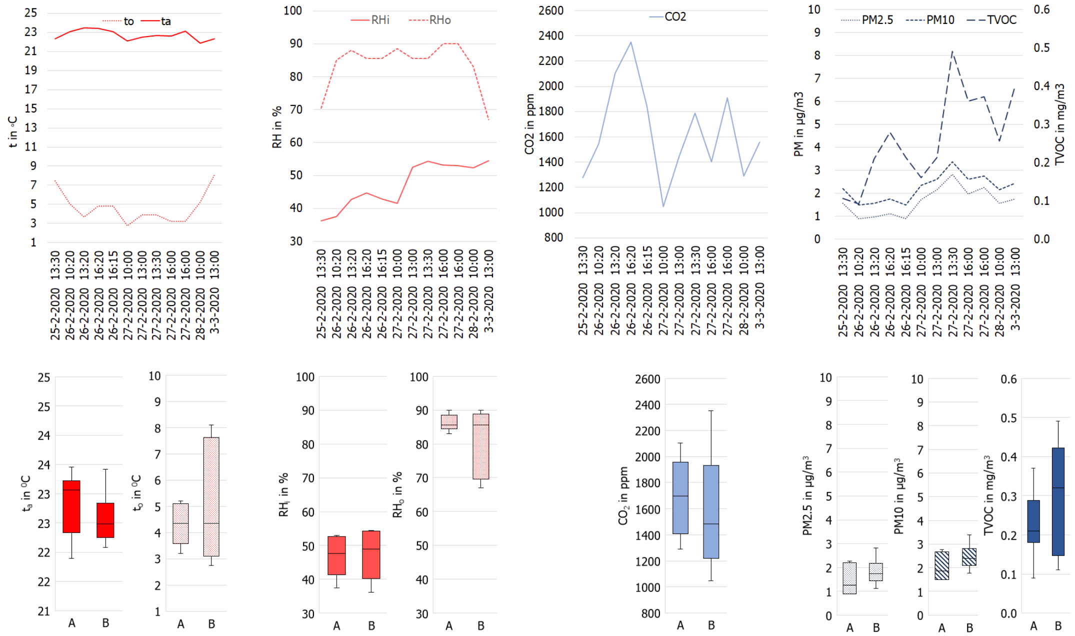
All linear regression models were checked using Cook's diagnostic measure. This value gives a measure of distance per respondent over which the maximum was evaluated. In case of a value that exceeded the cut-off value 4/n(Van der Meer et al., 2010), the significance of the regression unstandardized coefficients were compared with those from robust regression models (Yohai et al., 1991). When this comparison resulted in a different conclusion with respect to the coefficient, it was reported. For multivariate associations the tolerance values should be .10 or higher to rule out multicollinearity (Cohen, Jacob et al., 2013). In the case of multicollinearity, the variable with the lowest bivariate standard correlation coefficient was excluded from the model. In the Poisson regression analysis, the moderation effect was determined by including all moderators separately in the regression model, as covariates or factors. The missing values in all of the linear regression models were excluded listwise. For all tests, the confidence interval (CI) was set at 95 %. The lm function (lme4) and the robust lmm function (robustlmm) in R version 3.5.0 (R Foundation for Statistical Computing, 192 Vienna, Austria) and IBM SPSS Statistics Version 28.0.1.0 were used for statistical analyses.

To determine the effect of response moderators, a logistic regression path analysis modelling tool was used (Hayes, 2017).

3.2.5 Results

3.2.5.1 Indoor environment

The outdoor temperature varied between 3.2 and 8.1°C. The indoor air temperature was regulated using the installed heating system and varied slightly, remaining at 23°C. The mean air velocity was considered to be < 0.09 m/s because the windows in both classrooms were closed during the pilot study; therefore, the assumption was made that this indicator did not influence students' perceived thermal comfort. The average differences in air temperature and carbon dioxide concentration registered in the center of the classroom, compared to those registered at the front and back of the classroom were marginal (+1 % and +3 % respectively), indicating that the textile air distribution hose of the heating system (see Figure 3-6) mixed the ambient air sufficiently. The average carbon dioxide concentration outside was approximately 422 ppm (Global Monitoring Laboratory, 2020). The amount of daylight in the classrooms was low, because of a window-to-floor area ratio of 3 % and the North to North-West orientation of the classrooms that prevented the entry of direct sunlight during the experiment. The measured level of horizontal illuminance of the participants' desktops was 661 ± 162 lx. The major source of sound in the classroom, besides the installed heat pump, was the lecturer's voice. The average reverberation time at frequencies between 250 and 2000 Hz, in classroom A and B were 0.44 and 0.56 s, respectively, and the average background noise in both classrooms varied between 35 and 42 dB(A). Figure 3-7 shows the natural variations of the thermal environmental and indoor air quality conditions in classrooms A and B.



Note: RH_i = indoor relative humidity; RH_o = outdoor relative humidity; t_a = air temperature; t_o = outdoor temperature; CO_2 = carbon dioxide; PM10 = particles < 10 µm; PM2.5 = particles < 2.5 µm; TVOC = total volatile organic compounds.

Figure 3-7 Observed indoor and outdoor thermal environmental conditions (in red color accents) and indoor air quality (in blue color accents) during the 12 observed lectures at the moment students filled in the questionnaire. The line graphs show the natural variations in the classrooms during the experiment; the boxplots show the conditions in classrooms A and B.

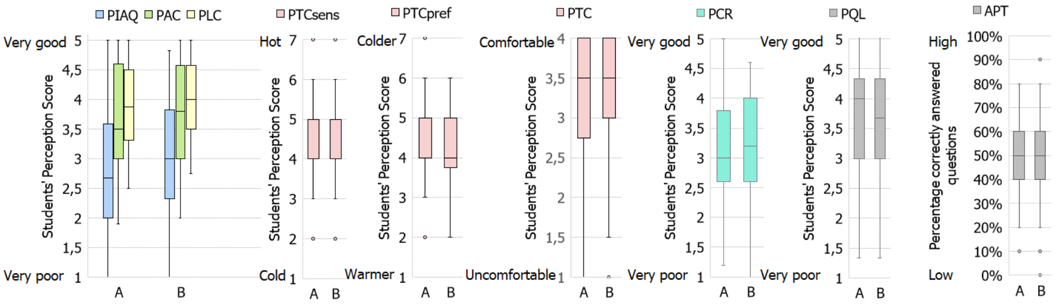
3.2.5.2 Perceived indoor environmental quality, response moderators, student responses, and academic performance

Data on the perceived indoor air quality, thermal sensation, thermal preference, acoustic comfort and lighting comfort were collected. To assess the internal validity, the α-values were calculated for the perception scales thermal, acoustic, and lighting comfort and indoor air quality. All items contributed to the internal validity of the scales, except for the statement addressing the perceived lighting comfort, namely “In the classroom, the light rarely flickers”, which was therefore excluded. The α-values for the perception scales ranged from .70 to .89, showing that these scales have considerable reliability (Tavakol & Dennick, 2011). Average perception scores for these sub-categories of perceived IEQ were used for further analyses. The average value for clothing insulation value was 0.5 ± 0.1. With the deletion of the one statement addressing the perceived lighting comfort, the systematic approach for examining the perceived IEQ was adjusted.

Of the five identified response moderators, data of four response moderators were used. The position of the lecturer in the classrooms, as presented Figure 3-6, was the same during the pilot study and did not vary during the lectures or according to the classrooms used. Therefore, this variable was not analyzed during the pilot study. A total of 163 students, with average age of 19.2 ± 1.6 years participated in the pilot study, of whom 64 were female students. The row average in which the students sat, which reflected the relative distance between the lecturer and the individual student, was row 3 ± 1 and an average of 14 ± 3 students were present during the lectures.

Of the students, 20 % reported one symptom, 9 % reported two symptoms, 1 % reported four symptoms, and 1 % reported five symptoms. In addition, students' perceived cognitive response was collected. The α-value of the perceived cognitive response scale is .87, showing that this scale has considerable reliability (Tavakol & Dennick, 2011); therefore, the average perception score of this scale was used for further analyses.

Academic performance was derived from students' perceived quality of learning. The quality of learning items in the questionnaire contributed to the reliability of this perception scale except for the statement "I was very productive during the lecture". This scale was omitted from further analysis because of the low α-value of .68. Furthermore, to measure students' short-term academic performance, they completed a content-related test at the end of each lecture. The percentage of questions correctly answered by the students were used for further analyses. Figure 3-8 presents a summary of the results of the pilot study, with boxplots of all perception and academic performance test scores. Table 3-3 presents the composition of perception scales, α-values of scales, and the α-value when an item was deleted.



Note: APT = academic performance test score; PCR = perceived cognitive response; PIAQ = perceived indoor air quality; PLC = perceived lighting comfort; PTCpref = thermal preference; PTCsens = thermal sensation; PTC = perceived thermal comfort.

Figure 3-8 Perceived indoor environmental quality, cognitive response, and quality of learning scores and academic performance test scores.

Table 3-3 Composition of all perception scales, including α values and related items per category and supporting references.

Scale	Cat.	Item	RS	α Del[1]
PTC (α = 0.70)	Thermal sensation	Please classify the indoor temperature at this moment: cold, cool, slightly cool, neutral, slightly warm, warm, hot	[a]	-
	Thermal preference	At this moment, would you prefer to feel much warmer, warmer, a little warmer, neither warmer nor colder neutral a little colder, colder, much colder	[a]	-
PIAQ (α = 0.82)	Quality of air	There is some stale air in here	✓	0.76
		There is a lot of fresh air in here		0.80
	Ventilation	The classroom is properly ventilated		0.79
	Odor character and intensity	There is a bad smell in here	✓	0.78
	Moisture	The air is dry in here	✓	0.80
		The air is dusty in here	✓	0.80
PLC (α = 0.77)	Amount of (day)light	The visual comfort in the classroom is very bad	✓	0.73
		I can see well in this light		0.73
		The illumination provided by projectors appears to be inadequate	✓	0.70
		It is dark in the classroom	✓	0.73
	Flickering	In the classroom the light rarely flickers[2]		0.77
	Reflections and glare	In the classroom, I frequently experience annoying reflections produced from the outside	✓	0.68
	Color sensation	In the classroom, I frequently experience unpleasant color sensations	✓	0.71
	Contrast	In the classroom, windows create dark areas	✓	0.71
PAC (α = 0.89)	Noise from within the classroom	Students moving and mingling in the classroom interfere with my ability to hear in the classroom	✓	0.88
		Noise from the instrumentation used in the classroom interfere with my ability to hear in the classroom	✓	0.89
	Noise from outside the classroom	Students speaking outside the classroom interfere with my ability to hear in the classroom	✓	0.89
		Noise from people or instrumentation outside the classroom but inside the building interfere with my ability to hear in the classroom	✓	0.88
	Noise disturbance	I experience prolonged noise disturbance	✓	0.89
		I experience short noise disturbance	✓	0.88
		Noises that occur only once interfere with my ability to hear in the classroom	✓	0.88
		Noises that occur occasionally interferes with my ability to hear in the classroom	✓	0.88
		The noises I hear in the classroom bother me	✓	0.88
		The noise disturbs my concentration	✓	0.88
PCR (α = 0.87)	Alertness	I was very alert during the lecture		0.84
	Concentration	I was able to concentrate well during the lecture		0.84
	Memory	I can remember the content of the lecture well		0.83
	Perception	I was able to understand the lecture well		0.84
	Problem solving	I was able to solve complicated problems during lecture well		0.84
PQL (α = 0.68)	Productivity	I was very productive during the lecture		0.79
	Reading	I was able to read well during the lecture		0.42
	Typing	I was able to type well during the lecture		0.47

Note: APT = academic performance test score; PCR = perceived cognitive response; PIAQ = perceived indoor air quality; PLC = perceived lighting comfort; PTC = perceived thermal comfort. Cat. = perceived indoor environmental quality category; RS = reverse score was used to compute scale; α del. = α-value when item is deleted.

[a] = see Table 3-1.

[1] = α value after removing items from scale.

[2] = item was deleted before calculating mean score.

3.2.6 Data Analyses

Multiple regression analyses were conducted to examine how well the independent variables (*x*) could predict the dependent variable (*y*). Firstly, the assumption that the IEQ influences the perceived IEQ was tested. The outdoor conditions reflected in the outdoor temperature and relative humidity were excluded from the data analyses because the students spent more than 20 min in the classroom before they evaluated the thermal environment. Consequently, it was presumed that this time would be sufficient for their bodies to acclimatize to these circumstances (Mishra et al., 2017). The multiple regression model of the indoor air quality and the perceived indoor air quality showed multicollinearity between PM10 and PM2.5. PM10 had the lowest bivariate standard correlation coefficient and was therefore excluded for further analyses. An analysis of the lighting environment revealed that only the horizontal illuminance varied during the pilot study. Therefore, this indicator was included in the analyses. Furthermore, the reverberation time was included in the analysis as an acoustic indicator, because the reverberation time of classroom A, compared to that of classroom B, was the only indicator that differed between the classrooms during the pilot study. A bivariate regression analysis of the assumed relation between students' clothing insulation value, as the independent variable, and students' perceived thermal comfort, as dependent variable, did not reveal a significant relation. Therefore, this relation was not further analyzed. Although the perceived IEQ scales did not pass the Shapiro-Wilk test, the Q-Q plots did not reveal large deviations from normality.

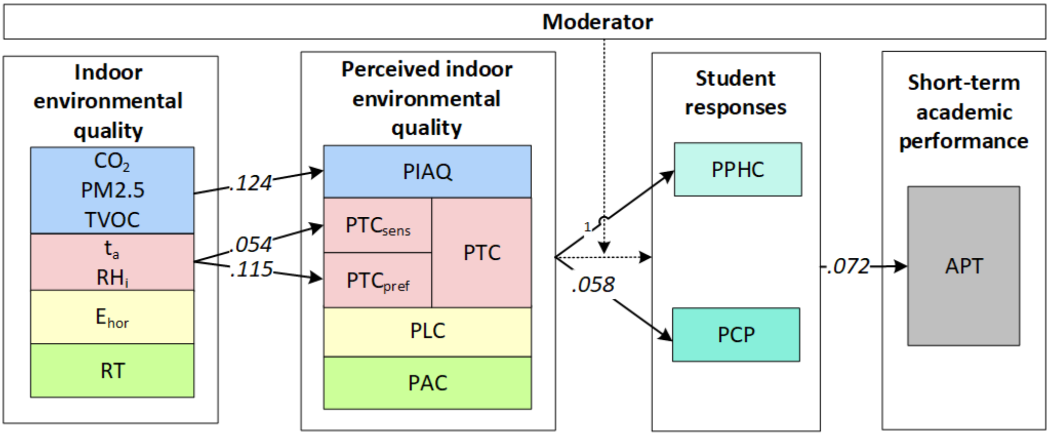
Next, the assumption that the perceived IEQ influences students' responses was tested. Although students' self-reported physiological health complaints and their perceived cognitive performance did not pass the Shapiro-Wilk test, Q-Q plots did not reveal large deviations from normality. The Q-Q plot of the perceived physiological health complaints revealed a skewed distribution of data, indicating that this variable was not normally distributed. The robust models showed higher estimates of all variables except for the model for perceived cognitive performance. However, this estimate was not significant and therefore did not lead to a different conclusion regarding this coefficient. Table 3-4 presents the outcome of all linear regression analyses or Spearman's rho, when the assumptions for regression were not met.

Table 3-4 Outcome of bivariate and multivariate linear regression analyses and Spearman rho coefficient for the data collected.

X	*y*	A	β	R^2_{adj}	F-value	Model sig.	df$_{regr}$	df$_{res}$	SP$_{coef}$
CO_2 PM2.5 TVOC	PIAQ^m	Yes	-.143 -.202* -.178*	.107	7.437	***	3	158	
RH$_i$ T$_a$	PTC$_{sens}^m$	Yes	.239 .112	.042	4.571	*	2	160	
RH$_i$ T$_a$	PTC$_{pref}^m$	Yes	.355*** .104	.104	10.389	***	2	160	
E$_{hor}$	PLC^b	No[1]	-.024	-.006	0.088		1	158	-.039
RT	PAC^b	No[1]	-.023	-.006	0.084		1	159	-.002
PIAQ PTC PLC PAC	PPHC^P	Yes	-.7662[2] .037[2] -.010[2] -.301[2]	0.465***[3] 1.038[3] 0.990[3] 0.740*[3]	n/a	***	4	155	
PIAQ PTC PLC PAC	PCR^m	Yes	.080 .060 .152 .045[4]	.033	2.369	*	4	155	
PCR	APT^m	Yes	.269***	.060	6.055	**	2	155	
PPHC			-.004						

Note: APT = academic performance test score; PCR = perceived cognitive response; PIAQ = perceived indoor air quality; PLC = perceived lighting comfort; PPHC = perceived physiological health complaints; PTC$_{pref}$ = thermal preference; PTC$_{sens}$ = thermal sensation; PTC = perceived thermal comfort.
x = independent variable; *y* = dependent variable; A = assumptions met; β = standardized coefficient beta; R^2_{adj} = squared regression coefficient; df$_{reg}$ = degrees of freedom of regression; df$_{res}$ = degrees of freedom of residual; SP$_{coef}$ = Spearman's rho correlation coefficient; ^{b} = bivariate linear regression analyses; ^{m} = multivariate linear regression analyses; ^{p} = Poisson regression analyses.
* = correlation is significant at the 0.05 level (1-tailed); ** = correlation is significant at the 0.01 level (1-tailed);
*** = correlation is significant at the 0.001 level (1-tailed).
[1] probability plot of standardized residuals and unstandardized residuals revealed a non-linear relationship and the Shapiro-Wilk test revealed a significance level of $p < 0.05$. Therefore, the assumption for normality was not met.
[2] coefficient estimate.
[3] exponentiated value of coefficient.
[4] robust estimate value was lower.

Furthermore, the interactions were analyzed of the response moderators (*w*), namely age, gender, classroom position of students, and number of students present in the classroom during lecture, with the independent (*x*) and the dependent variables (*y*). The aim was to determine whether the effect of *x* on *y* was moderated by *w*; that is, whether the size or sign of the effect of *x* on *y* varied with *w*. However, no significant moderation effects were found. Figure 3-9 depicts significant multivariate linear regression R^2 values between independent and dependent variables.



Note: APT = academic performance test score; PCR = perceived cognitive response; PIAQ = perceived indoor air quality; PLC = perceived lighting comfort; PPHC = perceived physiological health complaints; PTC_{pref} = thermal preference; PTC_{sens} = thermal sensation; PTC = perceived thermal comfort.

^{1} = only exponentiated values of coefficient could be calculated, see Table 3-4.

Figure 3-9 Significant multivariate linear regression R^2 values between independent and dependent variables. See footnote to Figure 3-5 for explanation of symbols and shading.

3.2.7 Discussion

The main objective of this study was to develop and validate a systematic approach that would enable an assessment of the combined influence of IEQ parameters on students' perceptions, responses, and academic performance. To develop this systematic approach, methods derived from 54 included publications were reviewed. This paragraph specifies those methods used to measure the influence of IEQ on students and their short-term academic performance. Possible adjustment behaviors in result to any discomfort experienced, such as opening windows or taking off or putting on clothes, were not included because the composed approach focuses on the consequences of experienced comfort or discomfort *ceteris paribus,* as induced by the IEQ. However, future studies that specifically focus on students' comfort level should account for the possibilities the students have to adjust indoor environmental circumstances. How the IEQ affects students and their performance, in this case with reference to multi-sensory influences on human responses, was ascertained from previously published work (see **Chapter 2**; Mamulova et al., 2022).

Although the identified publications did not always provide detailed information about the applied method, all methods could be linked to a category of the framework (see Figure 3-1), which demonstrates the practical applicability of this framework. The identified methods provide a rich and diverse perspective of how the influence of indoor environmental parameters on students' perceptions, responses, and short-term academic performance can most effectively be measured. The designed systematic approach combines these methods, enabling researchers to study both the individual and the combined influence of all indoor environmental parameters on students. This holistic character of the systematic approach responds to the need to develop human response models to assess the influence of multiple environmental parameters on performance

(Torresin et al., 2018). Students' emotional response and cognitive performance were not tested during the pilot study. The current systematic approach measures the immediate interaction and short-term academic performance of the students, and thus does not measure the long-term effects of the IEQ on students. However, application of this protocol over a longer period and inclusion of long-term academic performance measures, for example, students' grades, may reveal long-term effects. Below, the development, the applicability, and the testing of the systematic approach, is discussed.

3.2.7.1 Development of the systematic approach

The developed systematic approach, which measures the combined influence of all IEQ parameters on students, addresses four main categories: (1) indoor environment, (2) perceived indoor environment, (3) student responses, and (4) academic performance. To determine the IEQ, 54 indicators were identified that provide detailed information about the actual IEQ. In future studies, relevant indicators should be selected from this list of 54 indicators to measure the IEQ, depending on the aim and scope of the study. When studying the influence of the IEQ on students, inclusion of the Pittsburgh Sleep Quality Index and body-related parameters can be considered, depending on the study's aim. Furthermore, body composition and sweat excretion can considered when assessing students' thermal comfort, which may help to explain the variations in thermal comfort under similar conditions (Huiberts et al., 2017; Schweiker et al., 2018).

A comprehensive questionnaire was developed by including the methods that address the perceived IEQ, cognitive responses, and quality of learning. The validity of this questionnaire was tested and confirmed in the pilot study. To cover the cognitive response categories, i.e. attention, perception, memory, and problem-solving, empirically validated and practically feasible tests were selected. However, the tests which were identified during the initial search, were not included in the pilot study, as they were already validated in earlier studies. The advantage of using these existing tests is that a comparison with the results of these earlier studies becomes possible (Ahmed et al., 2017; Sarbu & Pacurar, 2015; Shelton et al., 2009; Siqueira et al., 2017; Xiong et al., 2018). However, possible disadvantages are that not all tests can be easily applied in practical settings and that it sometimes takes more time to determine the students' individual scores. The practical applicability of the selected test for the systematic approach will be tested in a follow-up study.

3.2.7.2 Applicability of systematic approach

The developed systematic approach was deployed in a real-life setting to assess the applicability and validity of new perception scales and to test academic performance, which could not be determined from the information available in the included studies. The internal consistency of the systematic approach measuring the perceived IEQ is acceptable for all scales ($\alpha > 0.70$). However, this evaluation of the internal consistency led to the exclusion of one item, *in the classroom, the light rarely flickers.* The negative contribution of this item to the perceived lighting comfort scale can be explained by the fact that both classrooms were equipped with high-quality LED armatures. In another real-life setting, with lower quality lighting fittings, assessment of this item may be necessary.

None of the identified studies assessed the general health of respondents. This topic, therefore, was not addressed in the pilot study. In general, a dysfunction, such as deafness, color blindness, or sickness, could influence individuals' response to IEQ and their performance, and this should be considered when analyzing results. An additional question, which assesses this topic, could be added to the systematic approach to incorporate awareness of this fact. The moderation effect of the number of sleeping hours, sleep quality, and room temperature at home were not included in the original systematic approach. However, these variables may moderate students' responses and academic performance and may be added to the systematic approach in future studies (Choi et al., 2019; Ahmed et al., 2017). Completing the developed questionnaire, covering the perceived IEQ, physiological and cognitive response, and the quality of learning takes approximately 10 min and requires the availability of a mobile phone, laptop or desktop computer.

3.2.7.3 Testing systematic approach

The pilot study aimed at assessing the applicability and the validity of the systematic approach for simultaneously assessing IEQ parameters in classrooms and focused specifically on those categories that were altered during the development of the approach. During this study, the indoor environment of two classrooms was not actively manipulated, resulting in similar conditions in both classrooms and limited natural variations. However, these natural variations confirmed, to some extent, the assumed associations, as presented by Bitner (1992). Here, significant associations or the absence of assumed associations are discussed. However, the pilot study was not intended to collect evidence about the influence of the IEQ on students. GPOWER was used to determine the statistical power of the collected data (Erdfelder et al., 1996). The achieved power ($1- \beta$) for a bivariate normal model (one-tailed) is sufficient (>0.80) to evaluate the assumed associations, given a relatively small expected effect of 0.20, an α of 0.05, and a sample size of 163.

Of the indicators measured in the pilot study, the indicators for the indoor air quality and indoor humidity showed significant associations ($p < 0.05$) with their related perception, revealing the construct validity of these indicators. Furthermore, significant associations ($p < 0.05$) between the perceived IEQ scales and the perceived physiological health complaints as well as the perceived cognitive response were observed, confirming the construct validity of these variables. Finally, a significant association ($p < 0.001$) was observed between the perceived cognitive response and short-term academic performance. The students reported their perceived cognitive response before they started the academic performance test. However, the explained variance of this perceived cognitive performance on actual academic performance was limited.

The limited variations of the actual IEQ may explain why the observed bivariate and multivariate standardized coefficients are relatively small. Furthermore, the multivariate linear regression model of the actual and perceived indoor air quality showed that indicators for particulate matter (PM10, PM2.5) caused multicollinearity; indicating that one indicator for determining the influence of particulate matter (PM2.5) may be sufficient. The observed indoor air temperature (23.0 ±0.4°C), as an indicator for the thermal environment, was not associated with the related perception scales for thermal comfort, possibly because of limited temperature variations during the study. The insulation value of the clothing was not associated with the indicators for the thermal environment or with the thermal perception scales, thus confirming the findings of Mishra et al. (2017). However, it might be relevant to assess students' ability to adjust their clothing when they experience thermal discomfort, and this item could be added to the systematic approach (Mishra et al., 2017). Furthermore, the assumption was made that the students were fully acclimatized at the time they evaluated their thermal sensation and preference (Mishra et al., 2017). Therefore, the effect of the outside conditions during the pilot study, representing winter conditions in the Netherlands, on students' thermal comfort was not further analyzed. However, climatic and seasonal differences may affect students' adaptive processes and therefore could be added to the protocol, when applicable (Schweiker et al., 2020).

The horizontal illuminance was the only studied indicator for the lighting environment that varied during the pilot study. However, this indicator was not correlated with the related perception scale. The reason may be that the average horizontal illuminance was relatively high (between 514 and 715 lx), low levels of horizontal illuminance levels (< 300 lx) were not observed. There was a small difference between classrooms in terms of the reverberation time (0.12 s), which was the only indicator considered for the acoustic environment that varied during the pilot study. However, it did not influence students' perceived acoustic comfort in the classrooms.

The α-values were acceptable for all indoor environmental perception scales (Tavakol & Dennick, 2011). These perception scales were calculated from the students' individual scores on at least five related statements, except for students' perceived thermal comfort which was derived from students' thermal sensation and preference scores. This assumed relation, see also Table 3-1, is only valid for an average of a large group, but does not hold necessarily for individual votes (Schweiker et al., 2020). The questionnaire covering the scale for perceived lighting comfort only addresses general visual aspects in the classroom. Desk-level lighting conditions were not addressed. These issues could explain the absence of an association between the horizontal illuminance and the related perception scale. Therefore, items that address the perceived task lighting conditions may improve the content validity in the systematic approach. Furthermore, items on perceived acoustic comfort only addressed the perceived noise from within and outside the classroom along with noise disturbance. The ability to hear the lecturer's voice, which entails speech intelligibility and is influenced by the reverberation time in a classroom, was not addressed. Items that address speech intelligibility may also improve the content validity of the systematic approach.

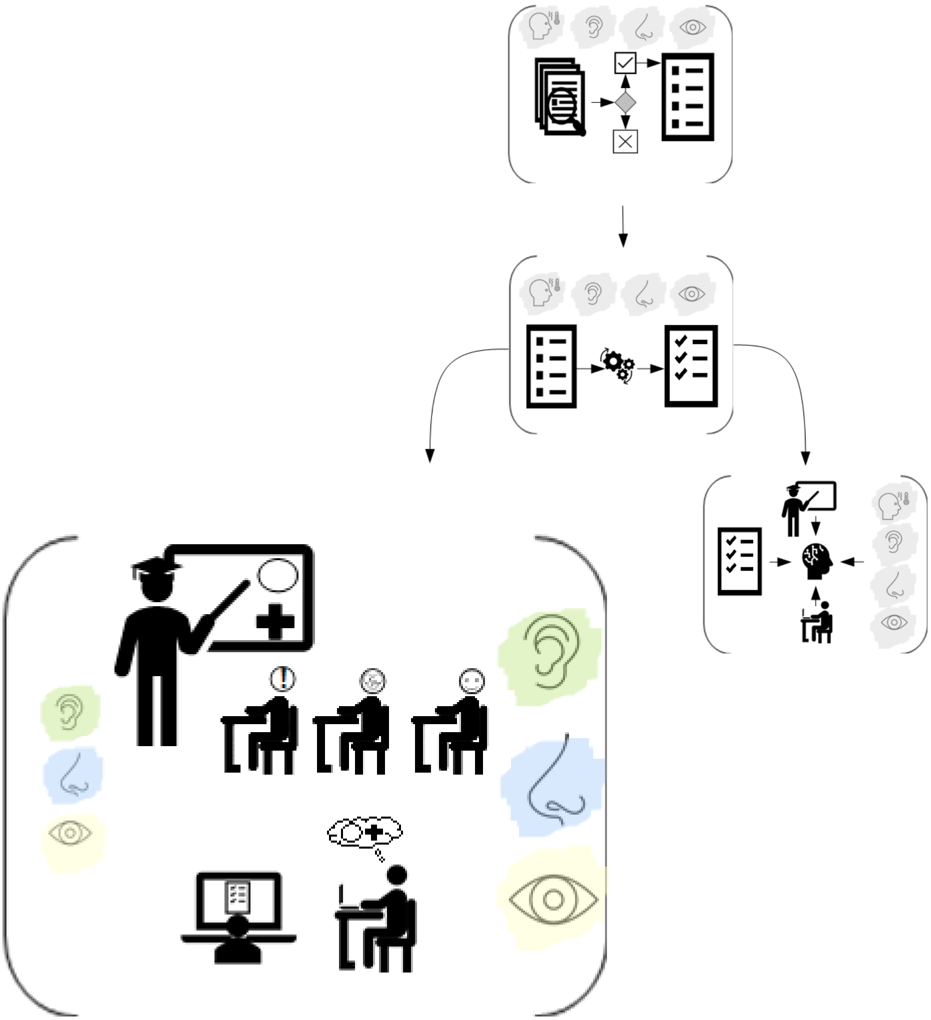
3.2.8 Conclusions

The developed systematic approach allows researchers to examine the combined influence of multiple environmental parameters on students' perceptions, responses, and short-term academic performance. As a result, this approach contributes to the need to develop human response models, which enable the influence of multiple environmental parameters on performance to be assessed and which account for the differences between individuals and their responses to the actual and perceived IEQ.

In a pilot study, associations were observed between the actual IEQ indicators, perceived IEQ, students' responses, and students' short-term academic performance, confirming the ecological validity of this approach. Significant associations (p < .05) between IEQ indicators, students' perceptions of the indoor environment and their reported physiological and cognitive responses were derived. Finally, students' short-term academic performance was found to be significantly associated with their perceived cognitive performance (p < .01). These observed associations confirm the construct validity of the systematic approach for these categories. However, not all assumed associations were confirmed in the pilot study. The validity of the systematic approach to investigate the influence of lighting and the acoustic environment has yet to be determined.

Application of the composed systematic approach facilitates future measurements of the influence of individual or combined IEQ parameters on students' short-term academic performance. Moreover, future studies could also examine the influence of long-term exposure to certain IEQ conditions and their impact on students' long-term academic performance. To make this type of research possible, the current systematic approach should be supplemented with an approach to measure long-term exposure and its influence on students' long-term academic performance. A potential option could be to look at students' grades, for example, before and after a renovation that has improved the IEQ.

4. Field experiment



This subchapter is based on:
Brink, H.W., Krijnen, W.P., Loomans, M.G.L.C., Mobach, M.P., Kort, H.S.M. (2023). Positive effects of indoor environmental conditions on students and their performance in higher education classrooms: A between-groups experiment. *Science of The Total Environment,* 869, 161813.

4.1 Introduction

This study explores the effect of the physical environment on students and their academic performance in higher education, either college or university (Wæraas & 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 & 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 & 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, Van Merriënboer, & Paas, 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 (see **Chapter 2**). 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 & 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 & Saju, 2017; Hoque & Weil, 2016; Rouag-Saffidine & 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 (see **Chapter 2**). 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 Ahmed et al.(2017) addressing neurobehavioral tasks revealed that decreasing temperature from 25°C and 23°C to 20°C, whille 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 proposition: indoor environmental conditions, meeting quality class A of the Dutch guidelines as compared to class B, 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.

4.2 Method

4.2.1 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). Figure 4-1 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.

Intervention condition

Control condition

Figure 4-1 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.

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 wall panels to meet quality class A or B specifications (RVO, 2015). Table 4-1 presents the reverberation time of both conditions at different frequencies.

Table 4-1 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

The intervention condition was fitted with twelve and the control condition with six ETAP U3352 lighting armatures with a color temperature of 3000K and a color 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 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). Figure 4-2 shows the classrooms' layout, including the location and technical details of the HVAC system and the position of the multi-sensor.

4.2.2 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 8 presents details about the used measuring equipment.

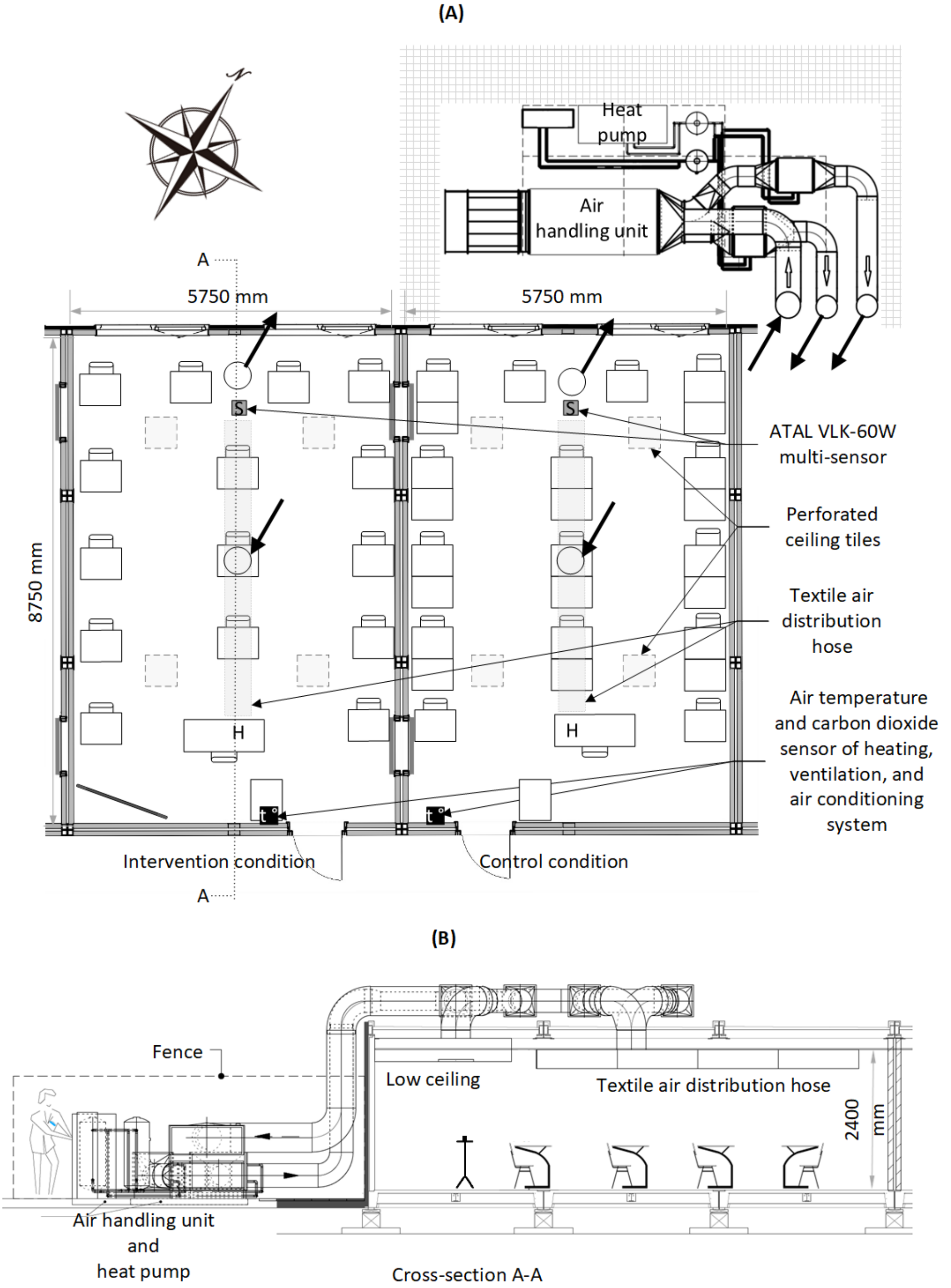


Figure 4-2 Layout of the intervention and control conditions, including the orientation and technical details of the HVAC system and (B) cross-section of the intervention condition.

4.2.3 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 (see **Chapter 3**). 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 statements covering the topics amount of light, reflections, and glare were used (Castilla et al., 2017; Castilla et al., 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, odor intensity and character, and moisture were used (Castilla et al., 2017; Corgnati et al., 2007; Mongkolsawat et al., 2014; Ramprasad & Subbaiyan, 2017; Valavanidis & 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 & Subbaiyan, 2017). Students' perceived health and self-reported physical health complaints were collected with an answering schedule (Ashrafi & 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 10 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 color-word task (Stroop, 1935), and (4) the Wisconsin Card Sorting test (Ozonoff, 1995) respectively (see Table 4-2). Appendix 11 presents more details about these tests and the calculation of the test scores.

Table 4-2 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 color-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]

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 & Gillberg, 1990; Choi et al., 2019). Appendix 7 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; Ahmed, 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 10 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.

4.2.4 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 one 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.

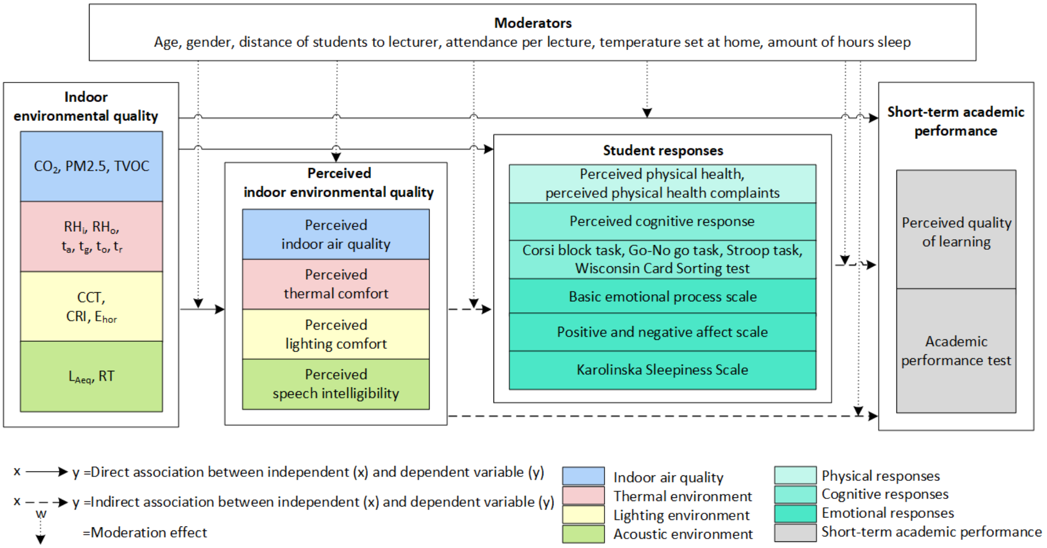
Before the experiment, students were randomly assigned to one of two groups, initially with 15 students each, following the academic course in the experimental or control condition. Students were not allowed to join a lecture in another classroom than pre-assigned. All lectures were given from Tuesday 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 acclimatized 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 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.

4.2.5 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 & Dennick, 2011). Next, the following three research questions were analyzed:

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)?

Figure 4-3 shows an overview of all examined direct and indirect associations and moderation effects, which were derived from a previously performed literature review (see **Chapter 2**). Furthermore, this figure shows all studied categories and variables related to students' perceptions, physical, emotional, and cognitive responses, and short-term academic performance.



Note: CCT = correlated color temperature; CO_2 = carbon dioxide; CRI = color 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.

Figure 4-3 Overview of studied categories and variables, including the examined direct and indirect associations and moderation effects (see ***Chapter 3****).*

4.2.6 Data and statical analysis

To analyze 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 <0.05.

The classroom in which the student attended the lecture (the control or intervention condition) was considered as the independent variable in all LMMs that analyzed direct associations, see Figure 4-3. Significant indirect 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, Figure 4-4 shows a schematic overview to summarize the IEQ interventions and in which academic weeks the campaigns were conducted.

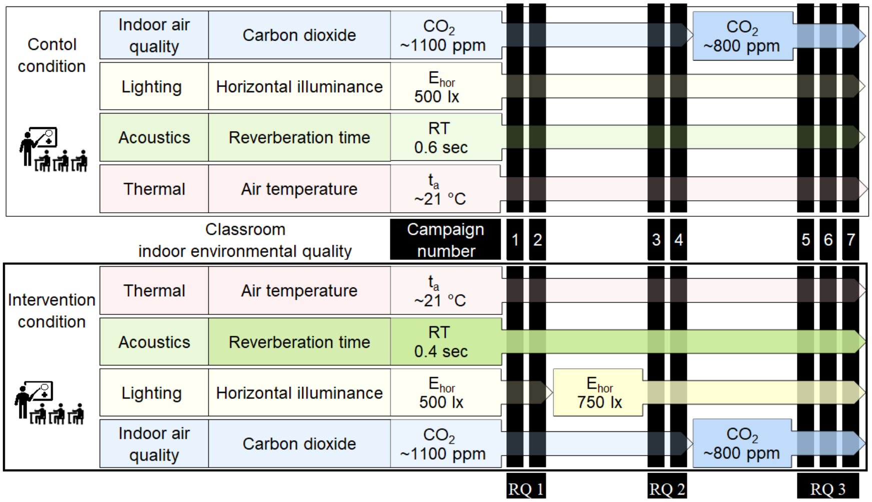


Figure 4-4 Overview of interventions during the experiment, including the intended indoor environmental quality in the intervention and control conditions, the campaigns numbers, and of the data of which campaigns were used to answer the three research questions (RQ). See footnote to Figure 4-3 for explanation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

4.3 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.

4.3.1 Participation and moderators

Table 4-3 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 12, 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.

Table 4-3 Overview student participation and moderators.

Week	Period 2020-2021	CP	CO	n	♀ (%)	Age	Row	AT	DO (%)	t_a set at home (◦C)	Estimated amount of hours sleep
4	29-9/30-9	1[1]	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[1]	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[1]	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[1]	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[2]	I	14	57	20 ± 2	4 ± 1	2 ± 2	13[3]	21 ± 1	7 ± 2
			C	15	53	19 ± 2	3 ± 1	2 ± 2	13[3]	20 ± 1	7 ± 2
13	5-1/8-1	6[2]	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[2]	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: AT = attendance per lecture; DO = desk occupancy; CO = condition; CP = campaign; n = number of participants; t_a = air temperature.

[1] = during partial lockdown to bring down COVID-19 infections in the Netherlands.

[2] = during full lockdown to bring down COVID-19 infections in the Netherlands.

[3] = first week in which the Netherlands were in full lockdown.

4.3.2 Actual indoor environmental quality

With reference to Table 4-1, 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). Figure 4-5 shows the average horizontal illuminance levels at lecturer's and students' desks and how the light was distributed in the classroom during the campaigns.

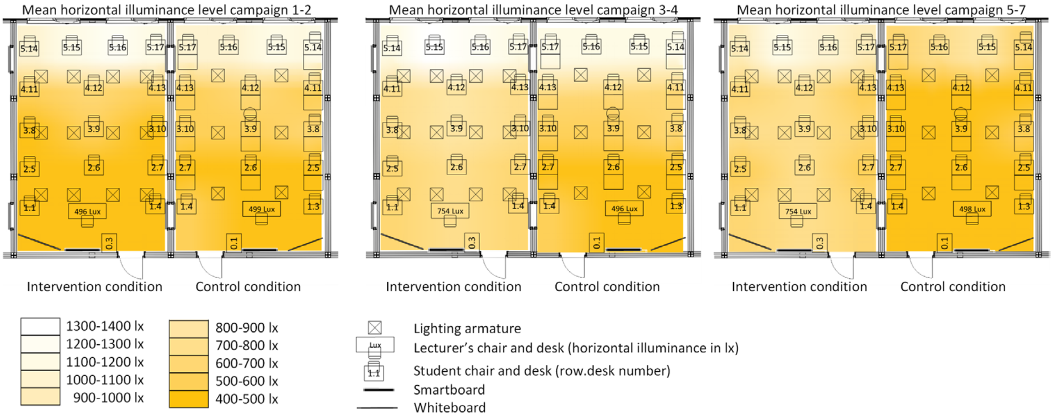


Figure 4-5 Measured average horizontal illuminance level in the classrooms during all campaigns, measured average horizontal illuminance level at lecturer's desk, the row and desk numbers of students' desks, and the location of the lighting armatures, smartboard, and whiteboard.

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 4-4 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.

Table 4-4 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)**
1^1	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
2^1	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
3^1	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
4^1	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
5^2	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
6^2	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
7^2	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.
^{1} = full recirculation system was operational; ^{2} = heating, ventilation, and air conditioning (HVAC) system was operational.

4.3.3 Students perceptions, internal responses, and academic performance

Regarding Table 4-4, 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 ($p = 0.020$; $\beta = 0.33$). 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 12 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.

4.3.4 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 analyze all direct 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 Figure 4-4. 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.

Model 1 Delta reverberation time (-0.2 s) at low horizontal illuminance conditions (500 lx) and low 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; β = 0.34; t(157) = -2.05; p = 0.042). There was a gender effect: male students on average scored higher on their perceived cognitive performance than female students (β = 0.38; t(115) = -2.40; p = 0.018). Also, an indirect association was observed between students' perceived cognitive performance and perceived quality of learning (β = 0.62; t(144) = 10.70; p = 0.000).

Model 2 Delta reverberation time (-0.2 s) and delta horizontal illuminance level (+250 lx) at low 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 (β = 0.37; t(143) = -2.78; p = 0.006). Furthermore, the perceived lighting comfort was negatively influenced when the number of students present was higher (β = -0.06; t(129) = -2.81, $p = 0.$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 (β = -2.10; t(127) = 2.04; p = 0.043), although the robust LMM showed a lower estimate (β = -0.59; t(138) = -1.35). This score was also associated with the row the student sat during the lecture (β = 0.68; t(165) = 2.20; p = 0.029). 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 (β = 0.17; t(202) = 2.96; p = 0.003). A significant effect of gender was observed: female students rated their health on average lower (β = -0.23; t(123) = -2.34; p = 0.003). Students' perceived cognitive performance was positively influenced when the perceived lighting comfort increased (β = 0.39; t(203)

=3.98; *p* = 0.000). Students' ability to hear the lecturers' voice was not significantly associated anymore with students' perceived cognitive performance (β = 0.04; t(197) = 0.45; *p* = 0.65). An improvement in perceived lighting comfort positively influenced the performance indicator matching rules of the Wisconsin Card Sorting test (β = 0.23; t(187) = 2.30; *p* = 0.022). Furthermore, an improvement in perceived lighting comfort positively influenced multiple emotional responses. Students' basic emotional status score was positively influenced (β = 0.10; t(194) = 3.04; *p* = 0.003). 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 (β = 0.04; t(196) = 2.01; *p* = 0.046). Students' emotional positive affect scale score was positively influenced by an improved perceived lighting comfort (β = 1.47; t(210) = 2.33; *p* = 0.021). Students' perceived level of sleepiness was positively influenced by an improved perceived lighting comfort (β = -0.41, t(185) = 2.56; *p* = 0.011).

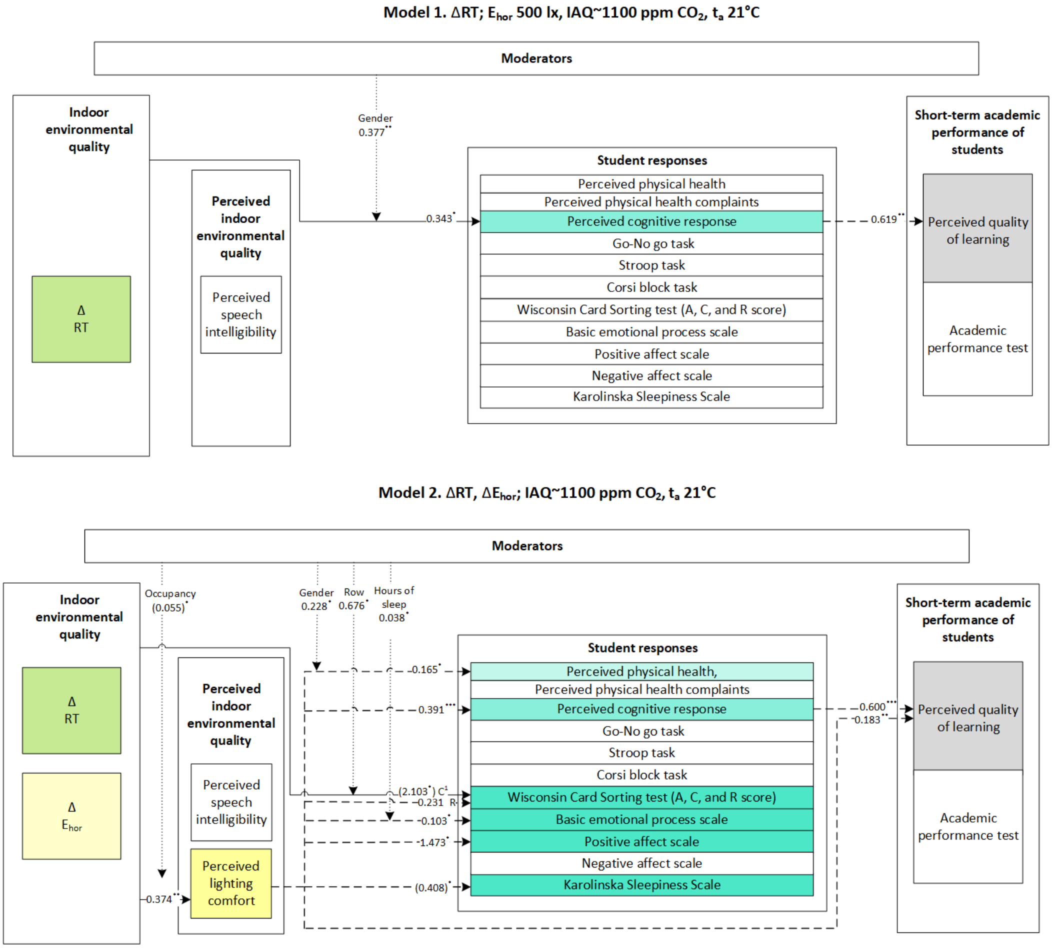
Students' perceived quality of learning score was also positively influenced by the perceived lighting comfort (β = 0.18; t(159) = 3.20; *p* = 0.002) and by the perceived cognitive performance (β = 0.60; t(185) = 11.42; *p* = 0.007). Also, the perceived quality of learning score is positively influenced by students' ability to hear the lecturer's voice (β = 0.12; t(141) = 2.72; *p* = 0.007). 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.

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.

4.3.5 Visualization of direct and indirect associations and moderation effects

Figure 4-6 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.



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.

Figure 4-6 Estimate values of significant associations between the improvement of indoor environmental parameters and students' perceptions, responses, short-term academic performance, and moderators. See Figure 4-3 for explanation of shading.

4.4 Discussion

The main objective of this study was to analyze the effect of multiple IEQ parameters on students' academic performance in higher education. The following proposition was examined: indoor environmental conditions meeting quality class A of the Dutch guidelines, have a positive effect on students' perceptions, responses, and performance. To analyze 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 paragraph 4.2.5, are discussed.

4.4.1 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 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 (see **Chapter 3**), the presented results in paragraph 4.3 do not confirm this relation.

4.4.2 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 analyzed 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 & 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 favor of the level of alertness. This positive effect on sleepiness was also reported by 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 paragraph 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 & 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.

4.4.3 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 4-3.

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 (see **Chapter 2**). 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.

4.5 Strengths 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.

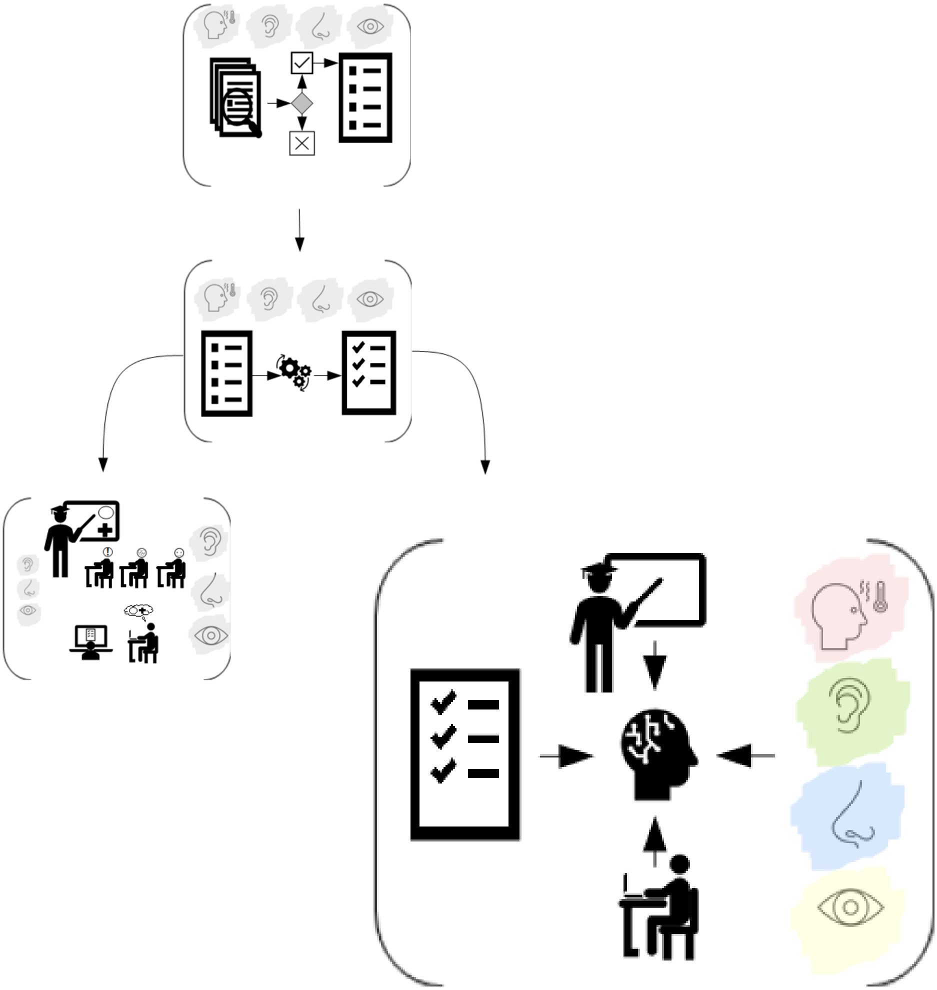
Due to low student attendance and participation during the last three campaigns compared to the first four campaigns of this study, most likely caused by COVID-19 restrictions during this period (Government of the Netherlands, 2020a), no conclusions should be drawn based on the results of these last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

4.6 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.

5. Qualitative case study



This subchapter is based on:

Brink, H.W., Lechner, S.C.M., Loomans, M.G.L.C., Mobach, M.P., Kort, H.S.M. Understanding how indoor environmental classroom conditions influence academic performance in higher education: A qualitative case study. Under review

5.1 Introduction

Classrooms' physical environment plays a significant role in facilitating educational processes (Wang and Degol, 2016). The quality of this environment affects teaching effectiveness and instructional practices (Dawson and Parker, 1998), which in turn affects students' short-term academic performance (see **Chapter 2**). Research on how the physical environment might impact teaching and learning is still relatively new (Granito and Santana, 2016), and until recently, the role that the physical environment plays in students' learning performance has largely been ignored in cognitive load research (Choi et al., 2014). However, there is increasing support to treat the physical environment as an independent variable with the capacity to directly influence educational processes (Choi et al., 2014).

The term physical environment refers to the physical characteristics of learning materials or tools, the physical presence of other people, and the physical attributes of the built environment, for example, volume, density, arrangement, and condition (Wang and Degol, 2016; Choi et al., 2014). This study focuses on the indoor environment, as part of the physical environment, which is a system of indoor air quality (IAQ) and thermal, acoustic, and lighting conditions (Frontczak and Wargocki, 2011). This environment, as observed by human sensors and the way the information of these sensors is processed by the central nervous system and the brain, determines how students and teachers experience the actual indoor environmental conditions (Hall, 1966).

In the Netherlands, currently more than a quarter of all school buildings for primary and secondary education do not provide acceptable IAQ conditions (Ruimte-OK, 2021) which may, for example, affect lecturers' and students' comfort, health, and performance (Brink et al., 2021). Furthermore, research indicates that optimal indoor environmental quality (IEQ) conditions may depend on how students respond to the IEQ and which task they have to perform (Choi et al., 2014; Ahmed et al., 2017, Xiong et al., 2018). However, no single condition has been identified which facilitates all types of cognitive tasks optimally. Furthermore, a recently published literature review did not reveal outcomes reflecting the influence of all IEQ parameters on the quality of teaching (see **Chapter 2**). In addition, this review identified only one study which examined the influence of the IEQ on students' in-class activities (Lee et al., 2012). Therefore, this study aimed to gain more knowledge about how IEQ conditions in classrooms influence short-term academic performance, i.e. the quality of teaching and learning.

A previously developed framework is used to identify relationships between perceived IEQ conditions on one hand and internal responses and short-term academic performance on the other (see **Chapter 3**). The IEQ-related aspects identified in that framework were used to explore and study in-depth how and why lecturers and students respond to different IEQ conditions and how these conditions may influence in-class activities, i.e. teaching and learning, as an indicator for short-term academic performance.

5.2 Purpose

Previous studies report on single-factor or, in some cases, multiple-factor IEQ effects on health, emotional status, or cognitive performance (see **Chapter 2**). Little is known about how both lecturers and students experience single as well as multi-IEQ factors in classrooms during regular academic courses and how these factors influence their teaching and learning activities; all of which is studied here. Moreover, this study also aims to gain insight into possible actions taken by lecturers and students to maintain or create acceptable IEQ conditions in classrooms. Because of the more exploratory nature of the topic, a qualitative research approach was applied and aimed to collect respondents' experiences instead of quantifiable measures. Both lecturers' and students' experiences were captured because there might be different attitudes toward a classroom's IEQ (Granito and Santana, 2016). The results of this study thus reflect the 'end-user' perspective of the IEQ in classrooms for higher education.

5.3 Methods

5.3.1 Design and setting

A qualitative research approach was applied in the context of discovery. This approach enables a deep, thorough, and profound understanding of the matter at hand. Central are the perceptions of lecturers and students and how they respond to actual conditions in classrooms. These classrooms are spread over differently aged buildings, ranging from roughly 1-30 years and are located on the Groningen campus for higher education in Northern Netherlands. All classrooms are suitable to give tutorials with a capacity of approximately 30 students and differ in size, height, and orientation. Furthermore, the classrooms are always equipped with an individual desk and chair for each lecturer and student, a large presentation monitor, and occasionally with a whiteboard. The classrooms are lit with fluorescent ceiling pendants or LED fixtures and daylight can enter the classrooms, directly through windows or indirectly through adjoining atriums, which function as a conduit between separate teaching blocks. In the classrooms there is a possibility to open windows; except for classrooms adjacent to an atrium. All classrooms are heated, with the use of radiators, floor heating, or with a heating, ventilation, and air-conditioning (HVAC) system. The classrooms are naturally ventilated, where outdoor air can enter the classroom through grilles located above the double glazing, and/or mechanically ventilated with the use of a HVAC system. Figure 5-1 shows six representative classrooms, which were discussed together in all sessions with the lecturers and students.

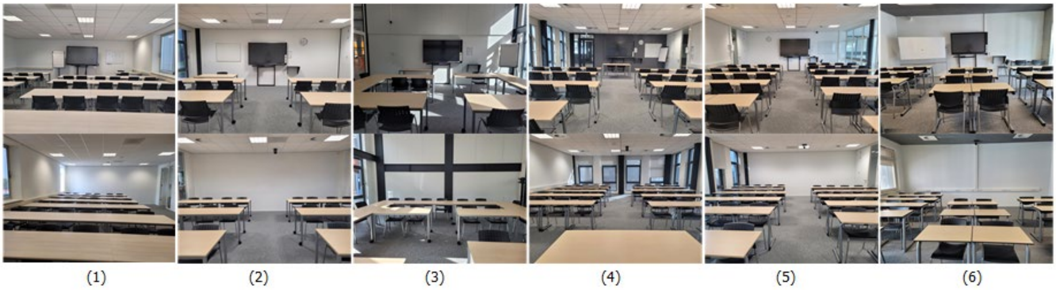


Figure 5-1 Photos of six classrooms. The top photos show the classrooms from a student's perspective, and the bottom photos show a lecturer's perspective.

5.3.2 Selection of lecturers and students

The lecturers who were invited to participate in this study were randomly selected out of a list of 42 lecturers, who taught in one of the classrooms described above for at least one year. After the selected lecturers were invited to participate in this study, one of the lecturers was unavailable. Subsequently, another lecturer was randomly selected and invited to participate. Finally, after all selected lecturers confirmed their participation, they received an email in which they were informed about the purpose of the study and that only their experiences with regular classrooms and not their experiences with open spaces or bullpen rooms would be discussed. In total, 11 lecturers of the Hanze University of Applied Sciences (UAS) were interviewed.

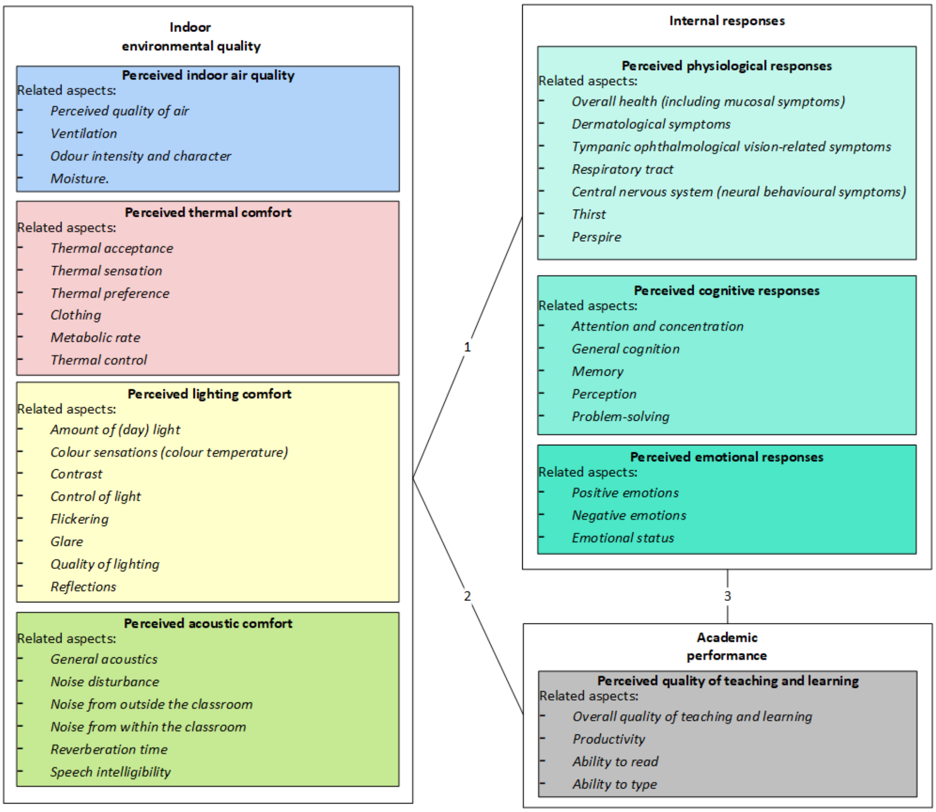
Students were invited to participate in this study in several ways. An announcement was published on the website in which students were invited to participate. At a seminar, first-year students were asked to list their names if they wanted to participate and both authors and lecturers asked students if they wanted to participate during class. All voluntary self-enrolled students for the study participated in one FG. In total, 24 Hanze UAS students participated in three FG discussions. The three FGs consisting of seven to ten students were composed based on the availability of the students and an even distribution of the number of students over the FGs. Similar sample sizes for interviews were applied by Van Someren et al. (2018) and for FGs by Granito and Santana (2016).

At the start of each FG, the students were instructed to share only their experiences with regular classrooms at the Campus Groningen and not their experiences with open spaces or bullpen rooms. The sample size of lecturers and FGs was assumed to be sufficiently large to collect a rich description of detailed information about each individual’s experiences and views. The sample size is determined by the concept of interview saturation, which means the point at which no new themes or insights are emerging from the data. The within-case sampling is nested, theoretically driven, and iterative, therefore, during data collection, the degree of data saturation was continuously assessed (Miles & Huberman, 1994) and established afterwards.

All lecturers and students signed an informed consent form, agreeing that they had no objection to audio and video recordings of the interview or discussion. They were asked to list their name, gender, and age. Lecturers reported how long they teach at Campus Groningen; Participating students reported in which year of what study they were enrolled. All collected data of the lecturers and students were anonymized before data analyses. The final study design was approved by the Ethical Committee of the Hanze UAS (No.2019.026A).

5.3.3 Data collection

Interviews were held using Microsoft Teams, each with a duration of approximately one hour, in February and March 2022. One of the authors moderated the interview with a guide; another author attended the interview and asked additional questions if deemed necessary. Figure 5-2 presents the discussed categories, sub-categories, the related aspects, and their mutual relations which originate from a previous study (see **Chapter 3**).



Note: 1 = direct relation between perceived IEQ and internal responses; 2 = direct relation between perceived IEQ and academic performance; 3 = indirect relation between internal responses and academic performance.

*Figure 5-2 Indoor environmental quality, internal responses, and academic performance sub-categories, related aspects, and their mutual relations (arrows 1,2 and 3) which were analyzed (see **Chapter 3**).*

First, lecturers were shown a presentation containing slides with the following questions, which remained visible to the lecturers during the interview:

1. In general, how do you experience the [sub-category] of classrooms?
2. When applicable, what would you change regarding the [sub-category] in the classrooms?
3. Which other aspects [list of related aspects] do you want to discuss?

The moderator asked the lecturer to answer these questions. All interviews were conducted in January and February 2022 and were video recorded on Microsoft Teams. The audio of these recordings was ripped for automatic transcription. The FG discussions took place at the campus in March 2022. Roles during FGs were the same as in the interview with the lecturers. After welcoming and gratitude, the moderator shared the research goal with the students, clarified the roles of the moderator and researcher, and asked for permission to record the meeting. The minutes were presented on a digital noticeboard during the discussion so students could read, reflect, and respond to these outcomes. When necessary, the minutes were altered during the discussion. The sub-categories (see Figure 5-2) were listed on the digital noticeboard to ensure that these sub-categories were covered during the discussions. The students were asked to share their opinions and experiences related to the IEQ. The moderator then asked the students how their experiences influenced their internal responses and academic performance. If shortcomings were mentioned, the moderator asked the students how these could be resolved in general. The moderator took on a less directive and dominant role during the discussion, mainly by using open-ended questions.

The presentation was only used to provide a common base line for all participants and to familiarize them with the topic. The moderator did not actively ask the lecturer or student to respond to a specific aspect, even when this aspect was not addressed during the interview or FG discussion. This less directive role of the moderator allowed participants to respond without setting too strict boundaries or providing too obvious clues for potential aspects (Krueger and Casey, 2000).

5.3.4 Data analysis

Audiotapes of the interviews were first automatically transcribed verbatim in Dutch with Amberscript (www.amberscript.com). Next, these transcriptions were grammar and spelling checked by one of the authors. All interview transcripts were inductively coded using directed content analysis and the interviews were coded in a random order (Hsieh and Shannon, 2005). Two authors coded the transcripts of the interviews by hand. The minutes of the FGs, reflecting the shared experiences, shortcomings, and practical solutions were coded by hand in the same way. After each interview and FG, the text was coded. The authors discussed the coding labels until consensus was reached.
All transcripts and minutes were then imported into the software package ATLAS.ti, version 22.1.3.0, and all codes were entered. Next, the codes were related to an IEQ aspect and both authors categorized independently all codes to the predefined aspects and related sub-categories (see Figure 5-2). Process to categorize coding labels was replicated from transcript coding and FG minutes.

Furthermore, the researchers evaluated all quotations in the documents as: “no effect (no relation)”, “negative effect (relationship)”, and “positive effect (relationship)”. When the lecturer or student described a specific IEQ condition, the quotation was labelled as a perceived “good” or “poor” condition. When the lecturer or student mentioned a preference for a particular IEQ condition or when a best practice was described, the quotation was labelled as a “solution”. Only one unique relation between a code, relating an IEQ aspect with an internal response or academic performance aspect was included per interview or FG. For example, during the interview when a lecturer mentioned a classroom as being too hot resulting in tiredness more than once within the same context, this relation was coded only once. This approach allowed calculating how often a relationship between these variables was mentioned per interview or FG.

Figure 5-2 shows the analyzed sub-categories, related aspects, and their mutual relations derived from a previously reported framework that guided the data-analysis (see **Chapter 3**). Both direct and indirect relations (see Figure 5-2) between sub-categories were analyzed. To visualize the identified relations and patterns, Sankey diagrams were composed (Sankey, 1898). These diagrams show the quantity sizes that are related to the total identified relations, as mentioned by lecturers and students. The quantity scale uses the width of an arrow and is proportional, for example, twice the number of relations is represented by an arrow that is twice as wide (Schmidt, 2008). Next, two authors independently studied the quotations and patterns related to an internal response or academic performance, which then were discussed and summarized (Miles and Huberman, 1994). Exemplifying quotations for a pattern or relation were selected, translated by all authors, and reported. The data analyses of interviews and FGs aimed to answer the following research questions:

1. How does the IEQ influence lecturers' and students' perceived physiological, emotional, and cognitive responses and the quality of teaching and learning during lectures;
2. What are the lecturers' and students' preferences regarding the IEQ conditions in classrooms?

The next section presents the findings. Identified patterns or conditions are summarized and the number of reported patterns or conditions is listed. However, given the qualitative nature of this study, this number should not be interpreted as a certain level of importance or representation of the pattern or condition. Furthermore, the next section presents quotes from lecturers or students that were exemplary.

5.4 Findings

This section presents the findings of both lecturers and students, summarized for each research question. Sample properties of Hanze UAS Groningen lecturers included gender (5 female; 6 male), age (M = 51 ± 7.3 year), full-time equivalent (FTE) (M = 0.78 ± 0.22), and tenure period (M = 13 ± 10 year). Sample properties of students consisted of gender (12 female; 12 male), age (M = 24.3 ± 5.1 years), and average study year (M = 3.0 ± 1.5). Of 24 students, five followed a part-time academic program, the other students followed a full-time academic program.

During the interviews and FGs, comfortable and uncomfortable conditions were extensively discussed. Of all 43 aspects related to the IEQ, internal responses, and academic performance sub-categories, 41 were identified during the interviews with lecturers. After the 10th lecturer interview these 41 aspects were covered. From a student's perspective, 35 aspects were discussed and 31 of these aspects were covered after the second FG. Table 5-1 presents all sub-categories and aspects, including the number of quotations related to these aspects per interview or FG in chronological order, as presented in code co-occurrence tables exported from ATLAS.ti.

Table 5-1 Overview of all aspects, related to indoor environmental quality, internal responses, and academic performance sub-categories, including the number of quotations per interview or focus group (FG) in chronological order and the moment when all aspects were identified during the interviews or FG discussions. See Figure 5-2 for explanation of shading.

	Interview number[1] (lecturer)											**FG number[1] (students)**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**1**	**2**	**3**
Perceived indoor air quality	✓												✓	
- moisture	1			1					2			2		
- odour intensity and character	2	1	1	2	3	1	1	1	1	4	2		1	1
- perceived quality of air	7	11	2	5	2	1	2	2	2	4	4	8	7	2
- ventilation	3	3	2	7	3	6	5		4	6	7		1	5
Perceived thermal comfort					✓									
- clothing (insulation)		2				1		1	2	1	1			1
- metabolic rate	1	1			1	1		2	1	1	1			
- thermal acceptance		2	2	1	7	2				3	2	2	1	1
- thermal control	2	1	3	1	3	2		1	5	2	2	1	7	4
- thermal preference					1				1		1			1
- thermal sensation	13	5	4	4	13	7	1	7	14	24	14	6	8	12
Perceived lighting comfort										✓				
- amount of (day) light	13	8	5	5	1	8	10	7	5	4	9	25	17	7
- colour sensations (colour temperature)		2	1									2	1	1
- contrast								1			2	1		
- control of light	2	6	2	2	3	1	4		3	7	4	1	3	2
- flickering										1	1		1	
- glare		1			1	1	2		2	1	2	1	1	1
- quality of lighting			1	2	1			1	2				3	
- reflections										1	1			
Perceived acoustic comfort	✓													✓
- general acoustics	3	6		1	1		3	1	1	3	5	4		1
- noise disturbance	4	3	1		1	1	6		4	3	1	2	3	3
- noise from outside the classroom	4	3	1	1	3	1	3	3	4	3	3		1	4
- noise from within the classroom	2	1	1			1				1	2		1	
- reverberation	1	1	1		2			4	4	2	5			3
- speech intelligibility	1	3	5	2	1	2	5	3	5	1	9		2	2
Perceived physiological response														
- central nervous system	2				2	1		1		3	3	1		2
- dermatological symptoms														
- overall health	3	3	1	1	1	2	1	1	2	2	1			1
- perspire				1	2							2	2	1
- respiratory tract	1	1							2					
- thirst	1											1		
- tympanic, ophthalmological, and vision related symptoms	1	1			1	2	1	3					2	2

Table 5-1 continued.

	Interview number[1] (lecturer)											**FG number[1] (students)**		
	1	2	3	4	5	6	7	8	9	10	11	1	2	3
Perceived cognitive performance							✓							
- attention and concentration	8	9	7	1	8	2	8	6	3	11	7	2	7	5
- general cognition			1			1	1						1	
- memory		2		6		1		1	2					
- perception					1		1							
- problem-solving							1				2	1		
Perceived emotional response	✓											✓		
- emotional status	2	3		2	1		1		2	1		2	1	
- negative emotions	10	7	2	3	8	3	9	4	6	4	11	6	5	3
- positive emotions	1	4	2	4	1	6	9	3	8	3	5	6	1	1
Perceived quality of teaching and learning														
- ability to read														
- ability to type	1			1					1		1			
- overall quality	6	1			2		2	3	4	8	7	2	2	1
- productivity	8	8	4	2	2	3	6	6	4	4	9	1	6	3

Note: [1] = interviews and focus group discussions are presented in chronological order; ✓ = moment that all aspects were covered.

Based on the results presented in Table 5-1, the researchers decided not to interview additional lecturers or conduct FGs. The information gathered from the initial interviews and FGs covered all deduced sub-categories. Deduced aspects that were not mentioned by any of the respondents remained unconfirmed empirically and were therefore assumed to be less relevant for respondents. Data collection was deemed sufficient, because saturation was achieved and no new themes emerged from the interviews and FGs.

Next, Sankey diagrams were composed to analyse all positive and negative reported relations between IEQ subcategories and internal responses and academic performance sub-categories. Furthermore, Sankey diagrams were composed to analyse all perceived good and poor IEQ conditions and solutions, which were reported by lecturers and students. Figure 5-3 shows the composed Sankey diagrams. These diagrams noted patterns and themes and revealed plausibility to unravel the relationships and preferences of lecturers and students (Miles and Huberman, 1994).

The following section 5.4.1 presents an overview of the relations between the perceived IEQ, internal responses, and academic performance. Section 5.4.2 summarizes the preferences of lecturers and students regarding classrooms' IEQ conditions.

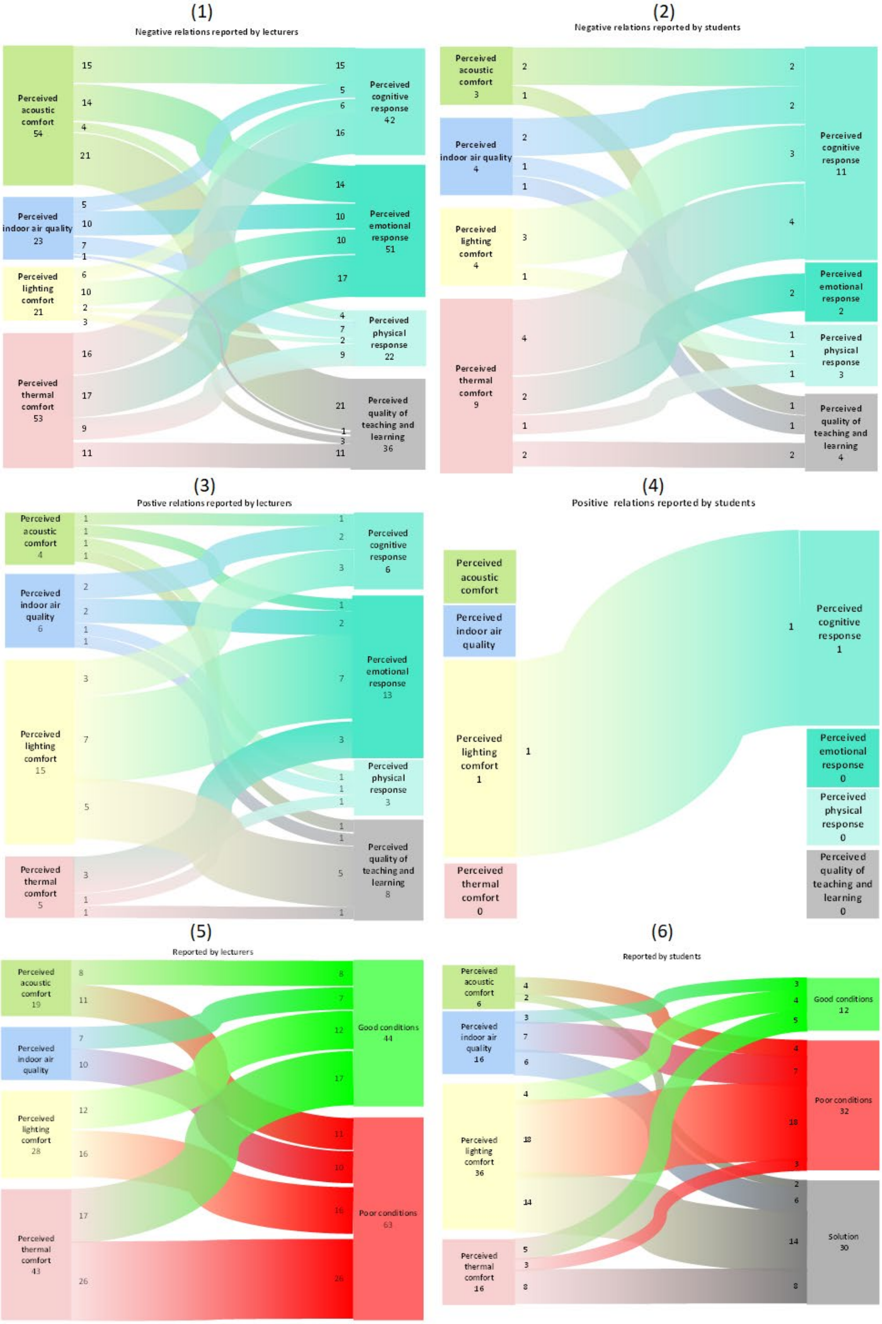


Figure 5-3 *Sankey diagrams of the number of reported positive and negative relations (1-4) and of reported good and poor conditions indoor environmental quality conditions and of the reported solutions by lecturers and students (5-6). These size of the relations in the diagrams is proportional and refers to the quantity sizes that are related to the total identified relations. See Figure 2 for explanation of shading in diagrams. In the diagrams five and six, green shading refers to "good conditions", red shading refers to "poor conditions", and grey shading refers to "solutions".*

5.4.1 Relations between the perceived IEQ, internal responses, and academic performance

This section presents an overview of the reported positive and negative relations between the perceived IEQ, internal responses, and academic performance by lecturers and students.

Impact of IAQ

The perception of the air quality in classrooms varied from lecturer to lecturer. Of the 11 lectures which were interviewed, four indicated that they are not aware of the air quality in the classrooms. However, three lecturers expressed the need to ventilate the room manually, for example, at the beginning of the lecture briefly but intensively (when a classroom was occupied) or when there were relatively many students present (related to the maximum capacity of the classroom), for example, by opening windows or doors. The possibility to open a window in the classroom also positively influenced lecturers' perceived health (n = 2). Furthermore, the perceived quality of teaching was positively influenced when lecturers perceived fresh air in the classroom (n = 2). Students experienced the air quality differently. At moments, the perceived air quality was acceptable. However, students also experienced a lack of ventilation in classrooms (FG1). When students perceived fresh air in a classroom, this positively influenced their ability to concentrate (FG1). A lecturer expressed the mutual interdependence between perceived IAQ, thermal comfort, lighting comfort, and physiological health:

> *"If I am in a classroom room where the windows cannot be opened, where the sun shines on the window and it gets hotter, and where it smells because students are active, then yes, I do not feel healthy."*

Impact of thermal comfort

In comparison with acoustic, lighting, and IAQ conditions, lecturers were the most dissatisfied with the thermal conditions (n = 10). Lecturers experienced the classrooms often as too warm or hot (n = 10). However, during the heating season, classrooms can also be too cold, especially on Monday morning (n = 4). Students perceived the thermal conditions in classrooms also as warm, too warm, or much too warm; especially when the classroom door was kept closed (FG1,3). In one FG, there was consensus that classrooms were never too cold (FG3). Thermal discomfort, due to feeling (too) warm, was the most frequently reported cause of physiological health complaints; lecturers related this thermal sensation of (too) warm mostly to headache (n = 4) and fatigue (n = 4). Other reported complaints related to thermal discomfort were eye irritation (n = 1), sweating (n = 1), drowsiness (n = 1), dizziness (n = 1), a drowsy or tired feeling (n = 1), and languor (n = 1). Students reported that thermal discomfort, due to high temperatures, caused nausea and sweating (FG1,2,3), made them feel tired and corny (FG2,3), and led to concentration problems (FG1,2). In thermal discomfortable conditions, lecturers experienced that students were less alert (n = 2) and were distracted (n = 2). One lecturer indicated that he had to put in more effort to keep students focused:

"If you had to teach in the sun all day, you are just very tired. Heat does something to you anyway. And also, the feeling that I teach financial courses and you know that a lot of students find these courses very difficult, that you really have to pay attention to them and that is just not possible in classrooms which are way too hot."

Thermal discomfort also affected the quality of teaching. For example, when it was too warm in a classroom it caused a decline in contact moments with students (n = 1). Lecturers decided to break earlier than originally planned (n = 3). Furthermore, lecturers speeded up the pace (n = 1) of the lecture or shorten the lecture when they noticed students became tired (n = 1).

Impact of lighting

When the IEQ in classrooms was discussed, students addressed lighting conditions the most; compared to lecturers, who mention thermal conditions the most. Lecturers experienced classrooms' lighting conditions as sufficient or good (n = 5). Students' comments addressing the perceived lighting conditions were "continuously not nice", "too bright", "intense", and "white"; uncomfortable lighting conditions caused heavy eyes, sweaty hands, and headaches (FG1,2). Students reported that light flicker caused distraction and bright light from above caused annoying reflections on their laptop screen (FG2). In addition, bright lights, from lighting fixtures in the ceiling (see Figure 1, classrooms 1, 2, 4, and 5) also distracted students:

"In a bright room, your eyes are slightly attracted to the ceiling."

A lecturer reported that direct sunlight in the classroom caused fatigue and headaches. However, when little or no daylight entered the classroom, lecturers felt unpleasant or enclosed (n = 2). When the amount of (day)light in classrooms was perceived as high, lecturers reported that students could concentrate better and were more active (n = 3). The presence of daylight contributed positively to the quality of teaching and learning (n = 3). The latter was also addressed by the students, who indicated that they are more active in bright lighting conditions (FG2). Furthermore, a lot of (day)light in a classroom gave lecturers a pleasant feeling and classrooms with a view to the outside gave lecturers a happy feeling (n = 2).

Impact of acoustics

Lecturers' experiences of classrooms' acoustic conditions can be divided into experiences related to the acoustic properties of the room and noise disturbances. The acoustic properties were described as fine or good (n = 5), or as an aspect that does not cause any problems (n = 1). However, other lecturers described specific classrooms as unacceptable, referring in particular to too much reverberation (n = 2). One lecturer described a classroom with long reverberation:

"[…] and there it is really dramatic. Then I would almost like to say, the acoustics are even worse than in the (other) building, because there are just concrete walls and noise resonates in all directions."

When lecturers can hear students well, this positively influenced their perceived health (n = 2). In FG3, there was agreement that classrooms' speech intelligibility was not sufficient when students sat at the back of the classroom. According to lecturers, students' attention or concentration was disrupted due to noise disturbances, either from within or outside the classroom (n = 9). When lecturers experienced noise disturbances, this led to a feeling of irritability (n = 2), fatigue (n = 2), and restlessness (n = 1). Students associated open classroom' doors specifically with noise disturbances (FG1).

5.4.2 Lecturers' and students' preferences regarding the IEQ conditions in classrooms

To determine what lecturers and students prefer in classrooms, all quotations coded with "good conditions", "poor conditions", or "solution" were selected. Next, Sankey diagrams were composed of the reported number of good and poor conditions and solutions, see Figure 5-3. The next two sections summarize the preferences of lecturers and students regarding classrooms' IEQ conditions.

Lecturers' preferences for classrooms

Lecturers related acceptable thermal conditions to a slightly cool, cool, or slightly warm sensation. Furthermore, two lecturers indicated that they can respond well to the different thermal conditions by adjusting their clothing (n = 2). Lecturers expressed the need to control the temperature to maintain an acceptable thermal environment (n = 5). Although lighting conditions were described as acceptable or good (n = 6), lecturers preferred bright conditions which may be a combination of daylight and artificial light (n = 5). Lecturers emphasized the importance of daylight present (n = 6), clearly illustrated by one lecturer:

> *"I experience it (the lighting conditions in a classroom) as good. I prefer daylight though."*

Furthermore, it is important to fix broken armatures as soon as possible, to prevent distraction due to light flicker and/or an irritating beep (n = 2). Lecturers expressed the need of having blinds or awnings that work (n = 3). These facilities should allow individual control to prevent annoying glare and to prevent thermal discomfort due to direct sunlight entering the classroom and causing high temperatures (n = 7). The possibility of manually controlling the light color was mentioned by one lecturer to activate students, specifically at the end of the day.

Lecturers describe the general acoustic properties of classrooms as good (n = 6). Critical factors are a short reverberation time and good speech intelligibility (n = 3); for example, when carpeting is applied. Moreover, to prevent noise disturbances, it is important to maintain acceptable thermal and IAQ conditions in a classroom. This will reduce the need to open a window (n = 5), and therefore, reduces the risk of noise disturbances which negatively influence the quality of teaching and learning.

Students' preferences for classrooms

To maintain an acceptable acoustic environment, students expressed the need to prevent noise disturbances (FG3). Furthermore, students prefer sound amplification of the lecturer's voice in classrooms where speech intelligibility is poor (FG2). Students in all FGs highlighted the importance of adequate ventilation. Furthermore, according to the students there is a relationship between good IAQ conditions on the one hand and acceptable thermal conditions on the other (FG2). In all FGs, students were the most dissatisfied with the lighting conditions in the classrooms. Students suggested that lighting conditions should be adjusted in intensity (FG2,3) and in color temperature (FG1,2), depending on the activity, for example, lecturing, presenting, or studying. Furthermore, bright light sources, which cause distraction and annoying glare should not be applied (FG1). According to the students in FG3, their thermal sensation was never too cold. When students felt thermal discomfort, this was due to too warm sensations (FG1,2). Students of FG1 expressed the need to control classroom temperature. Students of FG3 indicated that they prefer a slightly cool above slightly warm sensation.

5.5 Originality and discussion

This research qualitatively explored the experiences of lecturers and students with IEQ conditions and classrooms, intended to reveal the impact of these conditions on internal responses and the quality of teaching and learning. For this study, a previously composed framework was used to examine the relations between the IEQ conditions, lecturers' and students' internal responses, and academic performance (see **Chapter 3**).

To gain insight in these relations, a qualitative approach was chosen to understand how users experience and use a classroom and which actions they take when the IEQ did not meet their expectations. Lecturers and students emphasized the importance of optimal IEQ conditions, indicating that it must be taken into account when designing future academic teaching and learning environments. The findings also show that obtaining and maintaining acceptable IEQ conditions is challenging. Applying the highest quality class for the indoor environment, as specified in Dutch guidelines for school buildings (RVO, 2021), without further consideration can induce both positive and negative effects on users (Brink et al, 2023).

Although in the present study all students experienced thermal discomfort due to thermal warm sensations, individuals may experience a wide range of thermal comfort responses to the same environmental stimuli at different times and in different emotional or social contexts (Hoque and Weil, 2016). This makes it even more difficult to create acceptable conditions for all users. In an attempt to obtain acceptable thermal and IAQ conditions, lecturers report opening windows or doors. However, a related adverse effect is noise disturbances which, in turn, affect the quality of teaching and learning. This is consistent with the work of Chowdhury (2010). Maintaining acceptable acoustic conditions in classrooms is essential and contributes positively to students' quality of learning (Lee et al., 2012). When comfortable IEQ conditions are created in classrooms, which are conducive to students' learning quality, it might reduce teaching time and improve teaching efficiency (McDonald et al., 2004). Maintaining acceptable IAQ conditions at a minimum will improve students' perception of it (Norbäck et al., 2013).

The findings of this research show that lecturers and students are well aware of poor and good IEQ conditions and have preferences regarding these conditions. Lecturers and students, who participated in this research, expressed a preference for daylight in classrooms, in line with the findings of Kok et al. (2015), although direct sunlight entry should be prevented. Furthermore, lecturers expressed the need to adjust lighting conditions in order to improve students' ability to concentrate. Indeed, for example, exposure to blue-enriched white morning light lighting improves students' subjective perception of alertness, mood, and visual comfort (Choi et al., 2019). In addition, alterations in thermal and lighting conditions enhance different learning tasks, while relatively quiet sonic conditions should be maintained, as described, and specified in the study of Xiong et al.(2018). This argues for classrooms in which both lighting and thermal conditions can be adjusted while maintaining acceptable IAQ, with good acoustic properties, and in which no noise disturbances occur.

5.6 Strengths and limitations

The described findings are based on classrooms of only one campus for higher education. However, be reminded that the current study does not seek to generalize the findings to a population of lecturers and students. This study wanted to categorize and exemplify their experiences and using these in the context of understanding the relations between the IEQ and the perceptions of students and staff during lectures in higher education. However, lecturers and students with different educational backgrounds from other universities or educational programs may have experienced and reported other IEQ conditions and also may have had different qualifications and assessments of their experiences with the IEQ conditions and their influence on their internal responses and academic performance. These cautions notwithstanding, the interviews and FGs mostly showed consistent patterns and chains of evidence and revealed relations between the IEQ, internal responses, and academic performance. These findings can also be used in future research.

5.7 Conclusions

This study revealed relationships between the IEQ parameters and internal responses of lecturers and students. Relations were positive, e.g. when the perceived thermal comfort was acceptable, so was the perceived air quality. Relations were negative, e.g. when the perceived air quality was unacceptable, lecturers and student tend to open windows and doors which allow noises from hallways or outdoors to enter the classroom. These noise disturbances had adverse effects on lecturers' and students' perceived ability to concentrate. Both groups of respondents reported that uncomfortable IEQ conditions caused health complaints and affected their emotional status and ability to concentrate. Furthermore, in poor IEQ conditions, lecturers may decide to speed up the pace of a lecture, pause earlier than planned or end the lecture earlier than originally planned which may affect the academic performance of both lecturers and students. Therefore, in future research, the number of breaks, the pace of lecturing, and the duration of a lecture can be included as indicators for the quality of teaching and learning. In turn, comfortable conditions were reported to positively influence the emotional and cognitive status and academic performance of both lecturers and students. It is concluded that maintaining acceptable IAQ conditions, adjusting indoor temperatures, controlling and adjusting lighting conditions, and preventing noise disturbances are key aspects to facilitate in-class activities in higher education.

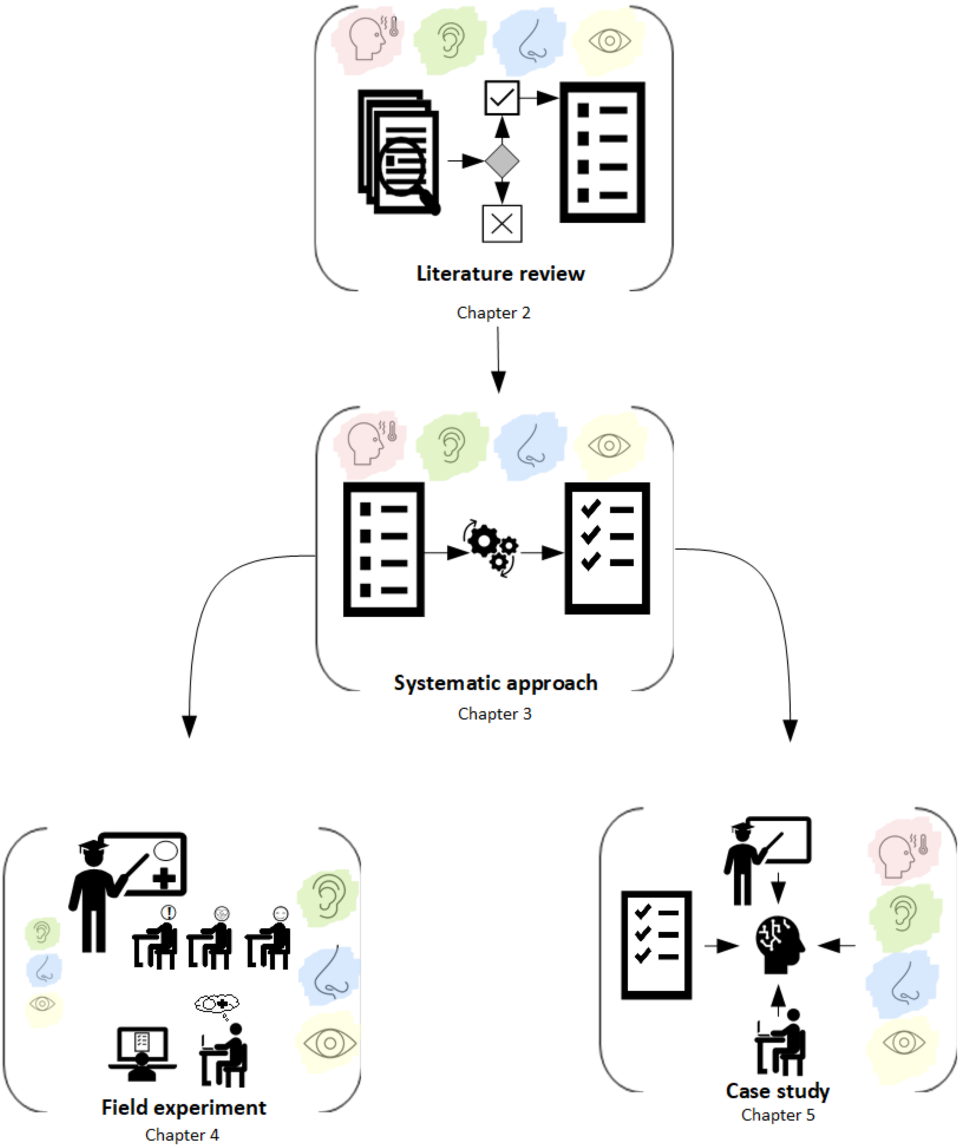
5.8 Practical implications

This study qualitatively examined the relations of IEQ parameters with physiological, emotional, and cognitive responses, and the quality of teaching and learning. This study revealed that lecturers and students experience a variety of IEQ conditions in classrooms and assess these very differently, from acceptable to poor conditions. The stance towards the incorporation of these end-user perceptions, emphasized by the facility manager in the renovation or construction of university buildings, is the primary responsibility of building engineers.

To maintain acceptable sonic conditions, classrooms' thermal and IAQ conditions must be within an acceptable range. Therefore, building-related installations, such as a HVAC system, must be designed in such a way that the system and end users can maintain acceptable IEQ conditions, especially when occupancy rates are high. Furthermore, noise disturbances from inside or outside the building should be prevented at all times and lecturers and students prefer classrooms with daylight in combination with awnings or blinds.

The results of this study contribute to the awareness that the IEQ can be designed in such way that it may improve the quality of in-class activities. Optimal IEQ conditions contribute to creating better teaching and learning conditions in school buildings which foster the development of students in higher education. In turn, upon graduation better trained students will enter the workforce, and by doing so, contribute and add value to society (Cohen et al., 2019).

6. General discussion



This thesis examines the influence of indoor environmental quality, defined by classrooms' acoustics, indoor air quality, thermal, and visual conditions on lecturers and students in higher education (Frontczak & Wargocki, 2011). The overall aim is to answer the following research question: How do IEQ conditions in higher education classrooms influence students and lecturers? In total four propositions are examined: (1) the IEQ influences the quality of teaching; (2) the IEQ influences the quality of learning, (3) the IEQ influences the students' academic achievement, and (4) indoor environmental conditions, meeting quality class A of the Dutch guidelines as compared to class B, have a positive effect on students' perceptions, responses, and performance. This thesis provides new knowledge about how to facilitate in-class activities in higher education, which can be used to design future learning environments and for the development of new guidelines. The central information in this thesis is organized around four studies.

The first study presents an overview of existing knowledge about the impact of IEQ conditions on lecturers and students and examines the first, second and third propositions (see **chapter 2**). The second study presents a systematic approach to measure the IEQ conditions and lecturers' and students' perceptions of it, their responses to these IEQ conditions and how the related academic outcome can be measured (see **chapter 3**). Applying the developed systematic approach, the third study examines the effect of improved IEQ conditions during a regular academic course and examines the fourth proposition (see **chapter 4**). Furthermore, the second and third propositions will be discussed in this chapter based on the results of this study. The fourth and final study presents insight into how lecturers and students experience actual IEQ conditions in classrooms and how these conditions influence their perceptions, responses, and academic outcomes (see **chapter 5**). Based on the findings of this study, propositions one, two, and three will be discussed in this chapter. The current chapter summarizes and discusses the key findings of the current work and describes the implications for science and practice. The final section of this chapter summarizes the strengths and limitations of the current work and provides suggestions for future research directions.

6.1 Key findings

6.1.1 Summary of key findings of the systematic literature review

The first study aimed to answer the following research question: What is the effect of the IEQ in classrooms in higher education on the quality of teaching and learning, and students' academic achievement? To understand the relationship between the IEQ, teaching and learning, and academic achievement, the framework developed by Donabedian (1988) was applied in an academic context. Figure 6-1 shows this adapted framework which was used to assess the quality of academic outcome, when the indoor environment was treated as an independent variable of structure which influenced consecutively teaching and learning processes and students' academic achievement. Academic outcome refers to students' short-term and long-term academic performance.

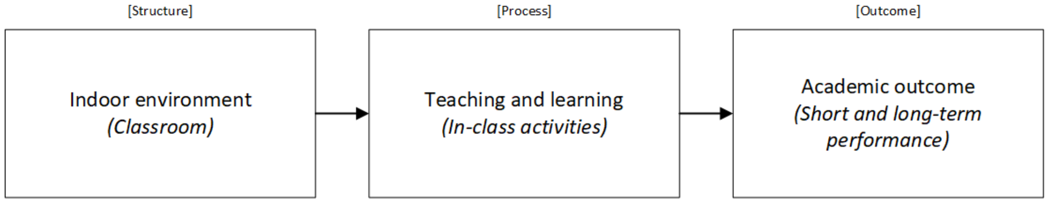
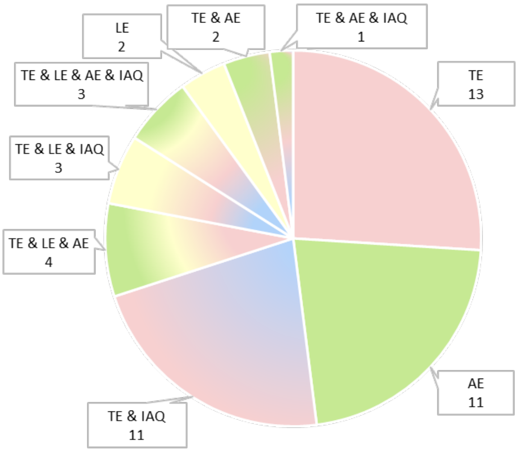


Figure 6-1 Conceptual framework to understand relations between classrooms' indoor environment, teaching, and learning, and academic outcome, adapted from Donabedian (1988).

In a systematic literature review, in total, 63 studies were identified which examined the effect of the IEQ on students or lecturers in higher education. Of these 63 studies, 50 measured one or more IEQ performance indicators. However, only three studies specified the accuracy of the used measuring equipment and described the location in the classroom where the measurements were performed (Bajc et al., 2018; Corgnati et al., 2007; Hoque & Weil, 2016). Of the 50 studies which measured at least one IEQ performance indicator, 37 studies measured thermal performance indicators, which makes the thermal environment the most studied IEQ parameter. The least studied IEQ parameter was the lighting environment (n = 12). Figure 6-2 presents how the four IEQ parameters are distributed among the 50 studies that measured the actual IEQ conditions.



Note:

🟦 IAQ = Indoor Air Quality
🟥 TE = Thermal Environment
🟨 LE = Lighting Environment
🟩 AE = Acoustic Environment

Figure 6-2 Distribution of the four IEQ parameters among the 50 studies that measured the actual IEQ conditions.

The IAQ was always measured in combination with thermal environmental performance indicators. According to Liu et al. (2019), students' thermal comfort and IAQ acceptability are correlated. This emphasizes the importance of examining these two parameters in conjunction or when examining the influence of one parameter the other should be controlled. All studies which measured the IAQ (n = 18), measured the CO_2 concentration, as a proxy for IAQ, indicating that this performance indicator is commonly accepted as an indicator for IAQ. In general, humans are the only source of CO_2 and other bio-effluents. None of the included studies analyzed the effect of pure elevated CO_2. Therefore, CO_2 concentration should be considered as an indicator of ventilation adequacy, which can be related to human bio-effluents. The effect of improved or poor IAQ conditions on students' comfort, health, and short-term academic performance was measured with a variety of instruments; none of the methods used was employed in other studies making the outcomes difficult to compare.

When assessing thermal comfort (n = 37), the air temperature was measured in 35 studies and in 25 of these studies the relative humidity was also measured; making these the most measured performance indicators. However, it should be noted that students' thermal comfort is also influenced by other thermal environmental performance indicators, such as mean radiant temperature, air movement, and clothing insulation (IUPS Thermal Commission, 2001). Students' thermal comfort, defined as subjective indifference to the thermal environment (IUPS Thermal Commission, 2001), was assessed with two thermal comfort models in 80 % of the studies. These models are the predicted mean vote - predicted percentage of dissatisfied (PMV-PPD) model, as defined by Fanger (1970) and applied in NEN-EN-ISO 7730 (2005). The other model is the adaptive comfort model, developed by De Dear and Brager (1998) and specified in NEN-EN 15251 (2007). The latter was developed because there was a discrepancy between the real thermal comfort of humans and the predicted comfort derived from the PMV-PPD model, mainly caused by human's capability of thermal adaptation. However, both methods use the same perception scales to evaluate humans' actual thermal sensation and thermal preference, which allowed comparing the results of these studies.

Studies that examined the acoustic environment, focused on different levels and types of background noise (Chin & Saju, 2017; Chowdhury et al., 2010; Jamaludin et al., 2016; Lee et al., 2012; Markides, 1989; Rabelo et al., 2019; Xiong et al., 2018), sound disturbance (End et al., 2010; Shelton et al., 2009), sound amplification (Jonsdottir, 2006), and reverberation time (Castro-Martínez et al., 2016; Chen & Ou, 2019; Pekkarinen & Viljanen, 1990). However, no standardized or similar methods to measure the effect of the acoustic or sonic environment were applied, which made it impossible to compare the study outcomes.

The lighting environment was the least studied environmental parameter (n=12). To determine this environment, the illuminance level was always measured; however, studies reported the ambient illuminance, horizontal illuminance, or vertical illuminance level. The included studies did not use similar methods to examine the influence of the lighting environment. However, four standardized methods were identified, i.e., Positive And Negative Affect Scales (Watson et al., 1988), Basic Emotional Process Scale (Kuller, 1991), Karolinska Sleepiness Scale, (Åkerstedt & Gillberg, 1990) and the Pittsburgh Sleep Quality Index (Buysse et al., 1989).

As defined in **Chapter 2**, the quality of teaching and learning is determined by the level of comfort, mental health, and physical health of students. Three studies measured performance indicators of all four IEQ parameters; none of these studies analyzed the combined influence of these parameters on the quality of teaching, learning, or academic achievement (Ahmed et al., 2017; Jamaludin et al., 2016; Lee et al., 2012). Therefore, the emergent properties of all four indoor environmental parameters cannot be determined yet.

The 21 selected studies of high quality and relevance revealed to some extent the influence of the IEQ parameters. All four parameters, i.e., IAQ, thermal conditions, acoustic conditions, and lighting conditions, were related to positive effects on students' perceptions, health, emotions, cognitive performance, and (self-reported) short-term academic performance (Bajc et al., 2018; Choi et al., 2019; Hoque & Weil, 2016; Ahmed et al., 2017; Norbäck et al., 2013; Xiong et al., 2018). One study applied a full factorial design. This design allowed examining the influence and interaction effects of multiple IEQ parameters, i.e., acoustic (noise), thermal (air temperature), and lighting (illuminance) (Xiong et al., 2018). The results of this study revealed that four cognitive tasks, i.e., an attention and concentration, a memory, a perception, and a problem-solving task, were performed best in different IEQ conditions (Xiong et al., 2018). These results indicate that optimal acoustic, thermal, and lighting conditions, in which the students performed at their best, are task dependent. This task dependency is also confirmed by Ahmed et al. (2017) and Siqueira et al.(2017). Students' quality of learning determines, among others, their academic achievement. The 21 studies of high quality and relevance provided sufficient evidence to confirm the proposition that the IEQ influences the quality of learning.

Only two studies examined the influence of IEQ parameters on the quality of teaching and revealed to some extent the influence of the IEQ on the quality of teaching. The lecturer's speech intelligibility, which is influenced by the reverberation time in classrooms, is an essential element in the transfer of knowledge from lecturer to student (Rabelo et al., 2019). Furthermore, high noise levels in classrooms can cause heavy strain on lecturers' vocal cords and increase teachers' health risks (Castro-Martínez et al., 2016). Because the evidence addressing the quality of teaching is limited, the proposition that the IEQ influences the quality of teaching was not confirmed or rejected.

Studies showing that the IEQ influences students' short-term academic performance partially confirm the third proposition. On one side, the available evidence that specifies the influence of the IEQ is sufficient to conclude that these conditions can either influence this performance positively or negatively. However, on the other side, the hypothesized influence of all IEQ parameters on students' long-term academic performance cannot be confirmed due to a lack of evidence. None of the included studies examined the effect of IEQ on students' long-term academic performance. Long-term academic performance focusses, for example, on the performance of students for a course or academic year. Although one study examined students' exam scores, the researchers assessed short-term academic performance because these scores were related to students' actual thermal sensation during the making of the exam (Hoque & Weil, 2016).

6.1.2 Summary of key findings of the systematic approach

The second study aimed to answer the following research question, How can the effect of all four IEQ parameters in higher education classrooms on students' perceptions, responses and academic performance be measured? During the systematic literature review, the identified methods which measured the influence of one or more IEQ parameter, provided a rich and diverse perspective of how the influence of the four IEQ parameters on students' perceptions, responses, and short-term academic performance can be measured most effectively. However, no methods were identified which examined the impact of all four IEQ parameters simultaneously. Therefore, the composed systematic approach combined existing methods allowing researchers to study both the individual and combined impact of all four IEQ parameters on students. Moreover, from the systematic literature review it was learned that this approach was also new because none of these methods were re-used after initial publication. Application of the composed systematic approach of existing methods in future studies allows comparison of study outcomes, which will contribute to a better and more thorough understanding of how IEQ conditions influence teaching and learning in higher education. For the development of the systematic approach, the framework of Bitner (1992) was used, who developed a framework for exploring the role of the physical environment in service organizations. This framework helped organize all the methods applied, as identified during the systematic review, and provided a more thorough understanding of the framework of Donabedian (1988), which was used during the literature review. The framework of Bitner (1992) contributed specifically to defining and understanding the in-class activities, i.e., quality of teaching and learning. The application of this framework led to a different operationalization of short-term academic performance, compared to how this was operationalized in the systematic literature review. This operationalization is elaborated in the next paragraphs.

During the systematic literature review, the quality of teaching and learning was determined by lecturers' and students' level of comfort, mental health, and physical health. Lecturers' and students' comfort relates to Bitner's concept of "perceived servicescape" (Bitner, 1992). She specifically mentioned, for example, environments with poor acoustics and high temperatures which prevented a person from succeeding in the goal with which he or she entered an environment, or at least made it not very easy. Furthermore, Bitner (1992) defined three individuals' internal responses, i.e., physiological, emotional, and cognitive responses. Lecturers' and students' mental and physical health, as defined in the systematic literature review, were related to individuals' physiological and emotional responses. Students' ability to pay attention, concentrate, remember, perceive, or solve problems, were related to students' short-term academic performance in the systematic review; Following Bitner's (1992) framework, the tests and questionnaires which measure students' ability to pay attention, concentrate, remember, perceive, or solve problems were included in the systematic approach as methods to measure students' cognitive responses. This recategorization of methods also influenced the categorization of methods to measure students' short-term academic performance.

To measure students' short-term academic performance, Donabedian's (1988) and Bitner's (1992) operationalizations of outcome guided the classification of identified methods in literature. Donabedian (1988) defines outcome as, for example, improvements in the knowledge and changes in behavior. Bitner (1992) refers Mehrabian & Russell (1974) who defined two general and opposite forms of behavior as a main outcome variable, i.e., approach and avoidance behaviors as a person's reaction to the environment. According to Bitner (1992), approach behaviors include all positive behaviors that might be directed at a particular place, such as the desire to stay, explore, work, and affiliate. Avoidance behaviors reflect the opposite, in other words, a desire not to stay, explore, work, and affiliate. Bitner (1992) stated that this behavior is mediated by a person's internal responses, i.e., cognitive, emotional, and physiological responses, and that these responses are interdependent.

The composed systematic approach adopted the improvement of the knowledge and the behavioral concept as indicators for short-term academic performance. Following Donabedian (1988), tests and questionnaires, such as academic tests which measure academic knowledge, were related to short-term academic performance. Furthermore, following Bitner (1992), all tests and questionnaires that addressed approach or avoidance behavior, i.e., the quality of instruction and the level of motivation of lecturers and students, were listed as methods to measure short-term academic performance and aligned with how Wang & Degol (2016) defined academic achievement. When, for example, lecturers desire to stop working, this will negatively influence the quality of teaching. Lecturers can, for example, decide to speed up the pace of the lecture to finish it before the scheduled time, which may affect the knowledge transfer between lecturer and student. When students, for example decide not to put any more effort (work) in listening to the lecturer, this will affect students' ability to understand the content of the lecture, as the qualitative case study has revealed (**Chapter 5**). During the composition of the systematic approach, no methods were identified which measured long-term academic performance. Consequently, these were not included in our approach. However, it was suggested that student grades in a course or academic year or grade point average (GPA) may reveal their long-term academic performance (Wang & Degol, 2016). The quality of learning and teaching and determines the short- and long-term academic performance, and were the dependent variables, following Donabedian's (1988) definition of outcome and Bitner's (1992) description of behavior.

The composed systematic approach presents relevant performance indicators to determine the actual IEQ and shows how lecturers' and students' perceptions of the IEQ, their responses to these IEQ conditions, and their short-term academic performance can be measured. Depending on the aim of the study, relevant performance indicators can be selected out of a list of 55 IEQ performance indicators. The IEQ parameters indoor air quality, thermal conditions, acoustic conditions, and lighting conditions were the independent variables, following Donabedian's (1988) definition of structure and Bitner's (1992) description of the physical environmental dimensions.

To measure students' perceptions of the IEQ, a questionnaire, covering 18 IEQ sub-categories with 27 statements was composed, originating from various existing questionnaires. To measure students' internal responses and short-term academic performance, both a questionnaire and tests became available. In a pilot study, performed during a regular academic course, all composed IEQ and cognitive response perception scales showed good reliability with α-values >0.70 (Tavakol & Dennick, 2011). The composed systematic approach was used to examine the effect of indoor environmental conditions on students and their performance during a between-groups experiment (see **Chapter 3**). Furthermore, the categorized subcategories and related aspects guided the conducted interviews with lecturers and group discussions with students during a case study (see **Chapter 4**). Perceptions of the IEQ and internal responses were, in accordance with Donabedian's (1988) definition of process, in our composed systematic approach also labelled as process variables. Figure 6-3 presents the composed systematic approach in a brief model.

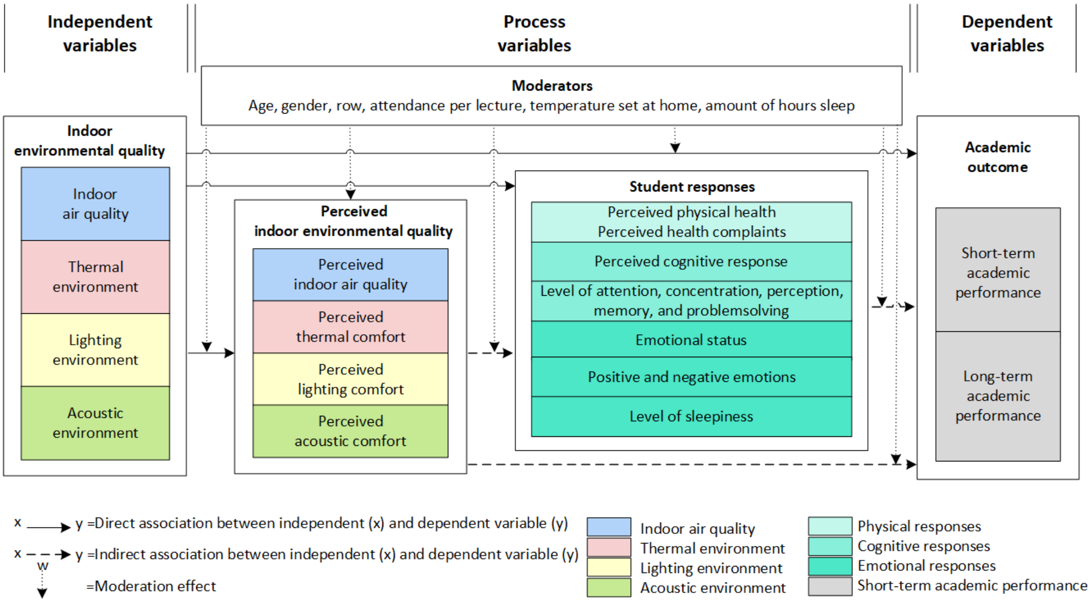


Figure 6-3 Categories covered in the systematic approach and their mutual relations.

6.1.3 Main results field experiment

The third study aimed to answer the following research question: Do students in a high-quality classroom, meeting quality class A requirements of the PoR "Fresh Schools", score higher on comfort, internal responses, and short-term academic performance when compared to students in a lower-quality classroom, meeting quality class B requirements of the PoR "Fresh Schools" (RVO, 2015)? A field study, with a between-group experimental design, was conducted to examine the effect of alterations of reverberation time, horizontal illuminance, and indoor air quality (IAQ). In this study, the developed systematic approach (Figure 6-3), enabled studying students' perceptions of the indoor environment, health, emotional status, cognitive performance, and short-term academic performance.

The results showed that a difference in reverberation time (0.6 vs 0.4 s) did not lead to a significant difference in student's ability to hear the lecturer's voice. The difference in reverberation time led to a higher score on students' perceived cognitive performance in the intervention condition, which represents their ability to concentrate, pay attention, understand the presented information, and solve problems. However, no difference was observed in short-term academic performance between students in the intervention condition and those in the control condition.

Furthermore, an indirect association was observed between students' perceived cognitive performance and perceived quality of learning. When lowering the reverberation time, by applying increasing amount of absorption in a classroom, the noise level will also reduce which will also increase the speech intelligibility if the student is close to the lecturer (Reinten et al., 2017). However, the results showed that the distance of the student to the lecturer did not influence the perceived speech intelligibility of the students. This can be explained by the relatively small distance (< 7 m) between lecturer and students. Furthermore, during the tutorial the students remained quiet and the lecturer spoke which prevented noise disturbances as much as possible. To facilitate different in-class activities might require additional interventions. Just lowering the reverberation time might not be enough. For example, to facilitate optimally a collaboration task Braat-Eggen et al. (2019) suggested that students may want to work in a quiet zone or a quiet room, as in activity based offices.

A simultaneous effect of reduced reverberation time (0.6 vs 0.4 s) and enhanced horizontal illuminance level (750 vs 500 lx) led to a significant improvement of the perceived lighting comfort. However, no difference in the ability to hear the lecturer's voice and students' short-term academic performance was observed between the intervention and control conditions. Furthermore, regarding students' cognitive performance test scores, a small direct negative effect of the higher horizontal illuminance level in the intervention condition was observed in students' ability to solve problems, measured with the Wisconsin Card Sorting test (Ozonoff, 1995), confirming the findings of Xiong et al. (2018). 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. As observed, in increase in horizontal illuminance of 500 to 750 lx at the lecturer's desk led to a higher perceived lighting comfort. However, a linear relation between horizontal illuminance and lighting comfort cannot be assumed. 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.

When the horizontal illuminance level was raised in the experimental conditions, multiple indirect associations were observed: when the perceived lighting comfort increased, this improved students' perceived physical health as did their perceived cognitive performance and ability to solve problems. Moreover, an improvement in perceived lighting comfort also positively influenced multiple internal responses: students' basic emotional status score and students' perceived level of sleepiness. Students perceived quality of learning score was positively associated with their perceived lighting comfort, students' ability to hear the lecturer's voice, and the perceived cognitive performance. However, these simultaneous effects of reduced reverberation time and enhanced horizontal illuminance level did not occur when both groups were additionally exposed to improved IAQ conditions Consequently, these findings suggest that the benefits of improved indoor air quality conditions (~610 ppm vs ~1100 ppm CO_2) may outweigh the benefits of improved acoustic and lighting conditions.

The results (see **Chapter 4**) showed that the application of quality class A conditions of the PoR “Fresh Schools” for reverberation time in combination with horizontal illuminance level at lecturers’ desk have positive effects on students’ perceived comfort, internal responses, and short-term academic performance, when compared to quality class B conditions. However, these positive effects are limited to students’ perceptions. Compared to quality class B, class A conditions do not improve students’ actual cognitive test scores and students’ short-term academic performance test scores. Moreover, the quality class A conditions negatively influenced students’ ability to solve problems. Therefore, caution should be exercised when applying relatively high levels of horizontal illuminance. The study of Xiong et al. (2018) revealed, for example, that not all cognitive response tasks, i.e., a memory and a problem-solving task, were performed best in bright conditions. Moreover, students may feel more comfortable with horizontal illuminance levels below 300 lx (Jamaludin et al., 2016). Furthermore, the systematic approach should include also “time of day”. De Bakker et al. (2021) examined the subjective level of alertness versus sleepiness among relatively young office workers (age mean = 25, SD = 5.3) and found the majority felt less alert when the morning progressed. As to the experiment in this thesis (see **Chapter 4**), the lectures were always scheduled on the same day and time. Consequently, it is not likely that students’ different levels of alertness during the day may have influenced the results.

6.1.4 Main results of the qualitative study with lecturers and students

The fourth study aimed to answer the following research question: Which relations can be identified between the indoor environmental quality, perceived internal responses of lecturers and students, and academic achievement? A case study, performed in the Netherlands, revealed how lecturers and students experience actual IEQ conditions in classrooms and how these conditions influence their perceptions, responses, and academic achievement (see **Chapter 5**). The listed IEQ, internal responses, and academic achievement sub-categories from the developed systematic approach, was used as a guidance for the interviews with lecturers and discussions with students and, by doing so, enabled systematic labelling of the collected information. Furthermore, patterns could be identified between the IEQ, internal responses, and academic achievement sub-categories using the identified relationships during the composition of the systematic approach (see **Chapter 3**). These patterns allowed testing propositions (1) the IEQ influences the quality of teaching; (2) the IEQ influences the quality of learning; (3) the IEQ influences the students’ academic achievement.

The results confirm that obtaining and maintaining acceptable IEQ conditions is challenging. Lecturers and students experience poor indoor environmental conditions in classrooms. Thermal and indoor air quality conditions are vulnerable, especially when occupancy rates are high. In an attempt to obtain acceptable thermal and indoor air conditions, lecturers report opening windows or doors. However, a related adverse effect is noise disturbances which, in turn, affect the quality of teaching and learning. Be reminded that maintaining acceptable acoustic conditions in classrooms is essential and contributes positively to students’ quality of learning.

Lecturers are well aware of poor and good IEQ conditions and have preferences regarding these conditions and expressed the preference for daylight in classrooms, although direct sunlight entry should be prevented. Furthermore, lecturers expressed the need to adjust lighting conditions in order to improve students' ability to concentrate. The results of the performed experiment (see **Chapter 4**) indicated that students preferred a relatively bright environment, when attending a tutorial. Furthermore, the study of Xiong et al. (2018) showed that students also scored highest on a perceptual task in a thermoneutral, relatively quiet and bright environment. However, other cognitive performance tasks scored best in warm, relatively quiet, and moderately light environments (Xiong et al., 2018). The study by Choi et al. (2019) showed that exposure to lighting with blue-enriched white morning light improves students' subjective perception of alertness, mood, and visual comfort. These findings, in combination with lecturers' need to adjust lighting conditions argue for classrooms where lighting color and intensity can be adjusted manually or are available as default setting for specific in-class activities.

Furthermore, lecturers and students expressed the need to maintain acceptable IAQ, thermal, and acoustic conditions. Surprisingly, the need for different thermal environments was not mentioned by lecturers or students. However, the results of the studies of Ahmed et al. (2017), Sarbu and Pacurar (2015), and Xiong et al. (2018) indicate that lower or higher temperatures contribute positively to students' cognitive response; and therefore, may positively mediate lecturers' quality of instruction and lecturers' and students' level of motivation, as a result of approach behavior (Bitner, 1992).

The findings show that lecturers and students experience poor thermal, lighting, acoustic and indoor air quality (IAQ) conditions which may influence their ability to teach and learn, confirming proposition one and two. The third proposition can only be confirmed partly. When lecturers experience poor IEQ conditions, lecturers decided to break earlier than originally planned. Furthermore, lecturers speeded up the pace of the lecture or shortened the lecture when they noticed students became tired which limited students' ability to gain knowledge. However, the long-term effect of the IEQ on academic performance remains unclear.

6.2 Implications for science

Research on how the IEQ impacts teaching, learning, and academic outcome is still relatively new (Granito & Santana, 2016). There has been an increasing interest in the last decade to examine the effect of multiple IEQ parameters simultaneously. However, no study has yet examined the combined influence of all four IEQ parameters (see **Chapter 2**). This current study has shown that effects of IEQ alterations can be examined with the composed systematic approach. This approach enables studying the effect of all four IEQ parameters simultaneously (**see Chapter 3**). When aiming to unravel the influence of two or more factors, including interaction effects, a full factorial design experiment could be applied. This type of research addresses the need to develop models for assessing the influence of multiple environmental parameters on academic outcomes (Torresin et al., 2018).

When examining IEQ conditions, the selection of relevant IEQ performance indicators is critical. Furthermore, additional IEQ performance indicators should be selected and monitored during the research. When examining the effect of single or multiple IEQ parameters, it is preferred that other IEQ parameters should be controlled, as these conditions could potentially have an unintended effect on studied dependent variables. The overview of performance indicators in relation to the outcome variable under study can help to make a good selection, see Appendix 6. Furthermore, it is critical to select accurate measuring equipment that preferably should be based on the present emission characteristics and space conditions (Zheng et al., 2022).

The results of the pilot study (see **Chapter 3**) in which the composed systematic approach was tested, showed good reliability of the composed perception scales for students' perceived IEQ comfort, cognitive responses, and the quality of learning, confirming the construct validity of this approach. Furthermore, the observed associations between the actual IEQ indicators and students' perceived IEQ comfort, cognitive response, and short-term academic performance confirmed the ecological validity of the systematic approach (see **Chapter 3**).

A multi-factorial assessment of indoor environmental conditions is important because of the mutual interaction of IEQ parameters. This interaction was observed by Kim and De Dear (2012), who developed a model to determine these interaction effects and the existence of a hierarchy among IEQ parameters in an office setting. Kim and De Dear (2012) categorized IEQ factors into basic, proportional, and bonus factors, according to their influence on office workers' overall satisfaction. Basic IEQ factors had a predominantly negative impact on overall satisfaction when the building underperformed. These factors can be considered as minimum requirements for the IEQ. Proportional factors had a predominantly linear relationship with overall satisfaction. No bonus factors were identified (Kim & de Dear, 2012). Although both researchers observed a hierarchy between IEQ parameters, to the best of our knowledge no hierarchy is yet determined in an academic environment. Furthermore, no evidence of improved IEQ conditions during regular academic in-class activities was found in the systematic literature review (see **Chapter 2**). Available evidence, in literature, examining the effects of improved IEQ conditions on students in higher education is yet only derived from experiments in simulated environments, such as climate chambers (Ahmed et al., 2017; Sarbu & Pacurar, 2015; Xiong et al., 2018). With the current composed questionnaire and tests, and by applying a research design that allows studying interaction effects, such as a full-factorial experiment (Torresin et al., 2018; Xiong et al., 2018), now this becomes possible and addresses the need to assess the effect of positive IEQ stimuli (Bluyssen, 2010).

The results of our field experiment (see **Chapter 4**), examined the effect of improvement of multiple IEQ parameters during a regular academic course, while monitoring and reporting other IEQ parameters which were controlled. Based on the results of this study the speech intelligibility could be classified as a basic factor. Furthermore, students' perceived lighting comfort could be classified as a proportional factor. For this classification, students' perceived speech intelligibility and lighting comfort was related to students' satisfaction and the perceived quality of learning respectively. However, this classification is based on limited data and should be interpreted as a first step to determining a hierarchy between IEQ parameters in a higher education context.

The case study (see **Chapter 5**) provided a rich and diverse perspective on how the IEQ influences lecturers' and students' perceptions, internal responses, and academic outcomes and focused on classrooms for tutorials with a capacity of approximately 30 students, located on a campus for higher education in Groningen, Northern Netherlands. Although the systematic literature review revealed to some extent how IEQ parameters influence students' quality of learning in higher education, studies which examine the influence of the IEQ on teaching are scarce. Furthermore, the impact of the IEQ on students' long-term academic performance was not determined yet, simply because our approach relied on existing methods from the review and methods with a long-term focus appeared absent. Furthermore, it is much more challenging to measure academic performance in higher education because there are, compared to primary and secondary education with standardized curricula no results available of academic tests scores of universities which can be easily compared (Duran et al., 2022). The case study (see **Chapter 5**) revealed that lecturers are well aware of poor and good acoustic, thermal, lighting, and indoor air quality conditions and that these conditions can affect teaching quality. However, good IEQ can contribute to lecturers' and students' short-term academic performance and is mediated by emotional, physiological, and cognitive responses (Choi et al., 2014). To present an overview, Figure 6-4 summarizes all identified relations between the IEQ, the perceived IEQ, lecturers' and students' internal responses, and academic outcomes of our studies. Different personal, cultural, climatical, social, and contextual factors can explain differences in individuals' reactions to the same IEQ (De Dear & Brager, 1998).

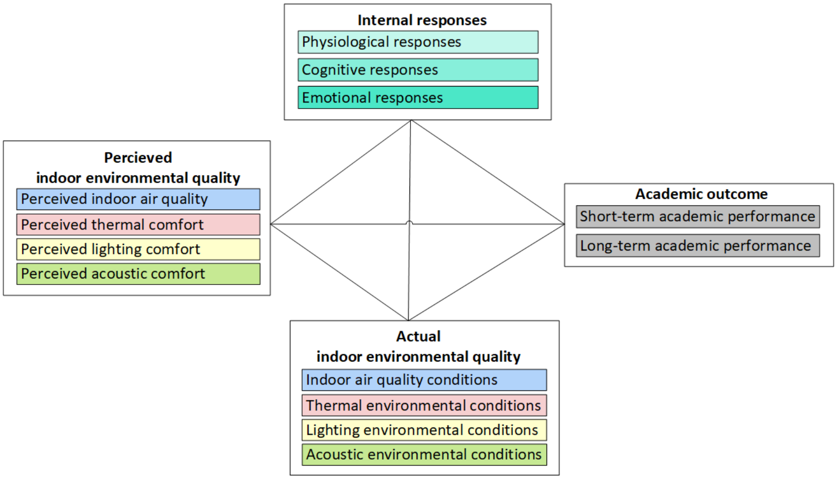


Figure 6-4 Indoor environmental quality, internal responses, and academic outcome sub-categories and their mutual relations. See Figure 6-3 for the explanation of shading.

6.3 Implications for practice

In practice, the IEQ seems subject to undeserved neglect. As mentioned in paragraph 1.1 a recent publication, which covers 88 recent examples of inspirational learning environments in the Netherlands, does not include the IEQ as one of the characteristics of a meaningful learning and working environment (Schooldomein, 2021). Moreover, deliberately manipulating indoor environmental conditions to optimally facilitate in-class activities is certainly not yet daily practice. It should be acknowledged that technical installations, such as lighting, heating, ventilation, and air-conditioning systems, and related maintenance are expensive. Let alone any change to such systems to allow creating different IEQ in classrooms. The cost to maintain an optimal IEQ absorbs a substantial proportion of a university budget and from a managerial perspective it is a potentially risky business, especially if interventions remain ineffective and complaints continue. Moreover, evidence revealing the impact on academic achievement is limited (see **Chapter 2**). This can create a gap between the world of policymakers and facility managers and that of building engineers and researchers. How positive are the observed effects and does that legitimize the necessary investments? Good IEQ conditions have the potential to improve the institution's school climate (Wang & Degol, 2016). But the question is whether these benefits outweigh the associated costs and risks.

Facilitating of knowledge transfer is one of the main responsibilities of schools' management (Wang & Degol, 2016). Extensive empirical research has demonstrated a link between positive features of school climate and optimal student outcomes across academic, behavioral, and psychosocial domains (Wang & Degol, 2016). Classrooms' physical environment, as part of school climate, plays a significant role in facilitating educational processes (Wang & Degol, 2016). This research examined the relationship between the IEQ in classrooms for higher education on one hand and lecturers' and students' perceptions, responses, and academic outcomes on the other hand. This paragraph aims to answer the following question: How can the outcome be improved and translated into practice-based specifications?

Facility management and building-related engineering partners of facility management can use the findings of this research to design a more user-oriented IEQ in classrooms for higher education, which increases the likelihood of improved educational outcomes. By doing so, facility managers are supported in underpinning the positive impact of IEQ on the institution's primary process, which can also rationalize the required investments. Moreover, improved IEQ conditions in classrooms allow future generations of lecturers and students to perform and learn better in a healthier indoor environment. To take the next step in improving IEQ conditions in classrooms, this research provides a thorough and profound understanding of the perceptions of lecturers and students towards classrooms' actual IEQ conditions and how these conditions influence the perceived quality of teaching and learning. Incorporation of these end-user perceptions in the renovation or construction of school buildings contributes to an improved school climate (Wang & Degol, 2016).

The systematic literature review (see **Chapter 2**) showed that there is no "one-size fits all" IEQ for students in higher education. Students perform at their best in different IEQ conditions, and these conditions are task dependent, suggesting that classrooms that can provide multiple IEQ classroom conditions can facilitate different learning tasks optimally.

Furthermore, the results of our field experiment (see **Chapter 4**) showed that the application of class A requirements for reverberation time and horizontal illuminance of the PoR "Fresh schools" can positively contribute to students' perceptions (RVO, 2015). When lecturers have to give a tutorial, like the context of our experiment, these tutorials may be best given in a classroom with a short reverberation time (0.4 s) which will improve the perceived cognitive performance of students and relatively high illuminance levels (750 lx at lecturer's desk) which also improved students' comfort, cognitive, emotional, and physiological responses and perceived quality of learning. However, application of class A requirements, instead of class B requirements, does not improve students' actual cognitive responses and short-term academic performance.

Relatively small changes in thermal conditions influence students' comfort, which may affect their internal responses and quality of learning (Jaakkola, 2006). Therefore, classrooms should facilitate adjustable thermal conditions and must prevent deviation from that setpoint through external influences, and also when occupancy rates are high. The indoor air quality in classrooms must be acceptable, and again, also when occupancy rates are high. However, generally accepted CO_2 levels of appr. 1200 ppm (class II, (NEN-EN 16798, 2019)), as a proxy for indoor air quality, might not be sufficient to facilitate in-class activities optimally. For example, the study of Ahmed et al. (2017) revealed that decreasing CO_2 levels from 1800 ppm and/or 1000 ppm to 600 ppm, significantly improved female students' performance in an attention task. The performed field experiment (see **Chapter 4**) seems to support these findings but did not provide conclusive evidence. However, maintaining acceptable IAQ conditions will prevent opening doors and windows, and by doing so, prevent noise disturbance from outside or hallways, specifically during tutorials, as our qualitative study revealed. Furthermore, classrooms should provide adjustable lighting settings. Variations in color temperature (3000-5000 K) and horizontal illuminance level (500-750 lx) with lighting armatures which do not blind students while looking at the lecturer can positively contribute to different types of activities and can positively influence lecturers' and students' mood (Choi et al., 2019; Xiong et al., 2018).

Although the qualitative case study (see **Chapter 5**) revealed that noise disturbances, caused by sound entering the classroom through an open door or open windows, affected lecturers' and students' ability to concentrate during a tutorial, this does not mean that other learning environments should be quiet. Distracting noises may induce a higher construal level and abstract processing, and consequently enhances students' creativity, which might be more appropriate for other activities than attending a tutorial (Choi et al., 2014). Our study (see **Chapter 5**) also revealed that lecturers find it difficult to maintain acceptable IEQ conditions, which is a necessary precondition for the next step, namely creating optimal conditions. Therefore, lecturers and students should be informed about how to maintain acceptable IEQ conditions. Furthermore, lecturers should be informed about which IEQ conditions they should create in a classroom to facilitate a specific in-class activity optimally. Alternatively, optimal IEQ conditions could also be created automatically or with artificial intelligence (AI), but it should always be possible to adjust or overrule such systems with in-class human interventions, because we lack knowledge still and are only at the beginning stages of understanding how these different factors interact.

The COVID-19 pandemic painfully revealed that in 23 % of all classrooms the ventilation did not fulfil the minimum requirements for Dutch schools (Ruimte-OK, 2021). Given the fact that students nowadays are taught almost exclusively in indoor classrooms makes them, and their lecturers, more vulnerable to airborne infections transmitted from person to person. Indoor classrooms should provide comfort, especially when outdoor conditions are not.

School management is advised to consider high quality ventilation systems, allowing daylight to enter the classrooms, adjustable lighting systems, and a comfortable acoustic environment in classrooms. Optimal IEQ conditions in classrooms will positively influence academic outcomes and contribute to a more positive school climate (Wang & Degol, 2016). Hence, optimal IEQ conditions in classrooms are worth the investment.

6.4 Strengths and limitations

6.4.1 Strengths

The performed systematic literature review revealed an increase in evidence addressing higher education classrooms' IEQ conditions (see **Chapter 2**). All studies which were identified during the systematic search were assessed on quality and reliability. This procedure was specifically developed by the promotor, co-promotors, and author as no other tool was applicable to this specific domain. Therefore, this tool can only be applied when studies related to the IEQ need to be assessed for relevance and quality. The between-groups experiment was performed during a regular academic course in which positive interventions in the IEQ of classrooms for higher education were examined (see **Chapter 4**). This type of research was not identified during the systematic review and the application of the developed systematic approach allowed studying the effect of a single IEQ parameter and the combined influence of two IEQ parameters.

Although the COVID-19 pandemic has affected the planning and the execution of this experiment, still reliable data was collected due to the in-between group design of the experiment (see **Chapter 4**). The data of the intervention and control group were collected on the same day and, nearly, the same time, thus excluding confounding effects due to social conditions such as travel restrictions and escalating global conflicts at that time. Furthermore, a lecturer gave the same number of lectures in both the intervention and the control conditions, which minimized possible differences in teaching quality between the intervention and control conditions. The participation rate during the experiment was high, reaching approximately 91 % of all students present. As part of the systematic approach and to test students' short-term academic performance, every week students took an in-class academic performance test. Because they received an e-mail to inform them about their personal score on this test every time they took the test, they received valuable information about their actual knowledge. Giving students this opportunity and feedback may have contributed to the relatively high level of participating. Because students participated multiple times during this research, it was necessary to take this into account when analyzing the data. The application of linear mixed models allowed statistical analyses of the results over multiple weeks and for an unequal number of repetitions.

The qualitative case study examined the influence of the IEQ on lecturers and students. Qualitatively exploring possible effects of the IEQ on the quality of teaching is a relatively new research approach and has provided rich insights into complex interactions between IEQ and the quality of teaching and learning. The interviews with lecturers and focus group discussions with students showed mostly consistent patterns and chains of evidence, emphasizing the importance of creating and maintaining optimal IEQ conditions, which contribute to the quality of teaching and learning.

6.4.2 Limitations

During the systematic literature review, cultural or geographical differences between the studies were not analyzed. Therefore, the optimal conditions, as presented in the collected evidence, may not be applicable in every situation and are bound to specific cultural and geographical cultural backgrounds. However, these conditions can be used as an indication for the development of optimal indoor environment conditions for teachers and students in a specific setting.

To determine the IEQ, 54 indicators were identified that provide detailed information about the actual IEQ. In future studies, relevant indicators can be selected from this list. However, other indicators, which are not listed yet, may also be relevant to measure the IEQ depending on the aim and scope of the study. Of all 54 studies, which were used to compose the systematic approach, only six studies (Castro-Martínez et al., 2016; End et al., 2010; Hoque & Weil, 2016; Markides, 1989; McDonald et al., 2004; Shelton et al., 2009) tested students' short-term academic performance. For the systematic approach, the method of McDonald (2004) and Shelton et al. (2009) was used to test short-term academic performance; however, other tests might also be applicable. A valid method to measure long-term academic performance, as identified in primary education (Duran et al., 2022), was not identified which limits the applicability of the composed systematic approach to measure short-term academic performance.

The conducted experiment examined the influence of different indoor environmental conditions on students' perceived comfort, emotions, health, different tasks which they had to perform (cognitive tasks), and an academic test. This test measured the amount of academic knowledge that students were able to remember when a tutorial was attended. No other academic in-class activities were examined. The reported effects of the experiment (see **Chapter 4)** are valid for classrooms with a capacity of 30 students and during a tutorial, the context of the conducted experiment.

Studying the combined (interaction) effect of multiple indoor environmental parameters may require a complex study design, such as a full factorial experimental design, which can be difficult to conduct in practical settings. Conducting research in a practical setting is time-consuming and vulnerable to bias due to changing conditions that apply for a whole group, for example, seasonal influences. Due to COVID-19, the research was hampered such that it was not possible to study the influence of the four IEQ parameters, as envisaged within the set timeframe.

The findings of the case study focused on classrooms of only one campus for higher education. This part of the study did not seek to generalize the findings to a population of lecturers and students but categorizes and exemplifies their experiences and uses these in the context of understanding the relations between the IEQ and the perceptions of students and staff during lectures in higher education. However, lecturers and students with different educational backgrounds from other universities or educational programs may have experienced and reported other IEQ conditions and also may have had different qualifications and assessments of their experiences with the IEQ conditions and their influence on their internal responses and academic outcomes. When applying the developed systematic approach, different higher education institutions can be compared on outcome variables related to the IEQ.

6.5 Future research directions

This research illuminates the influence of one or multiple IEQ parameters on the quality of teaching, learning, and students' short-term academic performance. However, research addressing all four indoor IEQ parameters simultaneously is rare, revealing this gap in existing knowledge. More in-depth knowledge is required to understand the combined influence of indoor environmental parameters, not only on students' physical health, emotional status, or cognitive response but also on how these parameters and these responses may contribute to students' performance on different academic tasks. Still, this research has revealed effects of acoustic and lighting conditions in an academic context. Based on the results of the experiment (see **Chapter 4**), a first step has been taken in identifying basic and proportional factors in an academic context, as described by Kano (1984). Identification of these factors will reveal not only how indoor environmental parameters influence satisfaction with the indoor environment, but it will also reveal its effect on academic outcomes. These findings might guide future guidelines for IEQ in classrooms for higher education. Furthermore, these findings may prioritize the design and control of IEQ parameters in such classrooms.

Based on this research, the exact influence of all IEQ parameters on the quality of teaching could not be determined or quantified yet. Furthermore, the effect of indoor environmental conditions on students' long-term academic performance, specifically among higher education students, is not revealed yet and should be addressed in future research. Future researchers are invited to adopt the developed systematic approach to complement the body of knowledge and to allow comparison of the results of future studies.

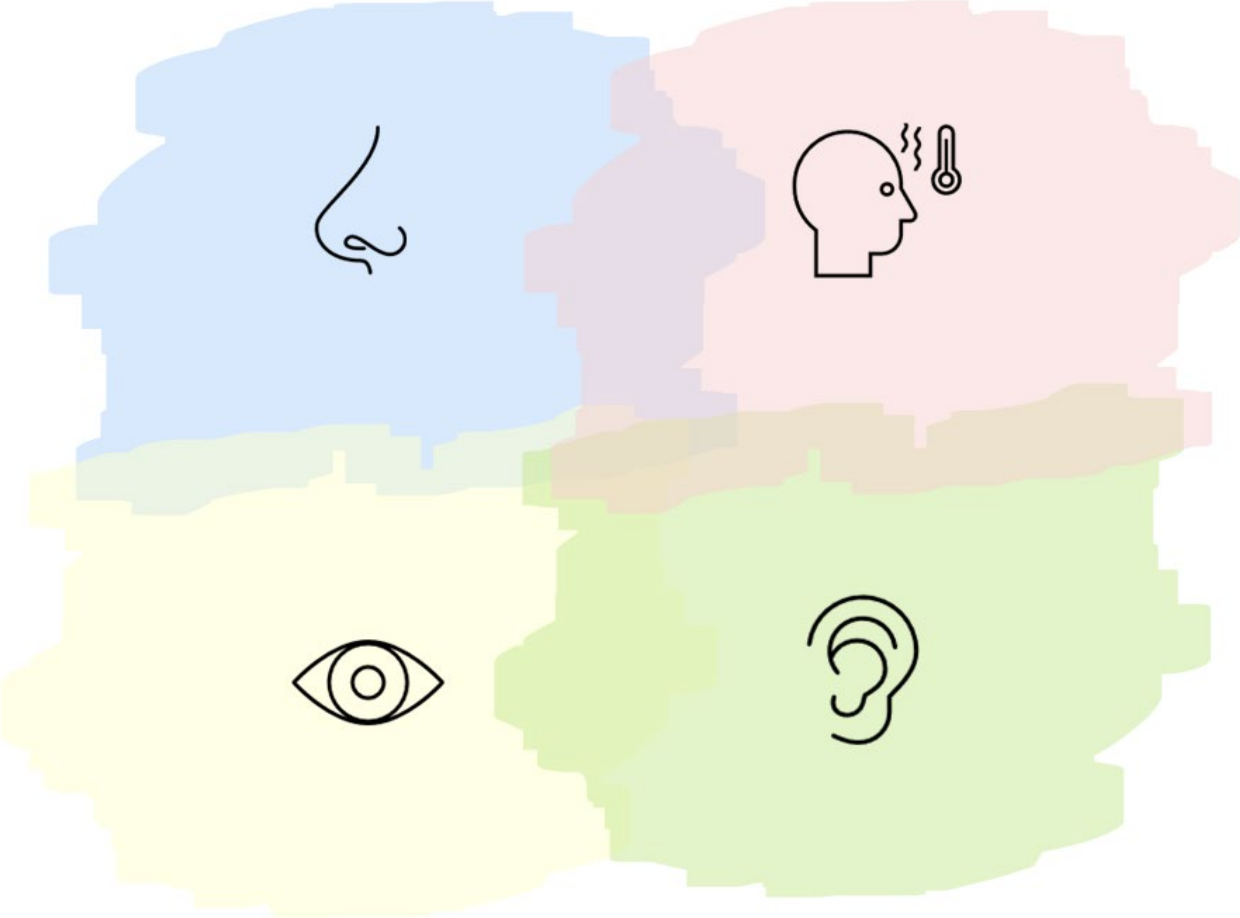
6.6 Conclusion

In higher education there is no "one-size fits all" IEQ for students. Students perform at their best in different IEQ conditions, and these conditions are task dependent, suggesting that classrooms that provide multiple IEQ classroom conditions can facilitate academic outcomes optimally. The experiment, conducted during a regular academic course, revealed that optimal acoustic and lighting conditions, as specified in the Dutch PoR "Fresh Schools" (2015), in classrooms for higher education positively influence students' perceived comfort, which in turn positively influences students' perceived health, cognitive performance, emotional status, and quality of learning. However, these optimal IEQ conditions did not improve students' actual cognitive and short-term academic performance and negatively influenced students' ability to solve problems. At IAQ conditions meeting quality class A of the Dutch PoR "Fresh Schools", the benefits of optimal acoustic and lighting conditions were not observed. Based on the results presented in this thesis, the individual and combined influence of all four IEQ parameters on students' comfort, internal responses, and short-term academic performance is not determined yet.

Lecturers and students are well aware of poor and good acoustic, thermal, lighting, and indoor air quality conditions. However, current facilities do not always make it easy for lecturers to maintain acceptable IEQ conditions, which is a necessary precondition for the next step, namely creating optimal conditions. Optimal IEQ conditions can positively influence lecturers' and students' short-term academic performance. Lecturers and students' internal responses, i.e., cognitive, emotional, and physiological responses, mediate the quality of teaching and learning. To create optimal conditions in classrooms, lecturers and students should be informed about how to maintain acceptable IEQ conditions in classrooms and about which IEQ conditions they should create in a classroom to facilitate a specific in-class activity optimally.

Application of the systematic approach in future research will enrich the existing knowledge base and quantify this positive effect. To complement the systematic approach, methods to reveal the influence of the IEQ on the quality of teaching and long-term academic performance should be included.

References



Afren, R., Benabbas, M., Zemmouri, N., & Djaghrouri, D. (2017). Impact of the typology of school buildings on the internal thermal conditions, in a hot and dry climate. *Cisbat 2017 International Conference Future Buildings & Districts - Energy Efficiency from Nano to Urban Scale, 122*, 505-510. https://doi.org/10.1016/j.egypro.2017.07.305

Ahmed, R. (2017). *The Effects of Indoor Temperature and CO2 levels as an Indicator for Ventilation Rates on Cognitive Performance of Adult Female Students in Saudi Arabia [doctoral thesis].* Retrieved on 22-2-2019, from http://discovery.ucl.ac.uk/id/eprint/10037938

Ahmed, R., Mumovic, D., & Ucci, M. (2017). The Effect of Indoor Temperature and CO2 Levels on Cognitive Performance of Adult Females in a University Building in Saudi Arabia. *Energy Procedia, 122*, 451-456. https://doi.org/10.1016/j.egypro.2017.07.378

Åkerstedt, T., & Gillberg, M. (1990). Subjective and objective sleepiness in the active individual. *International Journal of Neuroscience, 52*(1-2), 29-37. https://doi.org/10.3109/00207459008994241

Alderson, P., Green, S., & Higgins, J. (2004). In The Cochrane Library I. 1.,2004 (Ed.), *Cochrane reviewers' handbook 4.2.2 [updated March 2004]*. Chichester, UK: John Wiley & Sons.

Almaqra, A., Almuqri, M., Alshathri, A., Aloraini, A., Alrehaili, Y., Bin-Mubarak, A., Alabdulkarim, S., & Ragab, A. (2019). Effect of caffeine consumption and air temperature on student performance. In Proceedings of the *10th International Conference on E-Education, E-Business, E-Management and E-Learning*, 250-254. https://doi.org/10.1145/3306500.3309991

Almeida, R., Ramos, N., & de Freitas, V. P. (2016). Thermal comfort models and pupils' perception in free-running school buildings of a mild climate country. *Energy & Buildings, 111*, 64-75. https://doi.org/10.1016/j.enbuild.2015.09.066

Ashrafi, S. E., & Naeini, H. S. (2016). Determination of Effective Factors on Reduction of Sick Building Syndrome in Designing Educational Environments. *International Journal of Advanced Biotechnology and Research, 7 (Special Issue 4 May),* 144-152

Attia, N. A., Baig, L., Marzouk, Y. I., & Khan, A. (2017). The potential effect of technology and distractions on undergraduate students' concentration. *Pakistan Journal of Medical Sciences, 33*(4), 860. https://doi.org/10.12669%2Fpjms.334.12560

Bajc, T., Banjac, M., Todorović, M., & Stevanović, Z. (2018). Experimental and statistical survey on local thermal comfort impact on working productivity loss in university classrooms. *Thermal Science, 23*(1), 379-392. https://doi.org/10.2298/TSCI170920160B

Barbic, F., Minonzio, M., Cairo, B., Shiffer, D., Dipasquale, A., Cerina, L., Vatteroni, A., Urechie, V., Verzeletti, P., Badilini, F., Vaglio, M., Iatrino, R., Porta, A., Santambrogio, M., Gatti, R., & Furlan, R. (2019). Effects of different classroom temperatures on cardiac autonomic control and cognitive performances in undergraduate students. *Physiological Measurement, 40*(5), 054005. https://doi.org/10.1088/1361-6579/ab1816

Bidassey-Manilal, S., Wright, C. Y., Engelbrecht, J. C., Albers, P. N., Garland, R. M., & Matooane, M. (2016). Students' Perceived Heat-Health Symptoms Increased with Warmer Classroom Temperatures. *International Journal of Environmental Research and Public Health, 13*(6), 566. https://doi.org/10.3390/ijerph13060566

Bitner, M. J. (1992). Servicescapes: The impact of physical surroundings on customers and employees. *Journal of Marketing, 56*(2), 57-71.

Bluyssen, P. M. (2010). Towards new methods and ways to create healthy and comfortable buildings. *Building and Environment, 45*(4), 808-818. https://doi.org/10.1016/j.buildenv.2009.08.020

Braat-Eggen, E., van der Poll, M. K., Hornikx, M., & Kohlrausch, A. (2019). Auditory distraction in open-plan study environments: Effects of background speech and reverberation time on a collaboration task. *Applied Acoustics, 154*, 148-160. https://doi.org/10.1016/j.apacoust.2019.04.038

Broekhuizen, D. (2005). *Openluchtscholen in Nederland: architectuur, onderwijs en gezondheidszorg, 1905-2005*. Rotterdam: 010 Publishers.

Buysse, D. J., Reynolds, C. F., Monk, T. H., Berman, S. R., & Kupfer, D. J. (1989). The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. *Psychiatry Research, 28*(2), 193-213. https://doi.org/10.1016/0165-1781(89)90047-4

BZK. (2012). *Bouwbesluit 2012.* Retrieved on 1-7-2021, from https://rijksoverheid.bouwbesluit.com.

Cao, B., Ouyang, Q., Zhu, Y., Huang, L., Hu, H., & Deng, G. (2012). Development of a multivariate regression model for overall satisfaction in public buildings based on field studies in Beijing and Shanghai. *Building and Environment, 47*, 394-399. https://doi.org/10.1016/j.buildenv.2011.06.022

Castilla, N., Llinares, C., Bravo, M. J., & Blanca, V. (2017). Subjective assessment of university classroom environment. *Building and Environment, 122*, 72-81. https://doi.org/10.1016/j.foar.2018.07.002

Castilla, N., Llinares, C., Bisegna, F., & Blanca-Gimenez, V. (2018a). Affective evaluation of the luminous environment in university classrooms. *Journal of Environmental Psychology, 58*, 52-62. https://doi.org/10.1016/j.jenvp.2018.07.010

Castilla, N., Llinares, C., Bisegna, F., & Blanca-Giménez, V. (2018b). Emotional evaluation of lighting in university classrooms: A preliminary study. *Frontiers of Architectural Research, 7*(4), 600-609. https://doi.org/10.1016/j.foar.2018.07.002

Castro-Martínez, J. A., Roa, J. C., Benítez, A. P., & González, S. (2016). Effects of classroom-acoustic change on the attention level of university students. *Interdisciplinaria, 33*(2), 201-214. https://doi.org/10.16888/interd.2016.33.2.1

Chellappa, S. L., Steiner, R., Blattner, P., Oelhafen, P., Götz, T., & Cajochen, C. (2011). Non-visual effects of light on melatonin, alertness and cognitive performance: can blue-enriched light keep us alert? *PloS One, 6*(1), e16429. https://doi.org/10.1371/journal.pone.0016429

Chen, Q., & Ou, D. (2019). The effects of traffic noise on English learning of Chinese university students. In *Inter-noise and noise-con congress and conference proceedings* (Vol. 259, No. 9, pp. 860-864). Madrid: Institute of Noise Control Engineering.

Chin, C. S., & Saju, S. (2017). Effects of psychoacoustics and subjective noise annoyance level on student learning in classroom environment. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings* (Vol. 255, No. 7, pp. 370-379). Hong Kong: Institute of Noise Control Engineering.

Choi, H., Van Merriënboer, J. J., & Paas, F. (2014). Effects of the physical environment on cognitive load and learning: Towards a new model of cognitive load. *Educational Psychology Review, 26*(2), 225-244. https://doi.org/10.1007/s10648-014-9262-6

Choi, K., Shin, C., Kim, T., Chung, H. J., & Suk, H. J. (2019). Awakening effects of blue-enriched morning light exposure on university students' physiological and subjective responses. *Scientific Reports, 9*(1), 1-8. https://doi.org/10.1038/s41598-018-36791-5

Chowdhury, R. B., Dey, R., Alam, M. S., & Chakraborty, P. (2010). Extent of traffic induced noise in the noise sensitive institutions of Chittagong city, Bangladesh. *Noise and Vibration Worldwide, 41*(1), 28-36. https://doi.org/10.1260/0957-4565.41.1.28

Cohen, J., McCabe, L., Michelli, N. M., & Pickeral, T. (2009). School climate: Research, policy, practice, and teacher education. *Teachers College Record, 111*(1), 180-213. https://doi.org/10.1177/016146810911100108

Cohen, J., Cohen, P., West, S. G., & Aiken, L. S. (2013). *Applied multiple regression/correlation analysis for the behavioral sciences*. New York, NY: Routledge. https://doi.org/10.4324/9781410606266

Corgnati, S. P., & Viazzo, S. (2004). Indoor air quality in classrooms: field campaign by questionnaires and measurements. In *Proceedings of AIVC 25th conference, Ventilation and Retrofitting,* Czech Republic, 247-253.

Corgnati, S. P., Filippi, M., & Viazzo, S. (2007). Perception of the thermal environment in high school and university classrooms: Subjective preferences and thermal comfort. *Building and Environment, 42*(2), 951-959. https://doi.org/10.1016/j.buildenv.2005.10.027

Corsi, P. M. (1972). Human memory and the medial temporal region of the brain. *Dissertation Abstracts International, 34*(02), 819B.

Cowan, N. (1998). *Attention and memory: An integrated framework*. New York, NY: Oxford University Press.

Dawson, C. G., & Parker, D. R. (1998). A Descriptive Analysis of the Perspectives of Neville High School's Teachers Regarding the School's Renovation. Paper presented at the *Annual Meeting of the Mid-South Educational Research Association.*

de Abreu-Harbich, L. V., Chaves, V. L. A., & Brandstetter, M. C. (2018). Evaluation of strategies that improve the thermal comfort and energy saving of a classroom of an institutional building in a tropical climate. *Building and Environment, 135*, 257-268. https://doi.org/10.1016/j.buildenv.2018.03.017

de Bakker, C., Aarts, M., Kort, H., van Loenen, E., & Rosemann, A. (2021). Preferred luminance distributions in open-plan offices in relation to time-of-day and subjective alertness. *Leukos, 17*(1), 3-20. https://doi.org/10.1080/15502724.2019.1587619

De Dear, R., & Brager, G. S. (1998). Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions, 104*(part 1).

Donabedian, A. (1988). The quality of care: how can it be assessed? *Journal of the American Medical Association, 260*(12), 1743-1748.

Drewe, E. A. (1975). Go-no go learning after frontal lobe lesions in humans. *Cortex, 11*(1), 8-16.

Du, B., Tandoc, M. C., Mack, M. L., & Siegel, J. A. (2020). Indoor CO2 concentrations and cognitive function: A critical review. *Indoor Air, 30*(6), 1067-1082. https://doi.org/10.1111/ina.12706

Durak, A., Camgöz Olguntürk, N., Yener, C., Güvenç, D., & Gürçınar, Y. (2007). Impact of lighting arrangements and illuminances on different impressions of a room. *Building and Environment, 42*(10), 3476-3482. https://doi.org/10.1016/j.buildenv.2006.10.048

Duran, N., Eichholtz, P., & Palacios, J. (2022, 9 December). Betere ventilatie helpt om leerprestaties te bevorderen. Retrieved on 10-12-2022, from https://esb.nu/esb/20072704/betere-ventilatie-helpt-om-leerprestaties-te-bevorderen

Ellis, T. (2010). Fit for Purpose. *American School & University*, *82*(7), 45-47.

EN ISO 7726. (1998). *Ergonomics of the Thermal Environment— Instruments for Measuring Physical Quantities,* International Organization for Standardization. Geneva, Switzerland.

End, C. M., Worthman, S., Mathews, M. B., & Wetterau, K. (2010). Costly Cell Phones: The Impact of Cell Phone Rings on Academic Performance. *Teaching of Psychology, 37*(1), 55-57.

Erdfelder, E., Faul, F., & Buchner, A. (1996). GPOWER: A general power analysis program. *Behavior Research Methods, Instruments, & Computers, 28*(1), 1-11. https://doi.org/10.3758/BF03203630

European Commission's Directorates General for Health and Consumers & Joint Research Centre. (2014). *Guidelines for healthy environments within European schools*. Luxembourg.

Fanger, P. O. (1970). *Thermal comfort*. Copenhagen: Danish Technical Press.

Fisk, W. J. (2017). The ventilation problem in schools: literature review. *Indoor Air, 27*(6), 1039-1051. https://doi.org/10.1111/ina.12403

Fisk, W., Wargocki, P., & Zhang, X. (2019). Do Indoor CO2 Levels Directly Affect Perceived Air Quality, Health, or Work Performance? *ASHRAE Journal, 61*(9), 70-77.

Frontczak, M., & Wargocki, P. (2011). Literature survey on how different factors influence human comfort in indoor environments. *Building and Environment, 46*(4), 922-937. https://doi.org/10.1016/j.buildenv.2010.10.021

Gaihre, S., Semple, S., Miller, J., Fielding, S., & Turner, S. (2014). Classroom Carbon Dioxide Concentration, School Attendance, and Educational Attainment. *Journal of School Health, 84*(9), 569-574. https://doi.org/10.1111/josh.12183

Gentile, N., Goven, T., Laike, T., & Sjoberg, K. (2018). A field study of fluorescent and LED classroom lighting. *Lighting Research & Technology, 50*(4), 631-650. https://doi.org/10.1177/1477153516675911

Global Monitoring Laboratory. (2020). *ObsPack, Cooperative Global Atmospheric Data Integration Project, Multi-laboratory compilation of atmospheric carbon dioxide data for the period 2019–2020.*

Government of the Netherlands. (2020a). Lockdown in order to minimise contact between people. Retrieved on 18-11, from https://www.government.nl/latest/news/2020/12/14/lockdown-in-order-to-minimise-contact-between-people

Government of the Netherlands. (2020b). Partial lockdown needed to bring down infections. Retrieved on 18-11-2021, from https://www.government.nl/latest/news/2020/10/13/partial-lockdown-needed-to-bring-down-infections

Granito, V. J., & Santana, M. E. (2016). Psychology of learning spaces: Impact on teaching and learning. *Journal of Learning Spaces, 5*(1), 1-8. https://doi.org/10.1037/e623792013-001

Hall, E. T. (1966). *The hidden dimension*. New York: Anchor Books.

Haverinen-Shaughnessy, U., Pekkanen, J., Nevalainen, A., Moschandreas, D., & Husman, T. (2004). Estimating effects of moisture damage repairs on students' health—a long-term intervention study. *Journal of Exposure Science & Environmental Epidemiology, 14*(1), S58-S64. https://doi.org/10.1038/sj.jea.7500359

Hayes, A. F. (2017). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach*. New York, NY: The Guilford Press.

Heschong, L. (2002). Daylighting and human performance. *ASHRAE Journal, 44*(6), 65-67.

Holahan, C. J. (1982). *Environmental Psychology*. New York, NY: Random House, Inc.

Hongisto, V. (2005). A model predicting the effect of speech of varying intelligibility on work performance. *Indoor Air, 15*(6), 458-468. https://doi.org/10.1111/j.1600-0668.2005.00391.x

Hoque, S., & Weil, B. (2016). The Relationship between Comfort Perceptions and Academic Performance in University Classroom Buildings. *Journal of Green Building, 11*(1), 108-117. https://doi.org/10.3992/jgb.11.1.108.1

Hsieh, H., & Shannon, S. E. (2005). Three approaches to qualitative content analysis. *Qualitative Health Research, 15*(9), 1277-1288. https://doi.org/10.1177/1049732305276687

Huiberts, L. M., Smolders, K. C. H. J., & De Kort, Y. A. W. (2017). Seasonal and time-of-day variations in acute non-image forming effects of illuminance level on performance, physiology, and subjective well-being. *Null, 34*(7), 827-844. https://doi.org/10.1080/07420528.2017.1324471

IUPS Thermal Commission (2001). Glossary of terms for thermal physiology. *Journal of Applied Physiology, 51*(2), 245-280. https://doi.org/10.1152/jappl.1973.35.6.941

Jaakkola, J. J. K. (2006). Temperature and humidity. In H. Frumkin, R. J. Geller & I. L. Rubin (Eds.), *Safe and Healthy School Environments* (pp. 46-57). New York, NY: Oxford University Press.

Jamaludin, N. M., Mahyuddin, N., & Akashah, F. W. (2016). Assessment of Indoor Environmental Quality (IEQ): Students Well-Being in University Classroom with the Application of Landscaping. *MATEC Web of Conferences, 66.* https://doi.org/10.1051/matecconf/20166600061

Jonsdottir, V. I. (2006). Amplification in classrooms. The answer to students' listening problems and teachers' vocal strain? Paper presented at the *Euronoise 2006 - the 6th European Conference on Noise Control: Advanced Solutions for Noise Control.*

Kano, N., Seraku, N., Takahashi, F., & Tsuji, S. (1984). Attractive Quality and Must-Be Quality. *Journal of the Japanese Society for Quality Control, 14*(2), 147-156. https://doi.org/10.20684/quality.14.2_147

Kennedy, M. (2010). Light and Cool. *American School & University, 82*(11), 32-34.

Kim, J., & de Dear, R. (2012). Nonlinear relationships between individual IEQ factors and overall workspace satisfaction. *Building and Environment, 49*, 33-40. https://doi.org/10.1016/j.buildenv.2011.09.022

Kingsley, S. C., & Dresslar, F. B. (1917). Open-Air Schools. *Bulletin, 1916, No. 23*. Bureau of Education, Department of the Interior.

Kok, H., Mobach, M., & Omta, O. (2015). Predictors of study success from a teacher's perspective of the quality of the built environment. *Management in Education, 29*(2), 53-62. https://doi.org/10.1177/0892020614553719

Kooi, L., Loomans, M. G. L. C., & Mishra, A. K. (2017). Analysis of student thermal perception evolution in a university classroom during class hour. Paper presented at the *Healthy Buildings 2017 Europe.*

Krueger, R. A., & Casey, M. A. (2000). *Focus Groups: A Practical Guide for Applied Research* (3rd ed.). Los Angeles: Sage Publications, Inc.

Kuller, R. (1991). Environmental assessment from a neuropsychological perspective. In T. Garling, & G. W. Evans (Eds.), *Environment, Cognition, and Action: An Integrated Approach* (pp. 78-95). New York: Oxford University Press.

Kuru, M., & Calis, G. (2017). Understanding the Relationship between Indoor Environmental Parameters and Thermal Sensation of users Via Statistical Analysis. Paper presented at the *Creative Construction Conference 2017,* Primosten, Croatia. https://doi.org/10.1016/j.proeng.2017.08.011

Lamb, G., & Shraiky, J. (2013). Designing for competence: spaces that enhance collaboration readiness in healthcare. *Journal of Interprofessional Care, 27*(sup2), 14-23. https://doi.org/10.3109/13561820.2013.791671

Leavitt, R., & Flexer, C. (1991). Speech degradation as measured by the Rapid Speech Transmission Index (RASTI). *Ear and Hearing, 12*(2), 115-118. https://doi.org/10.1097/00003446-199104000-00006

Lee, J., & Shute, V. J. (2010). Personal and social-contextual factors in K–12 academic performance: An integrative perspective on student learning. *Educational Psychologist, 45*(3), 185-202. https://doi.org/10.1080/00461520.2010.493471

Lee, M. C., Mui, K. W., Wong, L. T., Chan, W. Y., Lee, E. W. M., & Cheung, C. T. (2012). Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms. *Building and Environment, 49*(1), 238-244. https://doi.org/10.1016/j.buildenv.2011.10.001

Liu, J., Yang, X., Jiang, Q., Qiu, J., & Liu, Y. (2019). Occupants’ thermal comfort and perceived air quality in natural ventilated classrooms during cold days. *Building and Environment, 158*, 73-82. https://doi.org/10.1016/j.buildenv.2019.05.011

Liu, W., Lian, Z., & Liu, Y. (2008). Heart rate variability at different thermal comfort levels. *European Journal of Applied Physiology, 103*(3), 361-366. https://doi.org/10.1007/s00421-008-0718-6

Madbouly, A. I., Noaman, A. Y., Ragab, A. H. M., Khedra, A. M., & Fayoumi, A. G. (2016). Assessment model of classroom acoustics criteria for enhancing speech intelligibility and learning quality. *Applied Acoustics, 114*, 147-158. https://doi.org/10.1016/j.apacoust.2016.07.018

Maierova, L., Borisuit, A., Scartezzini, J., Jaeggi, S. M., Schmidt, C., & Münch, M. (2016). Diurnal variations of hormonal secretion, alertness and cognition in extreme chronotypes under different lighting conditions. *Scientific Reports, 6*(1), 33591. https://doi.org/10.1038/srep33591

Majewski, G., Telejko, M., & Orman, L. J. (2017). Preliminary results of thermal comfort analysis in selected buildings. *Web of Conferences vol. 17*, UNSP 00056. https://doi.org/10.1051/e3sconf/20171700056

Mamulova, E., Brink, H. W., Loomans, M. G. L. C., Loonen, R. C., & Kort, H. S. M. (2022). A Multi-Domain Approach to Explanatory and Predictive Thermal Comfort Modelling in Offices. Paper presented at the *CLIMA 2022 REHVA 14th HVAC World Congress.*

Markides, A. (1989). Background noise and lip-reading ability. *British Journal of Audiology, 23*(3), 251-253. https://doi.org/10.3109/03005368909076507

Maxwell, L. E. (2009). Noise. In H. Frumkin, R. Geller & I. Leslie Rubin (Eds.), *Safe and Healthy School Environments* (pp. 34-45). New York, NY: Oxford University Press.

McDonald, D. D., Wiczorek, M., & Walker, C. (2004). Factors affecting learning during health education sessions. *Clinical Nursing Research, 13*(2), 156-167. https://doi.org/10.1177/1054773803261113

Mehrabian, A., & Russell, J. A. (1974). *An approach to environmental psychology*. Cambridge, MA: The MIT Press.

Meijer, G., & Duijm, F. (2010). GGD Groningen: Uit onderzoeken blijkt dat ventilatie in VO nog slechter is dan in PO. *Schoolfacilities,* 12-13.

Mendell, M. J., & Heath, G. A. (2005). Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. *Indoor Air, 15*(1), 27-52. https://doi.org/10.1111/j.1600-0668.2004.00320.x

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook* (2nd ed.). Thousand Oaks: Sage Publications.

Mishra, A. K., Derks, M. T. H., Kooi, L., Loomans, M. G. L. C., & Kort, H. S. M. (2017). Analysing thermal comfort perception of students through the class hour, during heating season, in a university classroom. *Building and Environment, 125*(11), 464-474. https://doi.org/10.1016/j.buildenv.2017.09.016

Mongkolsawat, D., Marmot, A., & Ucci, M. (2014). A comparison of perceived learning performance of Thai university students in fan-assisted naturally ventilated and air-conditioned classrooms. *Intelligent Buildings International, 6*(2), 93-111. https://doi.org/10.1080/17508975.2014.893863

Murre, J. (2021). *NeuroTask BV.* www.neurotask.com. Retrieved on 1 February 2020, from https://www.neurotask.com/

National Institute for Public Health and the Environment. (2022). *Luchtmeetnet dataset.* www.luchtmeetnet.nl. Retrieved on 7 April 2022, from https://data.rivm.nl/data/luchtmeetnet/

NEN-EN 15251. (2007). *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.* (No. ICS 91.140.01). Brussels: European Committee For Standardization.

NEN-EN 16798. (2019). *Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6.* (No. ICS 91.120.10; 91.140.01). Brussels: European Committee For Standardization.

NEN-EN-ISO 41011. (2018). *Facility management – Vocabulary* (No. ICS 01.040.03; 03.080.10). Brussels: European Committee For Standardization.

NEN-EN-ISO 7730. (2005). *Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.* (No. ICS 13.180). Brussels: European Committee For Standardization.

Nico, M. A., Liuzzi, S., & Stefanizzi, P. (2015). Evaluation of thermal comfort in university classrooms through objective approach and subjective preference analysis. *Applied Ergonomics, 48*, 111-120. https://doi.org/10.1016/j.apergo.2014.11.01

Norbäck, D., Nordström, K., & Zhao, Z. (2013). Carbon dioxide (CO2) demand-controlled ventilation in university computer classrooms and possible effects on headache, fatigue and perceived indoor environment: an intervention study. *International Archives of Occupational and Environmental Health, 86*(2), 199-209. https://doi.org/10.1007/s00420-012-0756-6

Ozonoff, S. (1995). Reliability and validity of the Wisconsin card sorting test in studies of autism. *Neuropsychology, 9*(4), 491. https://doi.org/10.1037/0894-4105.9.4.491

Pawlowska, D. K., Westerman, J. W., Bergman, S. M., & Huelsman, T. J. (2014). Student personality, classroom environment, and student outcomes: A person–environment fit analysis. *Learning and Individual Differences, 36*, 180-193. https://doi.org/10.1016/j.lindif.2014.10.005

Pekkarinen, E., & Viljanen, V. (1990). Effect of Sound-Absorbing Treatment on Speech Discrimination in Rooms. *Audiology, 29*(4), 219-227. https://doi.org/10.3109/00206099009072853

Persinger, M. A., Tiller, S. G., & Koren, S. A. (1999). Background sound pressure fluctuations (5 dB) from overhead ventilation systems increase subjective fatigue of university students during three-hour lectures. *Perceptual and Motor Skills, 88*(2), 451-456. https://doi.org/10.2466/PMS.88.2

Rabelo, A. T. V., Santos, J. N., Souza, B. O., Gama, A. C. C., & de Castro Magalhães, M. (2019). The Influence of Noise on the Vocal Dose in Women. *Journal of Voice : Official Journal of the Voice Foundation, 33*(2), 214-219. https://doi.org/10.1016/j.jvoice.2017.10.025

Ramprasad, V., & Subbaiyan, G. (2017). Perceived indoor environmental quality of classrooms and outcomes: a study of a higher education institution in India. *Architectural Engineering and Design Management, 13*(3), 202-222. https://doi.org/10.1080/17452007.2017.1287050

Reid, K. J., & Zee, P. C. (2011). Chapter 58 - Circadian rhythm sleep disorders. *Handbook of Clinical Neurology*, 99, 963-977. https://doi.org/10.1016/B978-0-444-52007-4.00017-5

Reinten, J., Braat-Eggen, P. E., Hornikx, M., Kort, H. S. M., & Kohlrausch, A. (2017). The indoor sound environment and human task performance: A literature review on the role of room acoustics. *Building and Environment, 123,* 315-332. https://doi.org/10.1016/j.buildenv.2017.07.005

Ricciardi, P., & Buratti, C. (2018). Environmental quality of university classrooms: Subjective and objective evaluation of the thermal, acoustic, and lighting comfort conditions. *Building and Environment, 127*, 23-36. https://doi.org/10.1016/j.buildenv.2017.10.030

Rouag-Saffidine, D., & Benharkat, S. (2006). Learning more from existing indoors: An investigation of roof lighting within lecture rooms. Paper presented at *PLEA2006 – The 23rd Conference on Passive and Low Energy Architecture*, 1797-1802.

Ruimte-OK. (2021). *Verdiepend onderzoek gebouwtypen en ventilatiesystemen.* Retrieved on 8-6-2022, from https://open.overheid.nl/repository/ronl-3b08523d-de24-418b-a89a-e68ed69484bc/1/pdf/verdiepend-onderzoek-gebouwtypen-en-ventilatiesystemen.pdf

RVO. (2008). *Programma van Eisen Frisse Scholen 2008.* Utrecht: Rijksdienst voor Ondernemend Nederland. https://www.rvo.nl/

RVO. (2015). *Programma van Eisen Frisse Scholen 2015.* Utrecht: Rijksdienst voor Ondernemend Nederland. Retrieved on 3-11-2017, from https://www.rvo.nl/sites/default/files/2016/01/Programma%20van%20Eisen%20Frisse%20Scholen%20-%20September%202015%20v3.pdf

RVO. (2021). *Programma van Eisen Frisse Scholen 2021.* Utrecht: Rijksdienst voor Ondernemend Nederland. Retrieved on 9-7-2021, from https://www.rvo.nl/sites/default/files/2021/06/PvE-Frisse-Scholen-2021.pdf

Sankey, H. R. (1898). Introductory note on the thermal efficiency of steam-engines. Report of the committee appointed on the 31st March, 1896, to consider and report to the council upon the subject of the definition of a standard or standards of thermal efficiency for steam-engines: With an introductory note. Paper presented at the *Minutes of the Proceedings of the Institution of Civil Engineers, 134,* 278–283 incl. Plate 5.

Sarbu, I., & Pacurar, C. (2015). Experimental and numerical research to assess indoor environment quality and schoolwork performance in university classrooms. *Building and Environment, 93*(P2), 141-154. https://doi.org/10.1016/j.buildenv.2015.06.022

Schmidt, M. (2008). The Sankey diagram in energy and material flow management: part II: methodology and current applications. *Journal of Industrial Ecology, 12*(2), 173-185.

Schooldomein. (2021). In Arbeek S., Breems B. and Pieterse C.(Eds.), *Samen werken aan de leeromgeving van morgen, Inspiratieboek 2010 – 2025* (1st ed.). Meppel: Ten Brink uitgevers.

Schweiker, M., André, M., Al-Atrash, F., Al-Khatri, H., Alprianti, R. R., Alsaad, H., Amin, R., Ampatzi, E., Arsano, A. Y., Azar, E., Bannazadeh, B., Batagarawa, A., Becker, S., Buonocore, C., Cao, B., Choi, J., Chun, C., Daanen, H., Damiati, S. A., . . . Zomorodian, Z. (2020). Evaluating assumptions of scales for subjective assessment of thermal environments – Do laypersons perceive them the way, we researchers believe? *Energy and Buildings, 211*, 109761. https://doi.org/10.1016/j.enbuild.2020.109761

Schweiker, M., Huebner, G. M., Kingma, B. R. M., Kramer, R., & Pallubinsky, H. (2018). Drivers of diversity in human thermal perception – A review for holistic comfort models. *Null, 5*(4), 308-342. https://doi.org/10.1080/23328940.2018.1534490

Shahid, A., Wilkinson, K., Marcu, S., & Shapiro, C. M. (2011). Karolinska sleepiness scale (KSS). In A. Shahid, K. Wilkinson, S. Marcu & C. M. Shapiro (Eds.), *STOP, THAT and One Hundred Other Sleep Scales* (pp. 209-210). New York, NY: Springer. https://doi.org/10.1007/978-1-4419-9893-4_47

Shelton, J. T., Elliott, E. M., Eaves, S. D., & Exner, A. L. (2009). The distracting effects of a ringing cell phone: An investigation of the laboratory and the classroom setting. *Journal of Environmental Psychology, 29*(4), 513-521. https://doi.org/10.1016/j.jenvp.2009.03.001

Singh, M. K., Ooka, R., Rijal, H. B., Kumar, S., Kumar, A., & Mahapatra, S. (2019). Progress in thermal comfort studies in classrooms over last 50 years and way forward. *Energy and Buildings, 188-189*, 149-174. https://doi.org/10.1016/j.enbuild.2019.01.051

Siqueira, J. C. F., da Silva, L. B., Coutinho, A. S., & Rodrigues, R. M. (2017). Analysis of air temperature changes on blood pressure and heart rate and performance of undergraduate students. *Work (Reading, Mass.), 57*(1), 43-54. https://doi.org/10.3233/WOR-172533

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*(6), 643.

Tanabe, S., & Nishihara, N. (2004). Productivity and fatigue. *Indoor Air, 14*, 126-133. https://doi.org/10.1111/j.1600-0668.2004.00281.x

Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. *International Journal of Medical Education, 2*, 53. https://doi.org/10.5116/ijme.4dfb.8dfd

The Royal Netherlands Meteorological Institute. (2022). Day and hour observations of weather stations. Retrieved on 14 February 2022, from https://www.daggegevens.knmi.nl/klimatologie/uurgegevens

Torresin, S., Pernigotto, G., Cappelletti, F., & Gasparella, A. (2018). Combined effects of environmental factors on human perception and objective performance: A review of experimental laboratory works. *Indoor Air, 28*(4), 525-538. https://doi.org/10.1111/ina.12457

Valavanidis, A., & Vatista, M. (2006). Indoor Air Quality Measurements in the Chemistry Department Building of the University of Athens. *Indoor and Built Environment, 15*(6), 595-605. https://doi.org/10.1177/1420326X06073182

Van der Meer, T., Te Grotenhuis, M., & Pelzer, B. (2010). Influential cases in multilevel modeling: A methodological comment. *American Sociological Review, 75*(1), 173-178. https://doi.org/10.1177/0003122409359166

Van Duijnhoven, J., Aarts, M. P. J., Rosemann, A. L. P., & Kort, H. S. M. (2018). Ambiguities regarding the relationship between office lighting and subjective alertness: An exploratory field study in a Dutch office landscape. *Building and Environment, 142*, 130-138. https://doi.org/10.1016/j.buildenv.2018.06.011

Van Someren, K. L., Beaman, C. P., & Shao, L. (2018). Users' experiences of lighting controls: a case-study. *Lighting Research & Technology, 50*(7), 1091-1106. https://doi.org/10.1177/1477153517709063

Veitch, J. A. (2001). Psychological processes influencing lighting quality. *Journal of the Illuminating Engineering Society, 30*(1), 124-140. https://doi.org/10.1080/00994480.2001.10748341

Wæraas, A., & Solbakk, M. N. (2009). Defining the essence of a university: Lessons from higher education branding. *Higher Education, 57*(4), 449. https://doi.org/10.1007/s10734-008-9155-z

Wang, M., & Degol, J. L. (2016). School Climate: a Review of the Construct, Measurement, and Impact on Student Outcomes. *Educational Psychology Review, 28*(2), 315-352. https://doi.org/10.1007/s10648-015-9319-1

Wargocki, P., Sundell, J., Bischof, W., Brundrett, G., Fanger, P. O., Gyntelberg, F., Hanssen, S. O., Harrison, P., Pickering, A., & Seppänen, O. (2002). Ventilation and health in non-industrial indoor environments: report from a European Multidisciplinary Scientific Consensus Meeting (EUROVEN). *Indoor Air, 12*(2), 113- https://doi.org/10.1034/j.1600-0668.2002.01145.x

Wargocki, P., & Wyon, D. P. (2017). Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork. *Building and Environment, 112*, 359-366. https://doi.org/10.1016/j.buildenv.2016.11.020

Wargocki, P., Wyon, D. P., Matysiak, B., & Irgens, S. (2005). The effects of classroom air temperature and outdoor air supply rate on the performance of school work by children. In *Proceedings of Indoor Air 2005, The 10th International Conference on Indoor Air Quality and Climate, Beijing, China (pp. 368-372)*.

Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: the PANAS scales. *Journal of Personality and Social Psychology, 54*(6), 1063. https://doi.org/10.1037/0022-3514.54.6.1063

WHO. (2019). *International Statistical Classification of Diseases and Related Health Problems 10th Revision (ICD-10).* Retrieved on 13 July 2020, from https://icd.who.int/browse10/2019/en#/I

Witkowska, A., & Gladyszewska-Fiedoruk, K. (2018). Analysis of thermal comfort in education building in surveys. Paper presented at *10th Conference on Interdisciplinary Problems in Environmental Protection and Engineering Eko-Dok 2018, 44*, 00189. https://doi.org/10.1051/e3sconf/20184400189

Wycherley, R. E. (1959). The Garden of Epicurus. *Phoenix, 13*(2), 73-77.

Xiong, L., Huang, X., Li, J., Mao, P., Wang, X., Wang, R., & Tang, M. (2018). Impact of Indoor Physical Environment on Learning Efficiency in Different Types of Tasks: A 3 x 4 x 3 Full Factorial Design Analysis. *International Journal of Environmental Research and Public Health, 15*(6), 1256. https://doi.org/10.3390/ijerph15061256

Yan, Y. H., Guan, Y., & Tang, G. L. (2012). Experimental Research of Visual Performance with Differenet Optical Spectrum Light Sources. *Advanced Materials Research, 433-440*, 6375-6383. https://doi.org/10.4028/www.scientific.net/AMR.433-440.6375

Yang, Z., Becerik-Gerber, B., & Mino, L. (2013). A study on student perceptions of higher education classrooms: Impact of classroom attributes on student satisfaction and performance. *Building and Environment, 70*, 171-188. https://doi.org/10.1016/j.buildenv.2013.08.030

Yohai, V. J., Stahel, W. A., & Zamar, R. H. (1991). A Procedure for Robust Estimation and Inference in Linear Regression. Paper presented at the *Directions in Robust Statistics and Diagnostics. the IMA Volumes in Mathematics and its Applications*, 365-374. https://doi.org/10.1007/978-1-4612-4444-8_20

You, Y., Bai, Z., Jia, C., Hu, X., Ran, W., Zhang, J., & Yang, J. (2007). Ventilation conditions and the related symptoms in selected indoor environments in a university. Paper presented at the *6th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings IAQVEC*, 1, 581-586.

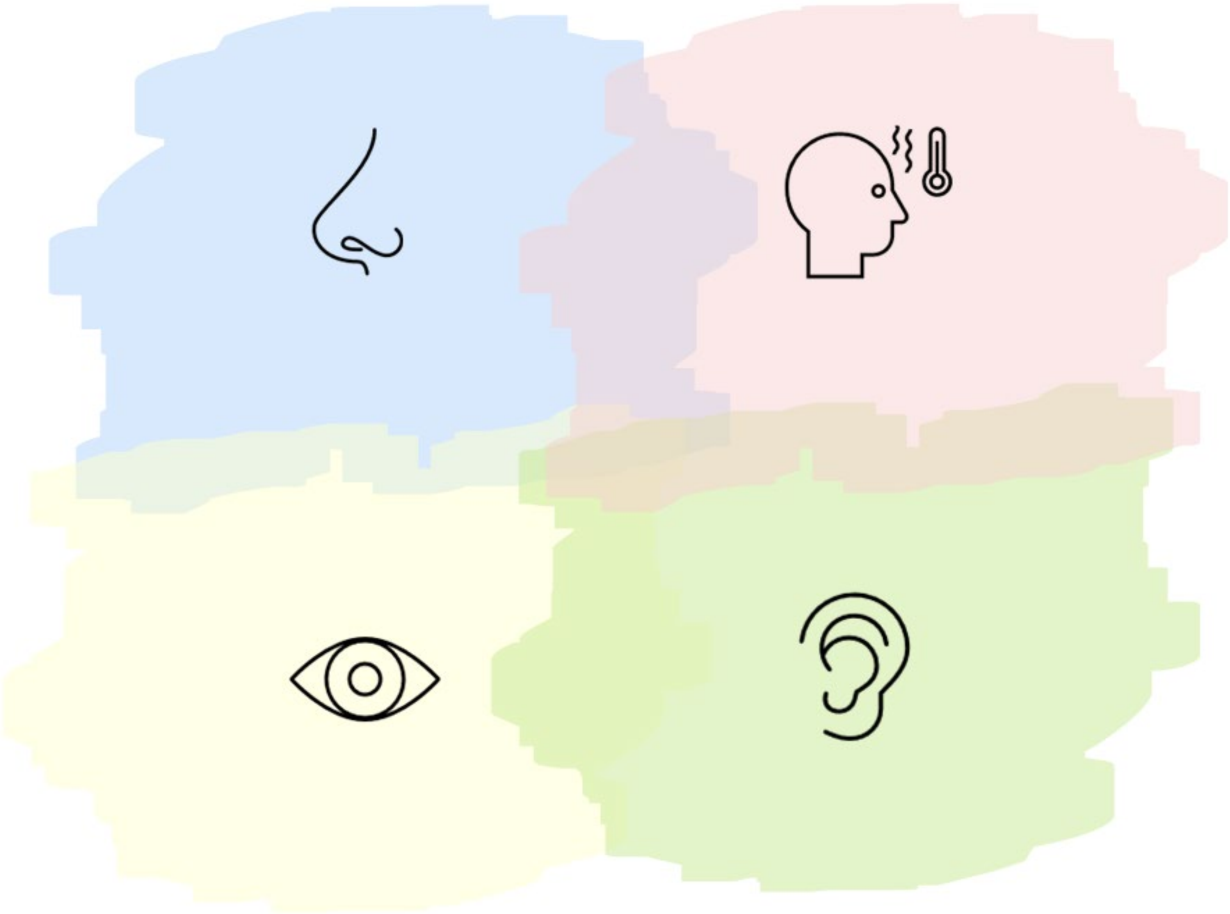
Zeiler, W. (2022). Sustainable Schools: Their Passive Systems to Provide Comfort with Natural Means as an Educational Example for Pupils and Their Parents. In: Sayigh, A. (eds) *Achieving Building Comfort by Natural Means. Innovative Renewable Energy*. Cham: Springer. http://dx.doi.org/10.1007/978-3-031-04714-5_1

Zhang, X., Wargocki, P., Lian, Z., & Thyregod, C. (2017). Effects of exposure to carbon dioxide and bioeffluents on perceived air quality, self-assessed acute health symptoms, and cognitive performance. *Indoor Air, 27*(1), 47-64. https://doi.org/10.1111/ina.12284

Zheng, H., Krishnan, V., Walker, S., Loomans, M., & Zeiler, W. (2022). Laboratory evaluation of low-cost air quality monitors and single sensors for monitoring typical indoor emission events in Dutch daycare centers. *Environment International, 166*, 107372. https://doi.org/10.1016/j.envint.2022.107372

Zomorodian, Z. S., Tahsildoost, M., & Hafezi, M. (2016). Thermal comfort in educational buildings: A review article. *Renewable & Sustainable Energy Reviews, 59*, 895-906. https://doi.org/10.1016/j.rser.2016.01.033

Appendices



Appendix 1 Overview of used keywords

Subject	**Keywords**
Higher education	Academy College Higher education University
Classroom	Classroom
Indoor environmental quality	Indoor built environment Indoor climate Indoor environment Indoor environmental quality
Indoor air quality	Carbon dioxide (CO_2) Humidity (humidification) Hygrothermal Indoor air (quality) Outdoor air supply rate Particulate matter Ventilation Volatile organic compound (exposures)
Thermal conditions	PMV PPD Predicted mean vote Predicted percentage of dissatisfied Temperature Thermal Cold Metabolic rate
Lighting conditions	Blinding Fluorescent Glare Illuminance (illumination) Light (lighting, daylight, artificial light) Luminance Visual (conditions)
Acoustic conditions	Acoustic (acoustics) Noise (noisiness) Sound Reverberation

Teaching	Classroom processes
	Instructional practices
	Quality of instruction
	Teacher quality
	Teachers’ use of supportive practices
	Teaching effectiveness
	Willingness of teacher
Learning	Active thinking
	Alertness
	Attention
	Concentration
	Intellectual engagement
	Learning environment
	Learning outcomes
	Learning quality
	Schoolwork
	Vigilance
Students’ academic achievement	Academic achievement
	Academic outcome
	Academic performance
	Cognitive performance
	Student achievement
	Student performance
	Student success

Appendix 2 Search strings

Search string for “quality of teaching” (Scopus):
(TITLE-ABS-KEY("academy" OR "college" OR "higher education" OR "university")) AND (TITLE-ABS-KEY("classroom")) AND (TITLE-ABS-KEY("indoor built environment" OR "indoor climate" OR "indoor environment" OR "indoor environmental quality") OR TITLE-ABS-KEY("PMV" OR "PPD" OR "predicted mean vote" OR "predicted percentage of dissatisfied" OR "temperature" OR "thermal" OR "cold" OR "metabolic rate") OR TITLE-ABS-KEY("acoustic*" OR "nois*" OR "sound" OR "reverbera* ") OR TITLE-ABS-KEY("blinding" OR "fluorescent" OR "glare" OR "illumina*" OR "light*" OR "luminance" OR "visual") OR TITLE-ABS-KEY("carbon dioxide" OR "CO2" OR "humidi*" OR "hygrothermal" OR "indoor air" OR "outdoor air supply rate" OR "particulate matter" OR "ventilation" OR "volatile organic compound*")) AND (TITLE-ABS-KEY("classroom processes" OR "instructional practices" OR "quality of instruction" OR "teacher quality" OR "teachers’ use of supportive practices" OR "teaching effectiveness" OR "willingness of teacher"))

Search string for “quality of learning” (Scopus):
(TITLE-ABS-KEY("academy" OR "college" OR "higher education" OR "university")) AND (TITLE-ABS-KEY("classroom")) AND (TITLE-ABS-KEY("indoor built environment" OR "indoor climate" OR "indoor environment" OR "indoor environmental quality") OR TITLE-ABS-KEY("PMV" OR "PPD" OR "predicted mean vote" OR "predicted percentage of dissatisfied" OR "temperature" OR "thermal" OR "cold" OR "metabolic rate") OR TITLE-ABS-KEY("acoustic*" OR "nois*" OR "sound" OR "reverbera* ") OR TITLE-ABS-KEY("blinding" OR "fluorescent" OR "glare" OR "illumina*" OR "light*" OR "luminance" OR "visual") OR TITLE-ABS-KEY("carbon dioxide" OR "CO2" OR "humidi*" OR "hygrothermal" OR "indoor air" OR "outdoor air supply rate" OR "particulate matter" OR "ventilation" OR "volatile organic compound*")) AND (TITLE-ABS-KEY("active thinking" OR "alertness" OR "attention" OR "concentration" OR "intellectual engagement" OR "learning quality" OR "learning environment" OR "learning outcomes" OR "schoolwork" OR "vigilance"))

Search string for “students’ academic achievement (Scopus):
(TITLE-ABS-KEY("academy" OR "college" OR "higher education" OR "university")) AND (TITLE-ABS-KEY("classroom")) AND (TITLE-ABS-KEY("indoor built environment" OR "indoor climate" OR "indoor environment" OR "indoor environmental quality") OR TITLE-ABS-KEY("PMV" OR "PPD" OR "predicted mean vote" OR "predicted percentage of dissatisfied" OR "temperature" OR "thermal" OR "cold" OR "metabolic rate") OR TITLE-ABS-KEY("acoustic*" OR "nois*" OR "sound" OR "reverbera* ") OR TITLE-ABS-KEY("blinding" OR "fluorescent" OR "glare" OR "illumina*" OR "light*" OR "luminance" OR "visual") OR TITLE-ABS-KEY("carbon dioxide" OR "CO2" OR "humidi*" OR "hygrothermal" OR "indoor air" OR "outdoor air supply rate" OR "particulate matter" OR "ventilation" OR "volatile organic compound*")) AND (TITLE-ABS-KEY("academic achievement" OR "academic outcome" OR "academic performance" OR "cognitive performance" OR "student achievement" OR "student performance" OR "student success"))

Appendix 3 Assessment procedure for relevance and quality of study

	Aspect (weight factor)	0 points	1 point	2 points
Relevance of study (33%)	Scope of study (17 %)	Only perceived comfort or perceived impact on performance is assessed (perception)	Physical conditions AND perceived comfort and/or perceived impact on performance is assessed (perception)	Physical conditions AND impact on performance is assessed with tests (performance)
		Number of marked rubrics:	Number of marked rubrics:	Number of marked rubrics:
	Context of study (17 %)	Lab study or 'in situ' research where the IEQ in classrooms is not monitored	Lab study or 'in situ' research where the IEQ in classrooms is controlled	Lab study or 'in situ' research where multiple indoor environmental conditions in classrooms are created
		Number of marked rubrics:	Number of marked rubrics:	Number of marked rubrics:
Quality of study (67 %)	Reliability (17 %)	congress proceeding professional magazine	scientific journal	peer reviewed scientific journal
		Population/sample size not available	Population/sample size available	Population/sample size available and consist of male and female students
		Age respondents/ standard deviation not available	Age respondents is available	Age respondents and standard deviation is available
		Number of marked rubrics:	Number of marked rubrics:	Number of marked rubrics:
	Method (50 %)	Method is clearly described	Method is clearly described and replicable	Method is clearly described, replicable and the study uses reliable performance tests
		Accuracy (how accurate the measurements are) of measuring equipment is not described	Accuracy (how accurate the measurements are) of measuring equipment is described	Accuracy (how accurate the measurements are) of measuring equipment is described and it is clear how the measurements were carried out in the classroom
		Zero or one indoor environmental conditions were measured (AC, TC, LC or IAQ)	Two indoor environmental conditions were measured (AC, TC, LC or IAQ)	Three or more indoor environmental conditions were measured (AC, TC, LC or IAQ)
		The indoor environmental parameter is measured but it is not clearly described which performance indicator is measured	The indoor environmental parameter (AC, TC, LC or IAQ) is measured with one performance indicator	The indoor environmental parameter (AC, TC, LC or IAQ) is measured with two or more performance indicators
		Number of marked rubrics:	Number of marked rubrics:	Number of marked rubrics:
Relevance and Quality (RQ) score = ((Score Scope of study[Number of marked rubrics*rubric points]*3] + Score Context of study[[Number of marked rubrics*rubric points]*3]+Score Reliability[[Number of marked rubrics*rubric points]*1]+Score Method[[Number of marked rubrics*rubric points]*2.25)/36)*100 %				

Appendix 4 General overview of all included studies in systematic literature review

See footnote to Table for explanation of all variables and symbols used.

Author	**Age (σ)**	**TC**	**LC**	**AC**	**IAQ**	**Outcomes**
Ahmed et al. (2017)	15-22	t_a t_r v_a = RH_i =	E_{amb} =	L_{Aeq} =	CO_2	Actual thermal sensation Thermal comfort sensations Air-conditioner set temperature at home Self-reported ability to focus related to thermal discomfort Self-reported ability to focus related to other symptoms than thermal discomfort Self-reported headache Self-reported fatigue Self-reported dizziness Percentages of errors for cognitive tasks
Sarbu and Parcurar (2015)	21.17 (0.79)	RH_i t_a t_g t_{op} v_a			CO_2	Actual thermal sensation Concentrated and distributive attention
Siqueira et al. (2017)	21 (2.89)	RH_i t_a t_g t_r t_{wb} v_a p_a				Verbal Reasoning Numeric Reasoning Abstract Reasoning Spatial Reasoning Mechanical Reasoning Overall Score Heart rate Blood pressure
Xiong et al. (2018)	20-24	t_a	E_{amb}	SPL		Perception Memory Problem-solving Attention
Yan et al. (2012)	18~21	RH_i t_a	CRI CT LF E_{amb}		CO_2	Recognition rate
Gentile et al. (2018)	16-17	RH_i t_a	E_c E_{amb} L_c L_w CRI CCT SPD		CO_2	Students' mood Light perception Saliva cortisol concentration
Barbic et al. (2019)	20.07 (3.1)	t_a	=		CO_2	Actual thermal sensation Short-term memory and verbal ability test Reasoning test

Appendix 4 continued.

Author	Age (σ)	TC	LC	AC	IAQ	Outcomes
Choi et al. (2019)	23.53 (0.87)	RH_i t_a	$L_{Log}Ch$ $L_{Log}Cy$ $L_{Log}Er$ $L_{Log}Ph$ $L_{Log}Rh$ E_{amb} CT	L_{Aeq}		Circadian system (melatonin and cortisol) Sleepiness perception Students' mood Visual comfort
Hoque et al. (2016)	20.7 (4.2)	RH_i RH_o t_a t_o v_a				Actual thermal sensation Exam scores
Almaqra et al. (2019)	22.02 (0.21)	Rh_i = t_a		SPL =		Cognitive performance
Bajc et al. (2018)	20-25	RH_i t_a t_o t_r v_a			CO_2 CO_2o	Concentration Productivity Actual percentage of dissatisfied Prediction of academic performance Actual thermal sensation
Mishra et al. (2017)	18-20	RH_i t_g t_o v_a v_{ao}			CO_2	Actual thermal sensation
Norbäck et al. (2013)	20-25	RH_i t_o			AC ACR CO_2 N_2O NCHO PM_{10} PSV VB VM	Sinusitis problems Perceived indoor air quality Actual thermal sensation
Shelton et al. (2009)	-			L_{Aeq}		Transfer of knowledge Lexical decision task
End et al. (2010)	20.21 (2.13)			L_{Aeq}		Knowledge
Liu et al. (2008)	20 (17-22)	CLO RH_i t_a t_g t_o t_{out} t_r v_a			CO_2 $PM_{2.5}$	Actual thermal sensation Perceived IAQ

Appendix 4 continued.

Author	Age (σ)	TC	LC	AC	IAQ	Outcomes
Rabelo et al. (2019)	29 (22-50)			F_0 SPL Pho CyD		Vocal intensity Percentage of phonation Cycle dose
Lee et al. (2012)	21-30	RH_i t_a t_r t_{op}	E_{hor}	L_{Aeq} SPL	CO_2	Actual thermal sensation Calculated occupants acceptance of the indoor environment The calculated overall acceptance of the indoor environmental quality Self-reported learning performance
Castro-Martínez et al. (2016)	22.4 (2.4) 21.7 (2.6)			RT		Statistics Mathematics Attention

Note: σ = standard deviation;
TC = thermal performance indicators; CLO = clothing insulation value; RH_i = indoor relative humidity; RH_o = outdoor relative humidity; t_a = air temperature; t_{db} = dry bulb temperature; t_f = floor temperature; t_g = globe temperature; t_{mr} = mean radiant temperature; t_o = mean outdoor temperature; t_{op} = operative temperature; t_r = radiant temperature; t_w = temperature of walls; t_{wb} = wet-bulb temperature; v_a = air velocity.
LC= lighting performance indicators; Cc = contrast ((object luminance/ambient luminance)/object luminance); CCT = correlated color temperature; CRI = color rendering index; CT = color temperature; DF = daylight factors; DFC = daylight factor contour; E_{amb} = ambient illuminance (illuminance); E_c = cylindrical illuminance; E_{hor} = horizontal illuminance; E_{ver} = vertical illuminance; L_c = average ceiling luminance; L_f = luminous Flux (lm); L_{og}Ch = chloropic lux; L_{og}Cy = cyanopic lux; L_{og}Er = erythropic lux; L_{og}Me = melanopic lux; L_{og}Ph = photopic lux; L_{og}Rh = rhodopic lux; L_w = average wall luminance; SPD = spectral power distribution.
AC = acoustic performance indicators; BGN = background noise or ambient noise; CyD = Cycle dose as a total quantity of complete oscillatory periods performed by the vocal folds in a set time; F_0 = fundamental frequency; Pho = the relative time spent in phonation compared with the elapsed time monitored expressed in a percentage; RT = reverberation time; SPL = sound pressure level.
IAQ = indoor air quality performance indicators: AC = allergen concentration; ACH = air exchange rate; Cl_2 = chlorine; CO = carbon monoxide; CO_2 = carbon dioxide; CO_2o = carbon dioxide outside; D = dust; Fl = flow; HCHO = formaldehyde; NO_2 = nitrogen dioxide; O_3 = ozone; P_a = pressure of water vapor in ambient air; PM_{10} = particles <10 µm; $PM_{2.5}$ = particles <2.5 µm; PSV = personal supply ventilation; SD = settled dust; SO_2 = sulfur dioxide; TSP = total respirable suspended particulate matter; TVOC = total volatile organic compounds; VB = viable bacteria; VM = viable mouts.
“ = ” behind performance indicator means that condition was kept constant.

Appendix 5 Nomenclature

Indoor air quality (IAQ)

AC	allergen concentration [units/mL]
AER	air exchange rate [ac/h]
Cl_2	chlorine [ppm]
CO	carbon monoxide [mg/m^3]
CO_2	carbon dioxide [ppm]
CO_{2o}	carbon dioxide outside [ppm]
D	dust [g]
HCHO	formaldehyde [µg/m^3]
NO_2	nitrogen dioxide [µg/m^3]
O_3	ozone [µg/m^3]
PM10	particles <10 µm [µg/m^3]
PM2.5	particles <2.5 µm [µg/m^3]
PSV	personal supply ventilation
SD	settled dust [g/g_{dust}]
SO_2	sulfur dioxide[µg/m^3]
TSP	total respirable suspended particulate matter
TVOC	total volatile organic compounds [mg/m^3]
VB	viable bacteria [cfu/m^3]
VM	viable mouts [cfu/m^3]

Thermal environment (TE)

CLO	clothing insulation value
RH_i	indoor relative humidity [%]
RH_o	outdoor relative humidity [%]
t_a	air temperature [◦C]
t_f	floor temperature [◦C]
t_g	globe temperature [◦C]
t_o	outdoor temperature [◦C]
t_{op}	operative temperature [◦C]
t_r	radiant temperature [◦C]
t_{r_asym}	radiant asymmetry temperature [µm]
t_w	temperature of walls [◦C]
t_{wb}	wet-bulb temperature [◦C]
v_a	air velocity [m/s].

Acoustic environment (AE)

L_{Aeq}	background noise or ambient noise [dB(A)]
F_0	fundamental frequency [Hz]
RT	reverberation time [sec]
SPL	sound pressure level [dB]
SPL_a	A-weighted sound pressure level [dB(A)]
SPL_c	C-weighted sound pressure level [dB(C)]

Lighting environment (LE)

Cc	contrast
CCT	correlated colour temperature [K]
CRI	color rendering index
CT	color temperature [K]
DF	daylight factor [%]
DFC	daylight factor contour
E_{amb}	ambient illuminance (illuminance) [lx]
E_c	cylindrical illuminance [lx]
E_{hor}	horizontal illuminance[lx]
E_{ver}	vertical illuminance [lx]
L_c	average ceiling luminance [cd/m^2]
Lf	luminous flux [lm/W]
$L_{og}Ch$	chloropic lux [lx]
$L_{og}Cy$	cyanopic lux [lx]
$L_{og}Er$	erythropic lux [lx]
$L_{og}Ph$	photopic lux [lx]
$L_{og}Rh$	rhodopic lux [lx]
L_w	average wall luminance [cd/m^2]
SPD	spectral power distribution
U_0	illuminance uniformity

Abbreviations

AP	academic performance
$APT_{(adj)}$	(adjusted) academic performance test score
BEPS	basic emotional process scale
BEPSA	BEPS activation
BEPSC	BEPS control
BEPSE	BEPS evaluation
BEPSS	BEPS emotional status
BEPSO	BEPS orientation
CBS	Corsi block score
CR	cognitive response
DSS	digit span score
ER	emotional response
F_{rt}	Flanker reaction time [sec]
IR	internal response
KSS	Karolinska sleepiness scale
NAS	negative affect scale
PAC	perceived acoustic comfort
PAS	positive affect scale
PCR	perceived cognitive response
PIAQ	perceived indoor air quality
PIEQ	perceived indoor environmental quality
PLC	perceived lighting comfort
PPHC	perceived physiological health complaints
PQL	perceived quality of learning
PR	physiological response
PTC	perceived thermal comfort
PTC_{pref}	thermal preference
PTC_{sens}	thermal sensation
STR	Stroop test
WCS	Wisconsin card sorting test
w_{ext}	external-related moderators
w_{gen}	general moderators

Appendix 6 Summary of included studies for the systematic approach

Reference	A	n	C	TE	LE	AE	IAQ	CAT	Studied variable	Applied method
Afren et al. (2017)	✓	n/a	n/a	RH_i, RH_o, t_a, t_o, v_a				PTC	Thermal comfort	Self-reported thermal preference on the ASHRAE-55 on a 3-points scale (very hot, hot, adequate)
Almeida et al. (2016)	✓	89[1] 96[1]	2	CLO, RH_i, t_a, t_f, t_r, t_{r_asym}, v_a				PTC	Thermal comfort	Self-reported thermal sensation (Fanger 7-points scale, ranging from -3 to +3, corresponding to very cold and very hot and 0 being the thermal neutral condition)
Ashrafi and Naeini (2016)	✓	30	1	t_a	E_{amb}	L_{Aeq}		PIAQ	Ventilation, breathing air	Self-reported suitability
								PLC	Lighting	Self-reported suitability
								PAC	Noise	Self-reported suitability
								CR	Subjective concentration	Self-reported inability in concentration
								PR	Health	Self-reported level of environmental health
Attia et al. (2017)	✓	265	1					PTC	Thermal comfort	Self-reported temperature (5-point rating scale too hot/ cold)
								CR	Distractions in classroom	Self-reported level of distractions
Bajc et al. (2018)	✓	40	1	RH_i, t_a, t_o, t_r, v_a			CO_2, CO_{2o}	PTC	Overall and local thermal comfort	Self-report sensation
								CR	Remembering information	Non-academic texts were read to subjects; after the reading, subjects were asked to answer five questions from the text that had been read

Appendix 6 *continued.*

Reference	A	n	C	TE	LE	AE	IAQ	CAT	Studied variable	Applied method
Bidassey-Manilal et al. (2016)	✓	252	5^2	t_a, v_a				ER	Tiredness	Hourly symptom log per day
								PR	Respiratory tract (upper respiratory symptoms)	Self-reported ability to breath
								PR	Central nervous system	Self-reported headaches, nausea, lethargy, dizziness
								PR	Health	Self-reported level of dehydration (thirsty)
Castilla et al. (2018a)	✓	854	1					CR	Reading, writing, reflecting, discussing, paying attention	Self-report ability
Castilla et al. (2017)	✓	918	1					PIAQ	Indoor air quality	Self-reported level of ventilation and damp air
								PAC	Acoustic comfort	Self-reported level of silence
								PTC	Thermal comfort	Self-reported level of "good temperature" and comfort
								PLC	Daylight, artificial lighting, well lit	Self-reported level
								CR	Subjective concentration	Self-reported level

Appendix 6 *continued.*

Reference	A	n	C	TE	LE	AE	IAQ	CAT	Studied variable	Applied method
Castilla et al. (2018b)	✓	427	1					PLC	Visual comfort	Self-reported level of attractiveness, stimulation, and coziness (attractive, good daylight, stimulating, comfortable, warm, cozy, pleasant, natural, dim (subtle), well lit, good artificial lighting, efficient, cutting edge technology, cosy, surprising, amazing, original, interesting, stimulating, suggestive, efficient, uniform, homogeneous, balanced, orderly, cheerful, colorful, friendly, lively, dynamic, beautiful, enabling, glaring (dazzling), intense, brilliant, calm, quiet, soft, clear, sharp (defined), with quality (rich), bright, functional, convenient, comfortable)
Corgnati et al. (2007)	✓	427	1	RH_i, t_a, t_r, v_a				PTC	Thermal comfort	Self-reported acceptability (at this moment, do you consider the thermal environment acceptable or not?), thermal preference (at this moment, would you prefer to feel warmer, cooler or no change), thermal sensation (Fanger 7-points scale, ranging from -3 to +3, corresponding to very cold and very hot and 0 being the thermal neutral condition)

Appendix 6 *continued.*

Reference	A	n	C	TE	LE	AE	IAQ	CAT	Studied variable	Applied method
Castro-Martínez et al. (2016)	✓	141 24	1			RT		CR	Level of attention	Average of the times students look away to a specific point. This average is calculated from the measurement and evaluation of the images of each participant's
								AP	Recognition	Questionnaire with words belonging and not belonging to the lecture, but related to the subject
Chin and Saju (2017)	✓	80	1			L_{Aeq}, SPL		PAC	Annoyance	Social and socio-acoustic surveys (noise sources which affect students)
Choi et al. (2014)	✓	15	2	RH_i, t_a	$L_{og}Ch$, $L_{og}Cy$, $L_{og}Er$, $L_{og}Ph$, $L_{og}Rh$, E_{amb}, CT	L_{Aeq}		PLC	Visual comfort	Self-assessment on a 100 mm visual analogue scale
								ER	Morning drowsiness, relaxation	Self-assessment on a 100 mm visual analogue scale
								ER	Subjective sleepiness	Karolinska Sleepiness Scale, a nine-point scale ranging from 1 (extremely alert) to 9 (extremely sleepy, fighting sleep)
								ER	Sleep quality	Pittsburgh Sleep Quality Index
								PR	Health	Level of salvia cortisol concentration and melatonin concentration

Appendix 6 *continued.*

Reference	**A**	**n**	**C**	**TE**	**LE**	**AE**	**IAQ**	**CAT**	**Studied variable**	**Applied method**
Chowdhury et al. (2010)	✓	480	1			SPL_{ac}		PAC	Acoustic comfort	Self-reported level of perceived traffic induced noise, noises from corridors and other rooms, and noise generated by themselves
								CR	Subjective concentration	Self-reported impaired concentration in their job
								PR	Ear	Self-reported earache and deafness
								ER	Tiredness	Self-reported tiredness
								PR	Respiratory tract (upper respiratory symptoms)	Self-reported respiratory distress
								PR	Central nervous system	Self-reported headaches
Ellis (2010)	n/a	n/a	n/a					PAC	Reverberation time	Application of flooring materials
End et al. (2010)	✓	71	2			L_{Aeq}		AP	Transfer of academic information	Academic information was presented through a video; the transferred knowledge was tested with two multiple-choice questions that assessed students' ability to recognize factual video content.

Appendix 6 continued.

Reference	A	n	C	TE	LE	AE	IAQ	CAT	Studied variable	Applied method
de Abreu-Harbich et al. (2018)	✓	200	1	RH_i, RH_o, t_a, t_o, v_a				PTC	Thermal comfort	Self-reported comfort (do you think this environment is? (comfortable, a little comfortable, uncomfortable, very uncomfortable, extremely uncomfortable), tolerance (this environment, in your opinion, regarding temperature, is it? (perfectly tolerable, a little difficult to tolerate, difficult to tolerate, very difficult to tolerate, intolerable), acceptance (taking into account only your personal preference, do you accept or reject the thermal conditions of this environment? (accept, reject), acceptance (at this moment do you prefer this environment? (much warmer, warmer, a little warmer, neither warmer nor colder (neutral), a little colder, colder, much colder), thermal sensation (Fanger 7-points scale, ranging from -3 to +3, corresponding to very cold and very hot and 0 being the thermal neutral condition)

Appendix 6 *continued.*

Reference	A	n	C	TE	LE	AE	IAQ	CAT	Studied variable	Applied method
Gentile et al. (2018)	✓	72	5	RH_i, t_a	E_c, E_{amb}, L_c, L_w, CRI, CCT, SPD, U_0		CO_2	PLC	Perception of lighting	Perceived Outdoor Lighting Qualities (POLQ) and has been successfully used in other indoor lighting studies: glaring from the light fixtures, glaring from the window, direct sunlight on your working space, flicker from the light fixtures, lighting quality
								ER	Positive en negative emotions	Positive and negative affect scales (PANAS)
								ER	Basic emotions	Basic emotional process scale (BEPS)
								PR	Health	salvia cortisol concentration
Granito & Santana (2016)	n/ap							PTC	Temperature	Focus group discussion
								PLC	Artificial room light Natural light	Focus group discussion
								PAC	Acoustics	Focus group discussion
Hoque et al. (2016)	✓	409	1	t_a, t_o, RH_i, RH_o, v_a				PTC	Thermal comfort	Self-reported sensation
								AP	Academic performance	Student exam scores
Jaakkola (2006)	✓							PR	Skin	Listing related health problems: itchy skin, skin irritation, skin rash, dermatological skin problem
								PR	Eye	Listing related health problems: itchy eyes, eye irritation, dry eyes
								PR	Respiratory tract (upper respiratory symptoms)	Listing related health problems: dry throat, nasal dryness, nose irritation
								PR	Central nervous system	Listing related health problems: headaches, nausea, lethargy
								PR	Mucositis	Listing related health problems: mucosal symptoms

Appendix 6 continued.

Reference	A	n	C	TE	LE	AE	IAQ	CAT	Studied variable	Applied method
Ahmed et al. (2017)	✓	499	9	t_a, t_r, $v_a^{=}$, $RH_i^{=}$	$E_{amb}^{=}$	$L_{Aeq}^{=}$	CO_2	PTC	Thermal comfort	Self-reported sensation
								ER	Fatigue	Self-report of level
								CR	Accuracy in vigilance tasks, memory tasks, complex tasks	BARS battery “behavioral assessment and research system”
								PR	Central nervous system	Self-report headaches
Jamaludin et al. (2016)	✓	20	1	RH_i, t_a	E_{amb}	L_{Aeq}	CO_2, TVOC	PIAQ	Perceived air quality	Perception of stuffy air
								PTC	Thermal condition	Students’ satisfaction level
								PLC	Lighting condition	Perceived lighting level
								PR	Skin	Self-reported dry skin
								PR	Eye	Self-reported itchy eyes, tired eyes, blurred vision
								PR	Respiratory tract (upper respiratory symptoms)	Self-reported sore throat, running nose, cough, breathing difficulties
								PR	Central nervous system	Self-reported headaches, dizzy
								PQL	Learning quality	Perceived learning productivity
Jonsdottir (2006)	✓	791	1			F_O, SPL		PAC	Ability to hear teacher voice	Self-report of effect amplification of teachers’ voice in classrooms
								ER	Fatigue	Self-report of prevalence of fatigue using a five-point rating scale
								CR	Subjective attention	Self-report of teachers regarding students paying attention using a five-point rating scale
								CR	Subjective concentration	Self-report of students regarding easiness to concentrate on lessons using a five-point rating scale

Appendix 6 continued.

Reference	A	n	C	TE	LE	AE	IAQ	CAT	Studied variable	Applied method
Kennedy (2010)	n/a							PLC	Illumination	Window selection and placement
Kuru and Calis (2017)	✓	235	1	t_a, t_r, RH_i, v_a				PTC	Thermal comfort	Self-reported thermal acceptability (yes = 1, no = 0), air velocity (low = -1, neither low nor high = 0, high = 1)
Lamb and Shraiky (2013)	n/a								Design concepts	
Lee et al. (2012)	✓	312	3	t_a, t_r, t_{op}, RH_i	E_{hor}	L_{Aeq}, SPL	CO_2	PIAQ	Indoor air quality	Self-assessment on a 7-point scale and acceptance (yes-no)
								PTC	Thermal comfort	Self-reported sensation
								PLC	Visual environment	Self-assessment on a 7-point scale and acceptance (yes-no)
								PAC	Aural environment	Self-assessment on a 7-point scale and acceptance (yes-no)
								PQL	Perceived learning performance	Self-reported performance scores for calculating, reading, understanding and typing
Madbouly et al. (2016)	✓	5325	1					PAC	Noise disturbance	Noises from inside and outside the classroom
								PAC	Importance of IEQ factors	Self-reported importance of acoustics properties (listening environment) and echo (comfortable, confusing, echoes, clear, irritating, relaxing, other)
								PIAQ	Importance of IEQ factors	Self-reported importance of ventilation
								PLC	Importance of IEQ factors	Self-reported importance of lighting
Majewski et al. (2017)	✓	101	2	CLO, t_a, t_o, t_w, v_a			CO_2	PTC	Thermal comfort	Self-reported thermal sensation (Fanger 7-points scale, ranging from -3 to +3, corresponding to very cold and very hot and 0 being the thermal neutral condition)

Appendix 6 continued.

Reference	A	n	C	TE	LE	AE	IAQ	CAT	Studied variable	Applied method
Markides (1989)	n/ap					L_{Aeq}		AP	Academic performance	The lip-reading test was used. A video (in black and white) and was presented to students through a recorder and monitor. Students' ability to read lips was scored
Maxwell (2009)	n/a								Noise	
McDonald et al. (2004)	✓	78	4			L_{Aeq}		AP	Transfer of academic information	Academic information was presented with a 5-minute videotape developed specifically for the study and knowledge. Next, immediately after watching the video, participants were instructed to write out their food intake during the past 24 hours on a blank sheet of paper. This task required the information learned while watching the videotape to be transferred into long-term memory. Finally, the participants were tested using 13 multiple-choice questions addressing the information presented in the videotape
Mishra et al. (2017)	✓	348	3	RH_i, t_a, t_g, t_o, v_a			CO_2	PTC	Thermal adaptation	Self-reported sensation
								PTC	Clothing insulation value	Reported clothing (top, shirt, long-sleeve shirt, sweater/blazer, dress, skirt, jacket, open shoes, shoes, trouser, boots, scarf)

Appendix 6 *continued.*

Reference	**A**	**n**	**C**	**TE**	**LE**	**AE**	**IAQ**	**CAT**	**Studied variable**	**Applied method**
Mongkolsawat et al. (2014)	✓	673	1	RH_i, RH_o, t_a, t_o, v_a				PIAQ	Air freshness (including odor)	Self-reported on a scale from 1 (very uncomfortable) to 5 (very comfortable).
								PTC	Thermal comfort	Self-reported on a scale from 1 (very uncomfortable) to 5 (very comfortable), acceptability (five-point ordinal scale)
								PLC	Visual comfort	Self-reported on a scale from 1 (very uncomfortable) to 5 (very comfortable)
								PAC	Hearing comfort	Self-reported on a scale from 1 (very uncomfortable)to 5 (very comfortable)
								ER	Sleepiness	Perception of freshness (as opposed to sleepiness) using a five-point rating scale
								CR	Subjective alertness	Perception of alertness using a five-point rating scale (from 1 – much lower than average to 5 – much higher than average)
								CR	Subjective attention	Perception of how the IEQ affected their attention using a five-point rating scale
								PQL	Perceived learning performance	Perception of how the IEQ affected their overall learning performance using a five-point rating scale
Nico et al. (2015)	✓	126	1	t_a, t_g, RH_i, v_a				PTC	Thermal Preference Index	Self-reported willingness to change, unacceptability of thermal environment, unacceptability of air movement, thermal sensation (Fanger 7-points scale, ranging from -3 to +3, corresponding to very cold and very hot and 0 being the thermal neutral condition)

Appendix 6 continued.

Reference	A	n	C	TE	LE	AE	IAQ	CAT	Studied variable	Applied method
Norbäck et al. (2013)	✓	232	2	RH_i, t_o			AC, AER, CO_2, N_2O, NCHO, PM_{10}, PSV, VB, VM	PIAQ	Air quality	Self-reported air quality (extremely poor (0)–extremely good (6)) when entering the classroom (the first 15 min and the last hour), and quality of odor (no odor (0)–extremely strong odor (6))
								PTC	Thermal comfort	Room temperature (too cold (0)–too hot (6)), air humidity (extremely dry (0)–extremely humid (6)), air movement (draught) (no movement (0)–extremely draughty (6))
								PLC	Visual comfort	illumination (very good (0)–very poor (6))
								PAC	Noise disturbance	Noise in general and noise from ventilation system (no disturbing noise (0)–very disturbing (6))
								PR	Eye	Self-reported eye symptoms, using a six-point rating scale
								PR	Skin	Self-reported dermal symptoms, using a six-point rating scale
								PR	Respiratory tract (upper respiratory symptoms)	Self-reported sore throat, sinusitis ●, and nasal symptoms and breathing difficulties, using a six-point rating scale
								PR	Central nervous system	Self-reported headaches and nausea, using a six-point rating scale
								ER	Tiredness	Self-reported tiredness, using a six-point rating scale

Appendix 6 *continued.*

Reference	A	n	C	TE	LE	AE	IAQ	CAT	Studied variable	Applied method
Persinger et al. (1999)	✓	21	4			L_{Aeq}		ER	Fatigue	Self-report rating scale using anchors of 1 through 7
								CR	Subjective concentration	Self-report rating scale for concentration using anchors of 1 through 7
Ramprasad and Subbaiyan (2017)	✓	1295	1	t_a, t_g, t_{op}, v_a				PTC	Thermal environment	Satisfaction with temperature (1 = very dissatisfied, 5 = very satisfied), temperature acceptability (yes-no), satisfaction with air movement (1 = more air movement, 2 = no change, 3 = less air), satisfaction with freedom to control the speed of ceiling fans, satisfaction with freedom to switch the ceiling fans, satisfaction with freedom to open/close the window/shutters
								PIAQ	Indoor air quality	Satisfaction with air quality, freshness of air (1 = very stale, 5 = very fresh), air quality acceptability
								PLC	Visual environment	Satisfaction with visibility to see the chalkboard/projector screen, satisfaction with daylight, daylight preference (1 = brighter, 2 = no change, 3 = less brighter), satisfaction with freedom to switch the fluorescent lamps on/off
								PAC	Acoustic environment	Satisfaction with acoustics, acoustics acceptability (1 = very dissatisfied 5 = very satisfied)
								PQL	Perceived academic performance	Self-reported overall academic satisfaction, academic ambience and academic performance

Appendix 6 *continued.*

Reference	A	n	C	TE	LE	AE	IAQ	CAT	Studied variable	Applied method
Rouag-Saffidine and Benharkat (2006)	✓	36	1		E_{ver}, DF, DFC			PLC	Perceived visual comfort	Do you appreciate daylight in your workplace? (answers on a 4 rating scale), do you assess indoor daylight as sufficient in summer/in winter? (answers on a 4/5 rating scale), do you experience incident sunlight upon your work-plane? (answers on a 3 rating scale), are you keen for some solar controls in this work place? (yes/no)
Sarbu and Pacurar (2015)	✓	200	2	RH_i, t_a, t_g, t_r, v_a,			CO_2	PTC	Thermal comfort	Self-reported sensation
								CR	Concentrated attention	Kraepelin test; pairs of numbers have to be compared and calculations have to be performed based on the outcome of the comparison
								CR	Distributive attention	Prague test; ordering and comparing figures with a model figure
Shelton et al. (2009)	✓	158 73 33 27	4 3 1 1			L_{Aeq}		CR	Level of attention	Lexical decision task; four different types of were pairs presented: 1) word, word; 2) non-word, non-word; 3) word, non-word; and 4) non-word, word. Subjects were asked to respond as quickly as possible; they had to press 1 on the keyboard if both stimuli were words and to press 2 otherwise
								AP	Academic performance	Academic information during class was discussed, the transferred knowledge was tested with 6 multiple-choice questions (with 4 answer options) and 2 short-answer questions

Appendix 6 continued.

Reference	A	n	C	TE	LE	AE	IAQ	CAT	Studied variable	Applied method
Siqueira et al. (2017)	✓	28	3	RH_i, t_a, t_g, t_r, t_{wb}, v_a, p_a				CR	Accuracy in reasoning tasks	The abstract reasoning, verbal reasoning, numerical reasoning, spatial reasoning and the mechanical reasoning test
								PR	Health	Measurement of heart rate and blood pressure
Valavanidis and Vatista (2006)	✓	1004	1	RH_i, t_a		L_{Aeq}	Cl_2, CO, CO_2, HCHO, SO_2, NO_2, O_3, SD, TSP, TVOC	PIAQ	Indoor air quality	Self-reported quality of air and smells
								PR	Central nervous system	Self-reported heavy-headed, headaches, dizziness (Yes, often", "Yes, sometimes" and "No, never"; experience of the past 2 months)
								PR	Eye	Self-reported burning or irritation of the eyes
								PR	Respiratory tract (upper respiratory symptoms)	Self-reported sore throat
Van Someren et al. (2018)	n/a							PLC	Lighting controls	
Witkowska and Gladyszews-Fiedoruk (2018)	✓	30	1	RH_i,t_a		L_{Aeq}		PTC	thermal comfort	Self-reported (scale 1-glad, 2-neutral, 3-dissatisfied), humidity and air temperature (scale 1-very dissatisfied, 2-dissatisfied, 3-no opinion, 4-glad, 5-very glad), air temperature (scale 1-too hot, 2-warm, 3-ok, 4-cold, 5-too cold), degree of humidity (scale 1-too high, 2-high, 3-ok, 4-dry, 5-too dry)
								PAC	Acoustic comfort	Noise level (scale 1-very dissatisfied, 2-dissatisfied, 3-no opinion, 4-glad, 5-very glad), noise level (scale 1-too loud, 2-loud, 3-ok, 4-quietly, 5-too quiet)

Appendix 6 *continued.*

Reference	A	n	C	TE	LE	AE	IAQ	CAT	Studied variable	Applied method
Xiong et al. (2018)	✓	10	36	t_a	E_{amb}	SPL		CR	Level of attention	Number searching test; numbers 0 through 99 were sequenced out of order on papers. Subjects were asked to search 15 designated numbers in normal order from these 100 numbers
								CR	Recognition of meaningless images	10 meaningless images on paper were presented for 10 s. When time was up, the subjects were asked to pick them out from all 20 meaningless images on another paper as quickly as possible
								CR	Perception-oriented task	The Rochester color word test; 15 words of colors in another color were presented on papers. Subjects were asked to pick out the word itself or its color sequentially
								CR	Problem-solving task	Reading comprehension; subjects were asked to pick out the only correct answer from multiple choices based on their own understandings. Previously printed out, five independent questions were randomly distributed to each subject from the administrative ability tasks for national civil servant selections
Yan et al. (2012)	n/ap			RH_i, t_a	CRI, , CT, LF, E_{amb}		CO_2	CR	Visual performance	Recognition ability of real objects in a controlled environment

Appendix 6 *continued.*

Reference	A	n	C	TE	LE	AE	IAQ	CAT	Studied variable	Applied method
Yang and Becerik-Gerber (2012)	✓	627	1					PTC	Temperature perception	Self-reported discomfort, heat from the sun, heat from classroom equipment, cold air from windows, cold air from ac unit or vent, cold air from door or outside room source, noticeably different temperature than other classrooms of hallways
								PIAQ	Air quality perception	Self-reported comfort, dirty air, humid air, dry air, odorous air, drafty air, stuffy air
								PLC	Artificial lighting perception	Self-reported adequate illumination, too bright, too dark, too much glare, lack of control, undesirable color, shadows, flickering
								PLC	Daylight perception	Self-reported adequate illumination, too bright, too dark, too much sunlight, lack of control, shadows
								PAC	Acoustics perception	Self-reported noise, from air vent/AC, from electronic equipment, from talking inside the classroom, from talking outside of the classroom
You et al. (2007)	✓	10005		RH_i, t_a, t_o			CO_2	PIAQ	Indoor air quality	Self-reported evaluation of how ventilation rate affected comfortlessness

Appendix 6 *continued.*

Reference	**A**	**n**	**C**	**TE**	**LE**	**AE**	**IAQ**	**CAT**	**Studied variable**	**Applied method**
Zomorodian et al. (2016)	n/ap							PTC		Study reports application of thermal sensation (seven-point ASHRAE scale and Bedford scale), thermal preference (McIntyre three-point rating scale and checklist for clothing and activity

Note: A = applicability; ✓ = method is applied for systematic approach; n = number of participants; C = number of campaigns, trials or runs; n/a = information about the applied method is not available; n/ap = information about the method is not applicable for quantitative research; = condition was kept constant during campaign(s).
TE = Thermal environment: RH_i = indoor relative humidity; RH_o = outdoor relative humidity; t_a = air temperature; t_f = floor temperature; t_g = globe temperature; t_o = outdoor temperature; t_{op} = operative temperature; t_r = radiant temperature; t_{r_asym} = radiant asymmetry temperature; t_w = temperature of walls; t_{wb} = wet-bulb temperature; v_a = air velocity.
LE = Lighting environment; Cc = contrast; CCT = correlated color temperature; CRI = color rendering index; CT = color temperature; DF = daylight factor; DFC = daylight factor contour; E_{amb} = ambient illuminance; Ec = cylindrical illuminance; E_{hor} = horizontal illuminance; E_{ver} = vertical illuminance; L_c = average ceiling luminance; L_f = luminous flux; L_{og}Ch = chloropic lux; L_{og}Cy = cyanopic lux; L_{og}Er = erythropic lux; L_{og}Ph = photopic lux; L_{og}Rh = rhodopic lux; L_w = average wall luminance; SPD = spectral power distribution; U0 = illuminance uniformity.
AE = Acoustic environment: L_{Aeq} = background noise or ambient noise; F0 = fundamental frequency; RT = reverberation time; SPL_a = A-weighted sound pressure level; SPL_c = C-weighted sound pressure level.
IAQ = Indoor air quality; AC = allergen concentration; AER = air exchange rate; Cl_2 = chlorine; CO = carbon monoxide; CO_2 = carbon dioxide CO_2o = carbon dioxide outside; D = dust; HCHO = formaldehyde; NO_2 = nitrogen dioxide; O_3 = ozone; PM10 = particles; PSV = personal supply ventilation; SD = settled dust; SO_2 = sulfur dioxide; TSP = total respirable suspended. particulate matter; TVOC = total volatile organic compounds; VB = viable bacteria; VM = viable mouts.
CAT = studied category; AP = academic performance; CR = cognitive response; ER = emotional response; PIAQ = perceived indoor air quality; PLC = perceived lighting comfort; PR = physical response; PTC = perceived thermal comfort;
[1] Number of university students.
[2] During 5 days participants filled in daily heat-health symptom log at each hour of the day between 8 a.m. and 2 p.m.
[3] All experiments were carried out on weekday evenings (Monday till Thursday, 6:30-10:00 p.m.) in a 3-month period.
[4] Study reports that more than 100 questionnaires were distributed.
[5] Study reports that questionnaire was distributed to 1000 undergraduate students.

Appendix 7 Overview of the PANAS and BEPS method, the Karolinska Sleepiness Scale and the Pittsburgh Sleep Quality Index

Method	Included	Score range	Dimension	Abbreviation	Items
PANAS	Yes	10–50	Positive affect scale	PA	Interested + excited + strong + enthusiastic + proud + alert + inspired + determined + attentive + active
		10–50	Negative affect scale	NA	Distressed + upset + guilty + scared + hostile + irritable + ashamed + nervous + jittery + afraid
BEPS	Yes	1–4	Activation	BEPSA	Average (rested - drowsy + awake)
		1–4	Evaluation	BEPSE	Average (friendly - sad - anxious)
		1–4	Orientation	BEPSO	Average (interested - quiescent + engaged)
		1–4	Control	BEPSC	Average (independent - indecisive - weak)
		1–4	Emotional status	BEPSES	Average (Activation + Evaluation + Orientation + Control)
Karolinska Sleepiness Scale	Yes	1-10	Sleepiness versus alertness	KSS	Scale from (1) Extremely alert to (10) great effort to keep awake, fighting sleep
Pittsburgh Sleep Quality Index	No	0-3	Sleep quality	PSQI	Subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, daytime dysfunction over a long period of time

Note: BEPS = basic emotional process scale; BEPSA = BEPS activation; BEPSC = BEPS control; BEPSE = BEPS evaluation; BEPES = BEPS emotional status; BEPSO = BEPS orientation; KSS = Karolinska sleepiness scale; PSQI = Pittsburgh sleep quality index.

Appendix 8 Measured indoor environmental parameters, used symbols, and descriptions of the measuring devices (systematic approach)

Performance indicator	Symbol	Description
Outdoor air temperature	t_o	The outside temperature was derived from the Royal Netherlands Meteorological Institute, www.knmi.nl, reading interval 1 hr
Indoor air temperature at desktop height	t_a	Air temperature in degrees Celsius (°C) and is measured with an ATAL VLK-60 temperature sensor at 1.1 m height, accuracy ±0.5 °C @ 0 to +50 °C
Outdoor relative humidity	RH_o	The outdoor relative humidity was derived from the Royal Netherlands Meteorological Institute, www.knmi.nl, reading interval 1 hr
Indoor relative humidity	RH_i	Indoor relative humidity in percentage (%) and is measured with an ATAL VLK-60 humidity sensor at 1.1 m height, accuracy, accuracy ±0.3 % RH_i @ 5 to 99 % RH_i
Background noise	BGN	Average sound pressure level in dB(A) over a period of 45 seconds and is measured with a Velleman DEM201, accuracy +/- 1.4 dB 94 dB @ 1 kHz
Carbon dioxide concentration	CO_2	Parts per million carbon dioxide concentration (ppm CO_2) is measured with an ATAL VLK-60 carbon dioxide sensor at 1.1 m height, accuracy ±75 ppm + 10 % of the actual reading
Particulate matter 10	PM10	Particulate matter is measured with an ATAL VLK-60 PM10 sensor at 1.1 m height sensor: accuracy < ±15 % @ 0 to 1,000 µg/m^3
Particulate matter 2.5	PM2.5	Particulate matter is measured with an ATAL VLK-60 PM2.5 sensor at 1.1 m height sensor: accuracy < ±15 % @ 0 to 1,000 µg/m^3
Horizontal illuminance	E_{hor}	Illuminance level in Lux and is measured with a VOLTCRAFT MS-1300, accuracy ± 5 % + 10 digits @ < 10.000 lx
Volatile organic compounds	TVOC	Volatile organic compounds is measured with an ATAL VLK-60 TVOC sensor at 1.1 m height sensor: accuracy ± 0.02 mg (or 10 %) @ 0 to 3.5mg/m^3

Appendix 9 Assumed linear relation between variables

KPI	Variable	Assumption of linearity	Assumed association	Remarks
CO_2 PM2.5 TVOC	PIAQ	An increase in all KPI's will lead to a deterioration in the perceived indoor air quality (PIAQ)	Negative correlation	PIAQ score, minimum score is 1 = very poor, and the maximum score is 5 = very good. Optimum is maximum score of scale, linear analyses is possible
RH_i t_a	PTC_{sens}	Increase of RH_i and T_a will lead to an increase of the thermal sensation vote (PTC_{sens})	Positive correlation	Optimum is 4 on a scale from 1 to 7. Although al linear correlation is assumed between the KPI's and the $PTC_{sen,}$ the optimum of this scale (neutral sensation) is in the middle (4) and prohibit further linear analyses. For linear analyses, this variable is recoded into the level of perceived thermal comfort (PTC) due to cold or heat.
RH_i t_a	PTC_{pref}	Increase of RH_i and T_a will lead to an increase of the thermal preference vote (PTC_{pref})	Positive correlation	Optimum is 4 on a scale from 1 to 7. Although al linear correlation is assumed between the KPI's and the PTCpref, the optimum of this scale (Neither warmer nor colder) is in the middle (4) and prohibit further linear analyses. For linear analyses, this variable is recoded into the level of perceived thermal comfort based on the thermal preference warmer or colder.
E_{hor}	PLC	Increase of amount of lux will lead to an increase of the perceived lighting comfort (PLC)	Positive correlation	PLC score, minimum score is 1 = very poor, and the maximum score is 5 = very good. Optimum is maximum score of scale, linear analyses is possible
RT	PAC	Increase of the RT will lead to a deterioration of the perceived acoustic comfort (PAC)	Negative correlation	PLC score, minimum score is 1 = very poor, and the maximum score is 5 = very good. Optimum is maximum score of scale, linear analyses is possible

Appendix 10 Overview of items and perception scales related to the perceived indoor environmental quality, student responses, and short-term academic performance

Perceived thermal comfort

Category: thermal sensation (PTC_{sens})

Please classify the indoor temperature at this moment: cold, cool, slightly cool, neutral, slightly warm, warm, hot

Category: thermal preference (PTC_{pref})

At this moment, would you prefer to feel much warmer, warmer, a little warmer, neither warmer nor colder neutral a little colder, colder, much colder

Category: thermal acceptance

At this moment, do you consider the thermal environment acceptable or not? yes, no

Scale perceived thermal comfort (PTC)

Item	Old value	Original classification	New value	Comfort classification
PTC_{sens}	1	Cold	1	Very uncomfortable
	2	Cool	2	Uncomfortable
	3	Slightly cool	4	Comfortable
	4	Neutral	4	Comfortable
	5	Slightly warm	4	Comfortable
	6	Warm	2	Uncomfortable
	7	Hot	1	Very uncomfortable
PTC_{pref}	1	Much warmer	1	Very uncomfortable
	2	Warmer	2	Uncomfortable
	3	A little warmer	3	Slightly uncomfortable
	4	Neither warmer nor colder	4	Comfortable
	5	A little colder	3	Slightly uncomfortable
	6	Colder	2	Uncomfortable
	7	Much colder	1	Very uncomfortable

Perceived Indoor Air Quality (PIAQ)

Likert 7-point scale

strongly disagree, disagree, slightly disagree, neutral, slightly agree, agree, strongly agree

Category: general perception

I’m satisfied with the air quality in this classroom

Category: air quality

The air in this classroom is not stale

There is a lot of fresh air in here

The classroom is properly ventilated

Category: odor intensity and character

The classroom has a pleasant smell

The scent of the air in the classroom doesn’t distract me

Category: moisture

The air is not dry in here

The air is not dusty in here

The perceived indoor air quality (PIAQ) mean score

Calculated from the score on the individual items, divided by the number of items

Perceived Acoustic Comfort (PAC)

Likert 7-point scale

strongly disagree, disagree, slightly disagree, neutral, slightly agree, agree, strongly agree

Category: speech intelligibility

I can hear the lecturer’s voice clearly in the classroom

Perceived Lighting Comfort (PLC)

Likert 7-point scale

strongly disagree, disagree, slightly disagree, neutral, slightly agree, agree, strongly agree

Category: general perception

I ’m satisfied with the lighting conditions in this classroom

Category: reflections and glare

1 don’t experience any annoying glare/reflections from my table or from the ceiling lights

Category: amount of (day)light

The amount of light is excellent for the work I have to do at my desk

1 can see the lecturer clearly

1 can see the whiteboard clearly

The perceived lighting comfort (PLC) mean score

Calculated from the score on the individual items, divided by the number of items

Perceived physical health (PPH)
What is your health like at this moment
Do you have any disabilities
Perceived physical health complaints (PPHC)
Are you experiencing any health problems at this moment (for example: skin, eye, ear, nose or other health problems)
Perceived cognitive response (PCR)
Topic: sleepiness and alertness (Karolinska Sleepiness Scale)
How are you feeling at the moment?
Extremely alert, very alert, alert, rather alert, neither alert nor sleepy, some signs of sleepiness, sleepy but no effort to keep awake, sleepy, some effort to keep awake, very sleepy great effort to keep awake fighting sleep, extremely sleepy can't keep awake
Likert 7-point scale
strongly disagree, disagree, slightly disagree, neutral, slightly agree, agree, strongly agree
Category: alertness
I was very alert during the lecture
Category: concentration
I was able to concentrate well during the lecture
Category: memory
I can remember the content of the lecture well
Category: perception
I was able to understand the lecture well
Category: problem solving
I was able to solve complicated problems during lecture well
The perceived cognitive response (PCR) mean score
Calculated from the score on the individual items, divided by the number of items

Perceived quality of learning (PQL)
Likert 7-point scale
strongly disagree, disagree, slightly disagree, neutral, slightly agree, agree, strongly agree
Category: general perception
I was very productive during the lecture
I was able to read well during the lecture
I was able to write (type) well during the lecture
The perceived quality of learning mean score
Calculated from the score on the individual items, divided by the number of items

Appendix 11 Psychometric tests, description of the test, and details about the calculation of the performance indicators

Category	Test	Description	Performance Indicator
Attention and concentration	Go-No Go	Letters P or R were shown on screen one at a time at constant intervals. Students were instructed to click on the space bar as soon as they saw a P but never when they saw a R. The task, which takes about 2.5 min. Feedback is given (including d-prime based on Hits and False Alarms).	D-prime score d' = z(H) - z(F), where z(H) and z(F) are the z transforms of hit rate H (proportion of trials where the stimulus was present and the student responded that the stimulus was present) and false alarm F (proportion of trials where the stimulus was not present, and the subject responded that the stimulus was present)
Memory	Corsi block	Test of visuospatial working memory, whereby blocks have to be clicked in the order in which they were flashed on the screen. The number of flashing blocks increases from 3 to 9	Actual score
Perception	Stroop	Color words: RED, YELLOW, GREEN and BLUE were shown on screen one at a time at constant intervals. Each time any of these words was presented it could be written in any one of the colors. Students were instructed to press resp. the <r>,<y>,<g>, or <b> key as fast as possible. In variant 1 students were instructed to confirm the color of word, disregarding the word itself. In variant 2 the student had to conform the word, disregarding the color of the word itself.	Average ((Number of correct responses variant 1 / reaction time (in ms) variant 1) + (Number of correct responses variant 2 / reaction time (in ms) variant 2)
Problem solving	Wisconsin Card Sorting	The task consists of 64 cards with four stimuli cards. The students were instructed to combine the cards and received feedback about the success or failure of each association. The students' task consisted of discovering the previous combination stipulated (matching rule) and to make the response apply to each new context (new matching rule). The test ended when all the cards were used.	Total number of correct Total number of errors Number of discovered matching rules

Appendix 12 Scores of students' perceptions, internal responses, and short-term academic performance in the control and intervention conditions.

CP	CO	PIAQ	PTC	PLC	SIR	PPH	PPHC
1	CC[1]	4.8 ±1.2	3.3 ±0.8	5.8 ±0.7	6.3 ±0.7	2.0 ±0.6	0.0 ±0.4
	IC[2]	4.9 ±1.0	3.2 ±0.9	6.0 ±0.7	6.4 ±0.6	1.9 ±0.7	0.0 ±0.0
2	CC[1]	5.4 ±1.0	3.1 ±0.7	5.9 ±0.7	6.4 ±0.7	2.1 ±0.6	0.0 ±0.0
	IC[2]	5.2 ±1.1	3.0 ±1.0	5.9 ±0.8	6.3 ±0.8	1.6 ±0.6	0.0 ±0.0
3	CC[1]	4.7 ±1.3	3.4 ±0.6	5.7 ±0.8	6.1 ±0.9	1.8 ±0.7	0.0 ±0.0
	IC[3]	5.0 ±1.1	3.6 ±0.5	5.9 ±0.8	6.1 ±0.9	1.8 ±0.6	0.0 ±0.0
4	CC[1]	4.9 ±1.2	3.3 ±0.8	5.5 ±1.0	5.9 ±1.2	1.9 ±0.6	0.0 ±0.1
	IC[3]	5.1 ±1.2	3.5 ±0.8	6.0 ±0.8	6.2 ±0.9	1.7 ±0.6	0.0 ±0.1
5	CC[4]	4.8 ±1.2	3.8 ±0.3	5.8 ±0.9	6.1 ±0.8	1.9 ±0.5	0.0 ±0.0
	IC[5]	5.9 ±0.6	3.8 ±0.3	6.3 ±0.4	6.3 ±0.6	1.9 ±0.6	0.0 ±0.0
6	CC[4]	5.6 ±0.9	3.4 ±0.7	6.1 ±0.7	6.4 ±0.7	1.8 ±0.7	0.0 ±0.0
	IC[5]	5.3 ±1.0	3.4 ±0.8	6.0 ±0.6	6.2 ±0.6	1.9 ±0.6	0.0 ±0.0
7	CC[4]	5.5 ±1.0	3.6 ±0.6	5.8 ±1.0	6.2 ±0.7	1.6 ±0.5	0.0 ±0.0
	IC[5]	6.0 ±0.8	3.4 ±0.8	6.2 ±0.6	6.2 ±0.9	1.6 ±0.6	0.0 ±0.0

CP	CO	PCP	CBS	WCSC	WCSR	WCSA	STR
1	CC[1]	4.7 ±1.1	6.0 ±1.7	55 ±3	4.1 ±0.9	6.2 ±2.3	38 ±11
	IC[2]	5.2 ±0.8	6.5 ±1.4	54 ±4	3.9 ±1.1	6.1 ±2.4	37 ±12
2	CC[1]	5.0 ±0.8	6.9 ±1.1	55 ±4	4.1 ±0.8	6.0 ±3.3	40 ±11
	IC[2]	5.2 ±1.0	6.8 ±1.1	53 ±7	4.0 ±1.3	5.9 ±1.8	39 ±13
3	CC[1]	4.9 ±1.0	6.8 ±1.0	55 ±3	4.2 ±1.0	6.0 ±3.0	41 ±16
	IC[3]	5.0 ±1.1	6.6 ±1.0	53 ±8	4.0 ±1.3	5.8 ±2.3	36 ±10
4	CC[1]	4.5 ±1.0	6.2 ±1.4	54 ±4	4.1 ±1.0	6.5 ±2.2	40 ±13
	IC[3]	5.0 ±1.1	6.7 ±1.3	53 ±7	4.0 ±1.3	5.3 ±2.1	39 ±10
5	CC[4]	5.2 ±1.0	6.8 ±1.0	54 ±6	4.0 ±0.7	5.3 ±1.5	43 ±8
	IC[5]	5.7 ±0.6	6.6 ±0.9	54 ±3	4.0 ±0.5	6.6 ±2.2	43 ±7
6	CC[4]	5.1 ±1.1	6.1 ±1.5	54 ±5	4.1 ±1.3	6.5 ±2.9	40 ±22
	IC[5]	5.0 ±1.0	6.7 ±1.2	55 ±3	4.0 ±0.9	5.8 ±1.8	41 ±10
7	CC[4]	5.1 ±1.1	6.5 ±0.9	53 ±4	3.9 ±1.1	7.1 ±3.4	35 ±11
	IC[5]	5.5 ±0.9	6.6 ±1.0	53 ±6	4.0 ±1.0	6.6 ±2.4	43 ±8

CP	CO	GNG	PAS	POS	BEPSS	KSS	PQL	APT
1	CC[1]	4.1 ±1.3	14 ±4	30 ±6	2.7 ±0.4	5.3 ±1.9	5.2 ±0.9	5.6 ±1.5
	IC[2]	4.1 ±1.1	15 ±7	31 ±6	2.8 ±0.4	4.5 ±1.5	5.5 ±0.7	5.4 ±1.7
2	CC[1]	4.1 ±0.9	14 ±5	32 ±6	2.9 ±0.3	4.4 ±1.6	5.0 ±0.9	5.8 ±1.6
	IC[2]	4.5 ±1.0	13 ±4	31 ±8	2.9 ±0.5	4.5 ±1.6	5.3 ±0.8	6.1 ±1.7
3	CC[1]	4.3 ±1.1	14 ±5	32 ±6	2.9 ±0.4	4.2 ±1.5	4.9 ±0.9	4.4 ±1.4
	IC[3]	4.1 ±1.3	13 ±5	29 ±6	2.9 ±0.3	4.5 ±1.9	5.0 ±1.1	4.2 ±1.4
4	CC[1]	4.3 ±0.9	14 ±5	30 ±7	2.8 ±0.4	4.4 ±1.6	5.0 ±1.0	5.7 ±1.9
	IC[3]	4.4 ±1.1	13 ±5	30 ±7	2.8 ±0.4	4.3 ±1.7	5.4 ±1.0	5.6 ±1.8
5	CC[4]	4.1 ±1.1	12 ±2	32 ±6	2.9 ±0.2	4.2 ±1.6	5.4 ±1.0	5.9 ±1.8
	IC[5]	4.4 ±1.2	13 ±3	35 ±5	3.0 ±0.2	3.7 ±1.3	5.8 ±0.6	7.0 ±1.9
6	CC[4]	4.2 ±0.9	11 ±2	32 ±8	2.8 ±0.4	4.4 ±1.9	5.6 ±0.7	8.2 ±1.7
	IC[5]	4.5 ±1.1	13 ±5	30 ±7	2.8 ±0.4	4.8 ±1.9	5.3 ±0.9	7.8 ±1.7
7	CC[4]	4.0 ±1.2	13 ±4	33 ±6	3.0 ±0.4	3.9 ±1.9	5.3 ±1.0	7.8 ±1.3
	IC[5]	4.4 ±0.9	13 ±4	33 ±5	3.0 ±0.3	3.5 ±1.3	5.8 ±0.8	7.4 ±1.8

Note: BEPSS = BEPS emotional status; CO = condition; CP = campaign number; CBS = Corsi block task score; GNG = Go-No Go task score; KSS = Karolinska Sleepiness Scale; NAS = negative affect scale; PAS = positive affect scale; PCR = perceived cognitive response; PIAQ = perceived indoor air quality; PLC = perceived lighting comfort; PPH = perceived physical health; PPHC = perceived physical health complaints; PQL = perceived quality of learning; PTC = perceived thermal comfort; STR = Stroop color-word task; SIR = speech intelligibility; WCSA = Wisconsin Card Sorting test attempts score; WCSC = Wisconsin Card Sorting test correct responses score; WCSR = Wisconsin Card Sorting test matching rules score.

[1] = control condition: air temperature ~21◦C, reverberation time = 0.6 s, horizontal illuminance 500 lx, indoor air quality ~1100 ppm.

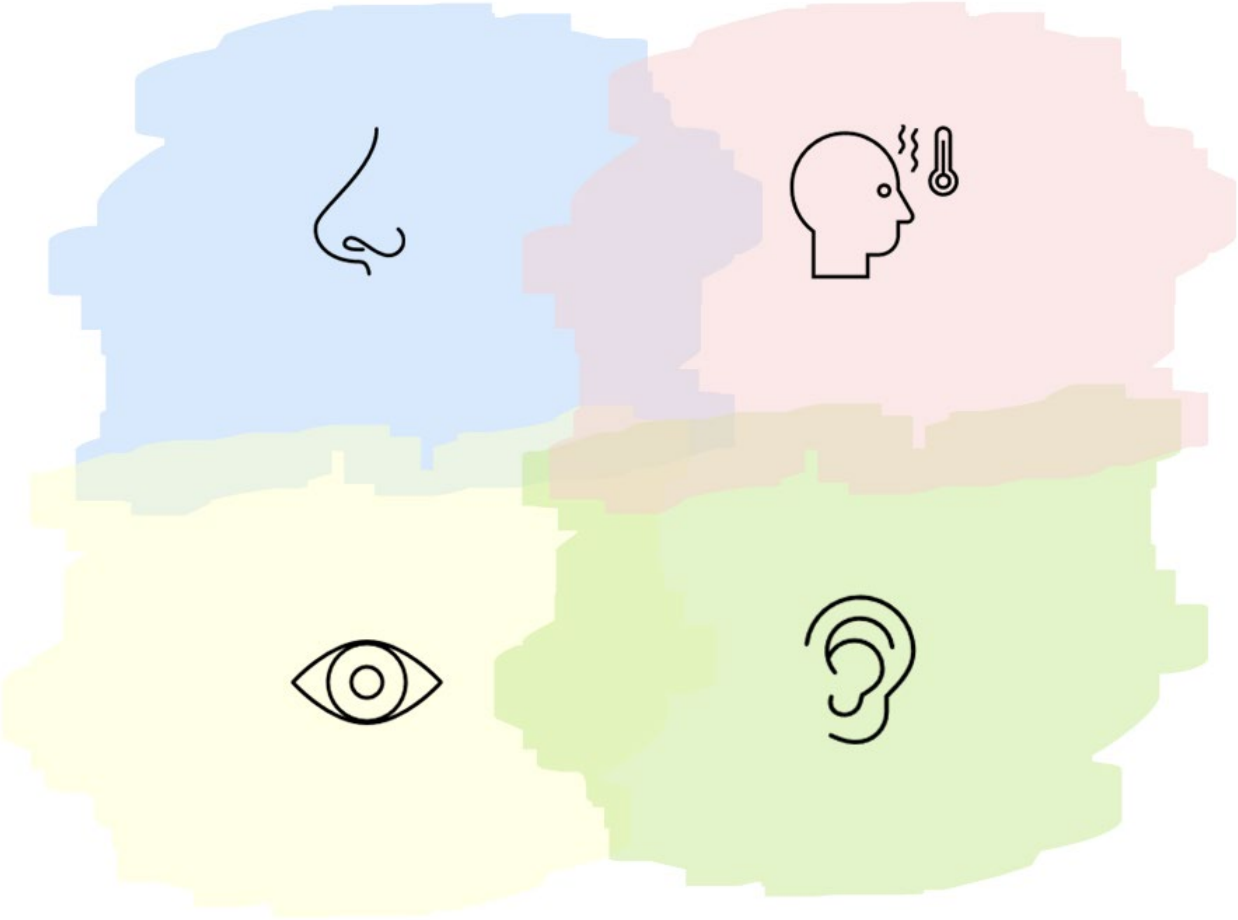
[2] = intervention condition: air temperature ~21◦C, reverberation time = 0.4 s, horizontal illuminance 500 lx, indoor air quality ~1100 ppm.

[3] = intervention condition: air temperature ~21◦C, reverberation time = 0.4 s, horizontal illuminance 750 lx, indoor air quality ~1100 ppm.

[4] = control condition: air temperature ~21◦C, reverberation time = 0.6 s, horizontal illuminance 500 lx, indoor air quality <800 ppm.

[5] = intervention condition: air temperature ~21◦C, reverberation time = 0.4 s, horizontal illuminance 750 lx, indoor air quality <800 ppm.

Curriculum Vitae



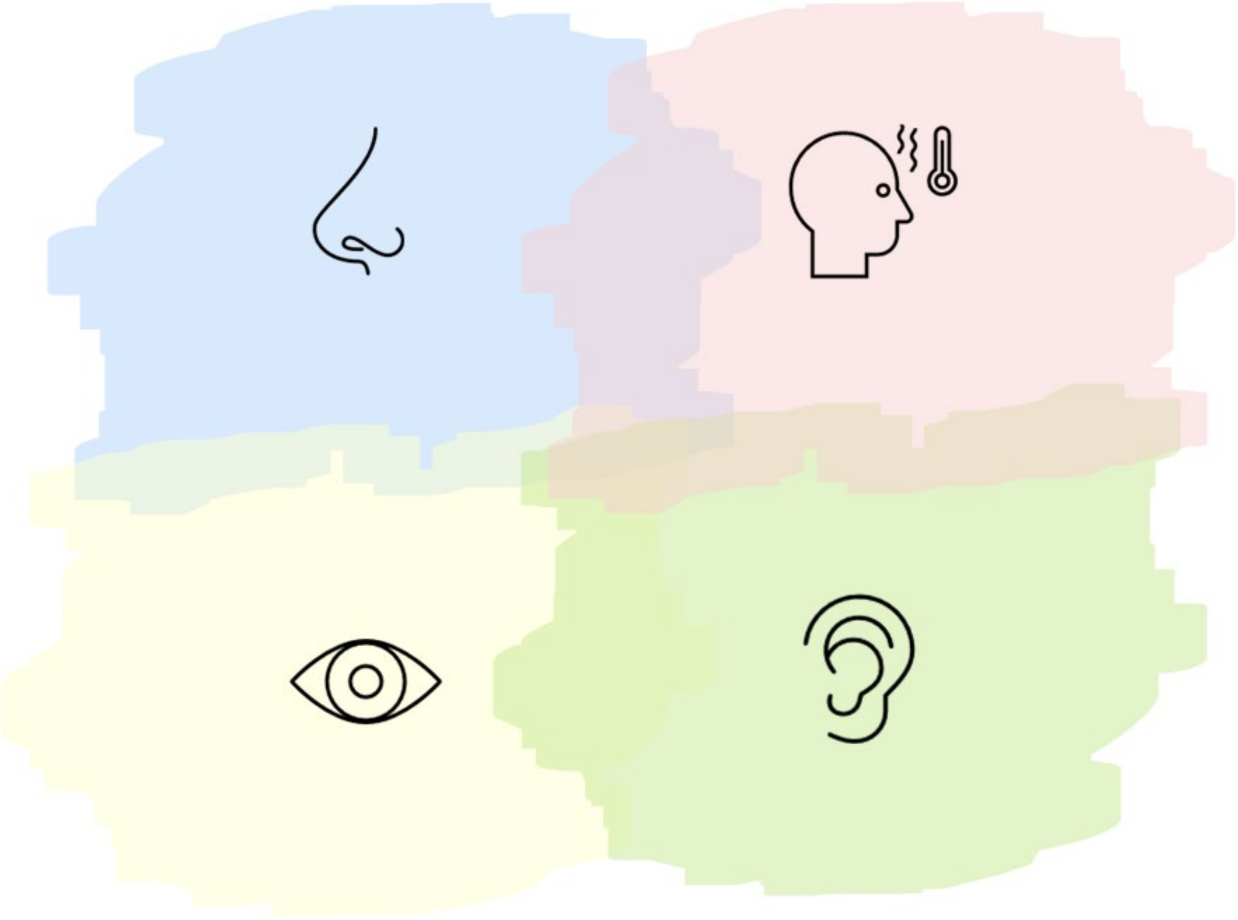
Henk Willem Brink was born on 16 December 1966 in Groningen, the Netherlands. After finishing the bachelor program Facility Management in 1998 at Hanze University of Applied Sciences in Groningen, The Netherlands, he studied Facility Management at the University of Greenwich in London, United Kingdom. In 2006 he obtained his MSc degree. From September 2018 he started a PhD project at Eindhoven University of Technology at Eindhoven, the Netherlands of which the results are presented in this thesis.

Since 2008 Henk is employed at Hanze University of Applied Sciences. Before, he worked as a Facility Manager for several years at the Dutch police force. Since 2014, Henk is a member of the research group Facility Management, which is embedded in NoorderRuimte, Research Centre for Built Environment of the Hanze University of Applied Sciences. He wrote a number of peer-reviewed scientific journal and conference papers as well as articles in Dutch professional magazines. Furthermore, he presented his research on a number of conferences, including Building the Future of Health conference (Groningen, 2016), European Facility Management International Conference (Milan, 2016) the 3rd Conference of Interdisciplinary Research on Real Estate (Groningen, 2018), the European Facility Management International Conference (Online, 2020), Healthy Buildings Europe 2021 (Online; Oslo, 2021).

In addition to his research activities, Henk was involved as a senior lecturer and researcher in many educational activities and is responsible for a part of the curriculum of the educational program Facility Management of the Hanze University of Applied Sciences (UAS). In his daily activities he closely worked together with the Facility Management Department of this UAS in various projects in which students of different educational programs are involved.

In 2021 the journal paper: '*Classrooms' indoor environmental conditions affecting the academic achievement of students and teachers in higher education: a systematic literature review*' which Henk wrote together with Marcel Loomans, Mark Mobach, and Helianthe Kort won the Top Downloaded Article Award of Wiley. This paper was one of the most downloaded papers during the first 12 months of publication in Indoor Air.

List of publications



Journal papers

Brink, H. W., Lechner, S.C.M., Loomans, M. G. L. C., Mobach, M. P., & Kort, H. S. M. (under review). Understanding how indoor environmental classroom conditions influence academic performance in higher education: A qualitative case study.

Brink, H. W., Krijnen, W.P., Loomans, M. G. L. C., Mobach, M. P., & Kort, H. S. M. (2023). Positive effects of indoor environmental conditions on students and their performance in higher education classrooms: a between-groups experiment. *Science of The Total Environment,* 869, 161813. https://doi.org/10.1016/j.scitotenv.2023.161813

Brink, H. W., Loomans, M. G. L. C., Mobach, M. P., & Kort, H. S. M. (2022). A systematic approach to quantify the influence of indoor environmental parameters on students' perceptions, responses, and short-term academic performance. *Indoor Air*, *32*(10), e13116. https://doi.org/10.1111/ina.13116

Brink, H. W., Loomans, M. G. L. C., Mobach, M. P., & Kort, H. S. M. (2021). Classrooms' indoor environmental conditions affecting the academic achievement of students and teachers in higher education: a systematic literature review. *Indoor Air*, *31*(2), 405-425. https://doi.org/10.1111/ina.12745

Conference papers

Mamulova, E., Brink, H.W., Loomans, M. G. L. C., Loonen, R. C. G. M., & Kort, H. S. M. (2022). A Multi-Domain Approach to Explanatory and Predictive Thermal Comfort Modelling in Offices. In *CLIMA 2022 The 14th REHVA HVAC World Congress,* TU Delft Open. https://doi.org/10.34641/clima.2022.181

Brink, H. W., Loomans, M. G. L. C., Mobach, M. P., & Kort, H. S. M. (2021). The influence of indoor air quality in classrooms on the short-term academic performance of students in higher education; a field study during a regular academic course. In *Healthy Buildings Europe 2021- online*, Oslo, Norway.

Brink, H. W., Loomans, M. G. L. C., Mobach, M. P., & Kort, H. S. M. (2020). The influence of indoor environmental quality on perceived quality of learning in classrooms for higher education. 11-18. Paper presented at *European Facility Management International Conference (EFMIC) 2020*, EuroFM Network, 1 October 2020, online conference. https://eurofm.org/wp-content/uploads/2020/09/Brink_etal_EFMIC2020.pdf

Fust, W., Brink, H. W., & Mobach, M. P. (2020). Tool development and application for vital workspace: a Dutch example of facility management valorisation. Paper presented at *European Facility Management International Conference (EFMIC) 2020*, EuroFM Network, 1 October 2020, online conference. https://eurofm.org/wp-content/uploads/2020/09/Fust_etal_EFMIC2020.pdf

Brink, H. W., & Mobach, M. P. (2016). Quality and satisfaction of thermal comfort in Dutch offices. In S. Balslev Nielsen, & P. A. Jensen (Eds.), *Research Papers: 15th EuroFM Research Symposium* (pp. 162-171). EuroFM: European Facility Management Network.

Presentations

Brink, H. W. The influence of indoor air quality in classrooms on students' short-term academic performance. Presentation at: Dutch Chapter ISIAQ Annual Symposium 2022, 27 September 2022.

Brink, H. W. The influence of indoor air quality in classrooms on students' short-term academic performance. Presentation at: Healthy Buildings Europe 2021 – 17th International Healthy Buildings Conference, 23 June 2021.

Brink, H. W. Influence of indoor environmental quality on perceived quality of learning in classrooms for higher education. Presentation at EuroFM "Stay Connected Sessions", 1 October 2020.

Brink, H. W. The effect of indoor air quality in Dutch higher education classrooms on students' health and performance. Presentation at: Joint meeting of the International Societies of Exposure Science (ISES) and Indoor Air Quality and Climate (ISIAQ), 22 August 2019.

Brink, H. W. The effect of indoor environmental conditions in classrooms of the Netherlands on educational outcome. Presentation at 2018 CIRRE Conference, Groningen, Netherlands, 20 September 2018.

Brink, H. W. Quality and satisfaction of thermal comfort in Dutch offices. Poster session presented at 24th European Facility Management Conference (EFMC) 2016, Milan, Italy.

Brink, H. W. Mitchell, T. An integrated talent management approach towards sustaining the value of facility management leadership. Presentation at 24th European Facility Management Conference (EFMC) 2016: enhancing people and business, 9 June 2016.

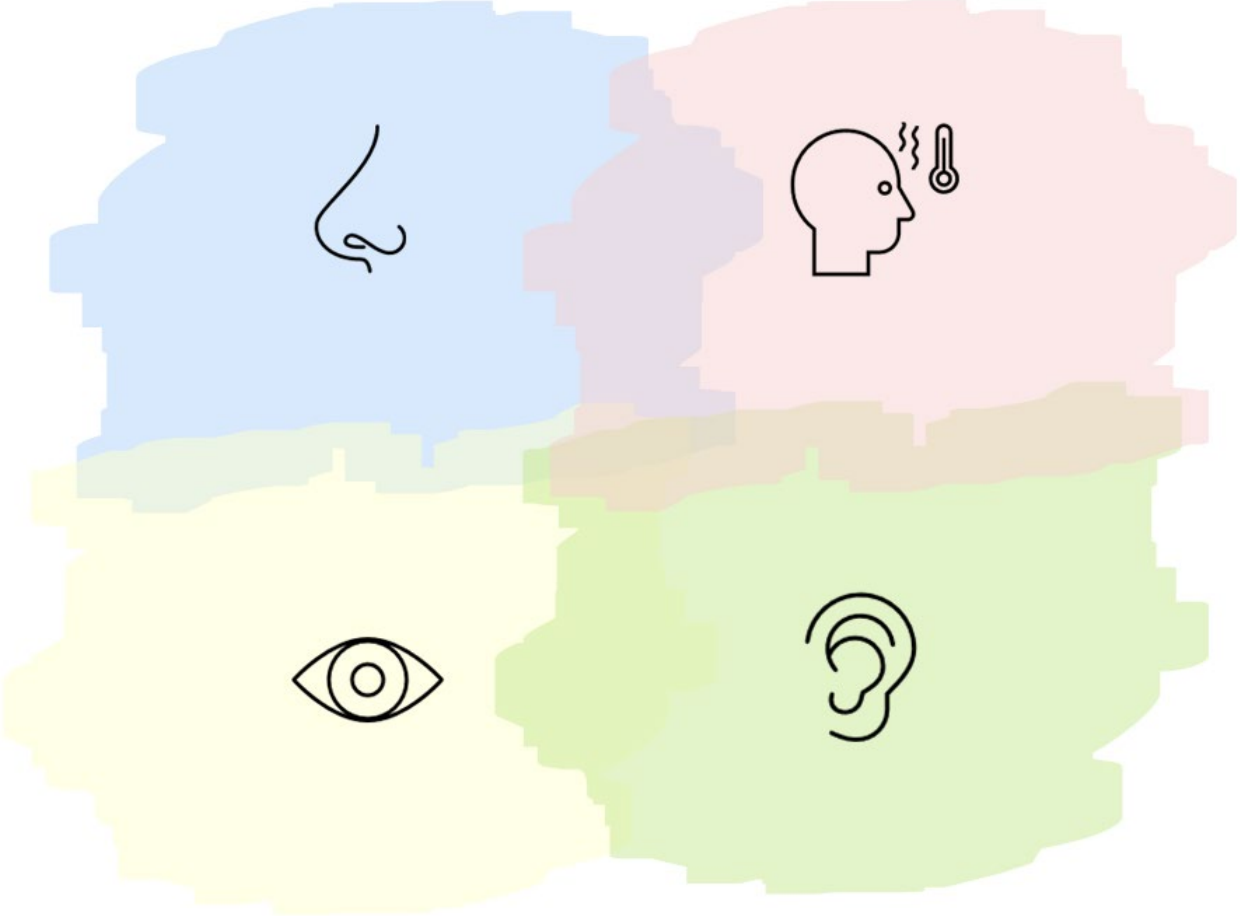
Brink, H. W. Quality and satisfaction of thermal comfort in Dutch offices. Presentation at: International Conference 'Building the Future of Health', 2 June 2016.

Articles in professional magazines

Brink, H. W., Veenstra, L. R., Mobach, M. P., Loomans, M. G. L. C., & Kort, H. S. M. (2019). De leeromgeving van de toekomst heeft aandacht voor het binnenmilieu. *TVVL*, 48(7), 18-22. https://view.publitas.com/tvvl/tvvl-magazine-07-2019/page/18-19.

Brouwers, M., Brink, H. W., & Mobach, M. P. (2017). Comfortabel binnenklimaat, gezonde werknemers. In *Inspiratie voor innovatie: 25 voorbeelden van toegepast onderzoek* (pp. 46-49). Hanze University of Applied Sciences.

Acknowledgements



Only because I received help and support of so many people it was possible to finish my PhD research project. Because Mark Mobach believed in me, made me to start this project. Although I was not sure that I could do this, Helianthe Kort her enthusiasm gave me the final push to start this project. I have to thank Helianthe for involving Marcel Loomans. Marcel played also a very important role in this project.

Helianthe, thank you for motivating me, for having faith in me, and for your personal attention which helped me so much to finish this project. Marcel, thank you for your positive feedback, your critical look at the research and for sharing your valuable knowledge about the indoor environment. This has enriched not only me as a person but also contributed significantly to our work. And finally, Mark, thank you for making this project possible. Your sharped-eye look and your never-ending help were essential to complete this project. Dear Helianthe, Marcel and Mark, just like the opening words I have used so many times in the numerous emails I have sent to you, thank you for all your support. Thank you all for keeping faith in me. The many comments and suggestions I have received from you all improved our manuscripts and learned me to develop a critical look at my research. Working together in this project made me grow as a person, as a researcher and as a lecturer.

Furthermore, I'm grateful to Ciska Bakema, Director of the Facility Management Department of the Hanze University of Applied Sciences. Only because you believed in this research project, I was able to perform this research. I am also greatly indebted to the staff of the Facility Management Department of the Hanze University of Applied Sciences for their support in the preparation, execution, and funding of this research project and the Hanze Executive Board for their financial support. Furthermore, this research was not possible without the funding of the School for Future Environments of the Hanze University of Applied Sciences. Mira en Emile, thank you for giving me this opportunity to do this PhD research and for investing in my personal development. I hope that the knowledge gained with this project may contribute to a better teaching and learning environment at the Hanze University of Applied Sciences and at all other schools for higher education.

Dear Atze Boerstra, Pascale Le Blanc, Michael Pitt, and Marcel Schweiker, thank you for being an external member of my thesis committee. I would also like to thank the two co-authors of my papers, Wim Krijnen and Stefan Lechner. Wim, thank you for helping me with all the statistical analyses, for sharing your valuable knowledge, and your patience with me. Stefan, I'm grateful that you shared your enthusiasm of qualitive research with me. It enriched my knowledge and I enjoyed so much working with you.

Dear Fienke Strijbos, thank you so much for your contribution to the reference and database management and for spelling checking part of my manuscripts. And I want to say thanks to all my (ex)colleagues from the research group Facility Management of the Hanze University of Applied Sciences: Arnoud, Berit Ann, Clements, Emma, Frans, Jan Gerard, Hans, Johan, Martijn, Michel, Miranda, Rachel, Ria, Rita, Rolinka, Sascha, Saskia, Sjoukje for all the help and support. Furthermore, I would like to thank the members of the research group Technology for Healthcare Innovations of the University of Applied Sciences Utrecht for the great discussions and valuable feedback.

The field studies I performed during this research project were not possible without the help of the School of Business Administration and Future Environments. I am

grateful to the involved students and lecturers, both for their contribution to this study and for their hospitality that allowed me being present during their lectures. Thank you Ans, Geke, Jaap, John, Marja, Rita, Rob, Rudolf, Stefan, Thierry and Willem for supporting this research project. Hein, Juanita, Jurrie and Marloes, thanks for scheduling all the lectures for my research.

I want to thank Ralph Thomassen of ETAP Lighting International for providing the lighting armatures. And I want to thank Ecophon Saint Gobain for providing acoustic ceiling panels, with which the classrooms are equipped. I remember that together with Bianca Scherpenhuyzen and Boudewijn van Grinsven we installed all the panels ourselves, good memories. And thank you Kristiaan Blokzijl of Equans for your help to install the HVAC system and for supporting this research project. Furthermore, I want to thank the technical support of Equans, Bert Vrijhof of DGMR , and Eltjo Leinenga of Nijeboer-Hage for their help.

Heel graag wil ik mijn geliefde vrouw Petra bedanken voor haar geduld en begrip. Zonder jouw liefde, hulp en steun was dit niet gelukt. Mijn kinderen Thomas, Daniel en Ruben wil ik bedanken voor hun belangstelling voor het onderzoek en voor het hebben van begrip voor al die keren dat ik toch weer naar boven moest om aan het werk te gaan. En Thomas, bedankt voor het maken van de prachtige plaatjes van de verlichtingssterkte in de klaslokalen (zie Figure 4-5). Lieve papa en mama, ik weet dat jullie me af en toe hebben moeten missen. Maar jullie zorg en liefde voor mij en mijn gezin doet mij goed en heeft me gebracht tot waar ik nu sta, dank hiervoor.

Mijn dank gaat ook uit naar Aaltje Bijlsma en Rudolf Kamphuis, mijn paranimfen. Aaltje, bedankt dat jij al die jaren mijn kamergenoot hebt willen zijn. Jouw warme en persoonlijke belangstelling en jouw geloof in mij stimuleerde mij om door te gaan. Rudolf, bedankt voor jouw vriendschap. De keren in de sneeuw, het onwijs genieten van sporten en de natuur laadde mijn batterij weer op. Jij en jouw familie gaven mij weer de energie om er vol tegen aan te gaan. Jammer dat ik mijn schouder brak tijdens onze laatste ski vakantie eind 2021. Gelukkig gaat het de goede kant op met mijn schouder en ik hoop dat we ook in de toekomst nog vele mooie en sportieve dagen mogen beleven.

Ten slotte denk ik aan John, mijn broer die al meer dan dertig jaar niet meer bij ons is maar voor altijd in mijn hart. Jij blijft voor mij een inspiratie om door te gaan, ook al is dat soms moeilijk.

Het Om symbool

Bouwstenen is een publicatiereeks
van de Faculteit Bouwkunde,
Technische Universiteit Eindhoven.
Zij presenteert resultaten van
onderzoek en andere activiteiten
op het vakgebied der Bouwkunde,
uitgevoerd in het kader van deze
Faculteit.

Bouwstenen en andere proefschriften van de
TU/e zijn online beschikbaar via:
https://research.tue.nl/

Reeds verschenen in de serie
Bouwstenen

nr 1
Elan: A Computer Model for Building Energy Design: Theory and Validation
Martin H. de Wit
H.H. Driessen
R.M.M. van der Velden

nr 2
Kwaliteit, Keuzevrijheid en Kosten: Evaluatie van Experiment Klarendal, Arnhem
J. Smeets
C. le Nobel
M. Broos
J. Frenken
A. v.d. Sanden

nr 3
Crooswijk:
Van 'Bijzonder' naar 'Gewoon'
Vincent Smit
Kees Noort

nr 4
Staal in de Woningbouw
Edwin J.F. Delsing

nr 5
Mathematical Theory of Stressed Skin Action in Profiled Sheeting with Various Edge Conditions
Andre W.A.M.J. van den Bogaard

nr 6
Hoe Berekenbaar en Betrouwbaar is de Coëfficiënt k in x-ksigma en x-ks?
K.B. Lub
A.J. Bosch

nr 7
Het Typologisch Gereedschap: Een Verkennende Studie Omtrent Typologie en Omtrent de Aanpak van Typologisch Onderzoek
J.H. Luiten

nr 8
Informatievoorziening en Beheerprocessen
A. Nauta
Jos Smeets (red.)
Helga Fassbinder
(projectleider) Adrie
Proveniers
J. v.d. Moosdijk

nr 9
Strukturering en Verwerking van Tijdgegevens voor de Uitvoering van Bouwwerken
ir. W.F. Schaefer
P.A. Erkelens

nr 10
Stedebouw en de Vorming van een Speciale Wetenschap
K. Doevendans

nr 11
Informatica en Ondersteuning van Ruimtelijke Besluitvorming
G.G. van der Meulen

nr 12
Staal in de Woningbouw, Korrosie-Bescherming van de Begane Grondvloer
Edwin J.F. Delsing

nr 13
Een Thermisch Model voor de Berekening van Staalplaatbetonvloeren onder Brandomstandigheden
A.F. Hamerlinck

nr 14
De Wijkgedachte in Nederland: Gemeenschapsstreven in een Stedebouwkundige Context
K. Doevendans
R. Stolzenburg

nr 15
Diaphragm Effect of Trapezoidally Profiled Steel Sheets: Experimental Research into the Influence of Force Application
Andre W.A.M.J. van den Bogaard

nr 16
Versterken met Spuit-Ferrocement: Het Mechanische Gedrag van met Spuit-Ferrocement Versterkte Gewapend Betonbalken
K.B. Lubir
M.C.G. van Wanroy

nr 17
De Tractaten van
Jean Nicolas Louis Durand
G. van Zeyl

nr 18
Wonen onder een Plat Dak: Drie Opstellen over Enkele Vooronderstellingen van de Stedebouw
K. Doevendans

nr 19
Supporting Decision Making Processes: A Graphical and Interactive Analysis of Multivariate Data
W. Adams

nr 20
Self-Help Building Productivity: A Method for Improving House Building by Low-Income Groups Applied to Kenya 1990-2000
P. A. Erkelens

nr 21
De Verdeling van Woningen: Een Kwestie van Onderhandelen
Vincent Smit

nr 22
Flexibiliteit en Kosten in het Ontwerpproces: Een Besluitvormingondersteunend Model
M. Prins

nr 23
Spontane Nederzettingen Begeleid: Voorwaarden en Criteria in Sri Lanka
Po Hin Thung

nr 24
Fundamentals of the Design of Bamboo Structures
Oscar Arce-Villalobos

nr 25
Concepten van de Bouwkunde
M.F.Th. Bax (red.)
H.M.G.J. Trum (red.)

nr 26
Meaning of the Site
Xiaodong Li

nr 27
Het Woonmilieu op Begrip Gebracht: Een Speurtocht naar de Betekenis van het Begrip 'Woonmilieu'
Jaap Ketelaar

nr 28
Urban Environment in Developing Countries
editors: Peter A. Erkelens
George G. van der Meulen (red.)

nr 29
Stategische Plannen voor de Stad: Onderzoek en Planning in Drie Steden
prof.dr. H. Fassbinder (red.)
H. Rikhof (red.)

nr 30
Stedebouwkunde en Stadsbestuur
Piet Beekman

nr 31
De Architectuur van Djenné:
Een Onderzoek naar de Historische Stad
P.C.M. Maas

nr 32
Conjoint Experiments and Retail Planning
Harmen Oppewal

nr 33
Strukturformen Indonesischer Bautechnik:
Entwicklung Methodischer Grundlagen für eine ‘Konstruktive Pattern Language’ in Indonesien
Heinz Frick arch. SIA

nr 34
Styles of Architectural Designing: Empirical Research on Working Styles and Personality Dispositions
Anton P.M. van Bakel

nr 35
Conjoint Choice Models for Urban Tourism Planning and Marketing
Benedict Dellaert

nr 36
Stedelijke Planvorming als Co-Produktie
Helga Fassbinder (red.)

nr 37
Design Research in the Netherlands
editors: R.M. Oxman
M.F.Th. Bax
H.H. Achten

nr 38
Communication in the Building Industry
Bauke de Vries

nr 39
Optimaal Dimensioneren van Gelaste Plaatliggers
J.B.W. Stark
F. van Pelt
L.F.M. van Gorp
B.W.E.M. van Hove

nr 40
Huisvesting en Overwinning van Armoede
P.H. Thung
P. Beekman (red.)

nr 41
Urban Habitat: The Environment of Tomorrow
George G. van der Meulen
Peter A. Erkelens

nr 42
A Typology of Joints
John C.M. Olie

nr 43
Modeling Constraints-Based Choices for Leisure Mobility Planning
Marcus P. Stemerding

nr 44
Activity-Based Travel Demand Modeling
Dick Ettema

nr 45
Wind-Induced Pressure Fluctuations on Building Facades
Chris Geurts

nr 46
Generic Representations
Henri Achten

nr 47
Johann Santini Aichel: Architectuur en Ambiguiteit
Dirk De Meyer

nr 48
Concrete Behaviour in Multiaxial Compression
Erik van Geel
nr 49
Modelling Site Selection
Frank Witlox

nr 50
Ecolemma Model
Ferdinand Beetstra

nr 51
Conjoint Approaches to Developing Activity-Based Models
Donggen Wang

nr 52
On the Effectiveness of Ventilation
Ad Roos

nr 53
Conjoint Modeling Approaches for Residential Group preferences
Eric Molin

nr 54
Modelling Architectural Design Information by Features
Jos van Leeuwen

nr 55
A Spatial Decision Support System for the Planning of Retail and Service Facilities
Theo Arentze

nr 56
Integrated Lighting System Assistant
Ellie de Groot

nr 57
Ontwerpend Leren, Leren Ontwerpen
J.T. Boekholt

nr 58
Temporal Aspects of Theme Park Choice Behavior
Astrid Kemperman

nr 59
Ontwerp van een Geïndustrialiseerde Funderingswijze
Faas Moonen

nr 60
Merlin: A Decision Support System for Outdoor Leisure Planning
Manon van Middelkoop

nr 61
The Aura of Modernity
Jos Bosman

nr 62
Urban Form and Activity-Travel Patterns
Daniëlle Snellen

nr 63
Design Research in the Netherlands 2000
Henri Achten

nr 64
Computer Aided Dimensional Control in Building Construction
Rui Wu

nr 65
Beyond Sustainable Building
editors: Peter A. Erkelens
Sander de Jonge
August A.M. van Vliet
co-editor: Ruth J.G. Verhagen

nr 66
Das Globalrecyclingfähige Haus
Hans Löfflad

nr 67
Cool Schools for Hot Suburbs
René J. Dierkx

nr 68
A Bamboo Building Design Decision Support Tool
Fitri Mardjono

nr 69
Driving Rain on Building Envelopes
Fabien van Mook

nr 70
Heating Monumental Churches
Henk Schellen

nr 71
Van Woningverhuurder naar Aanbieder van Woongenot
Patrick Dogge

nr 72
Moisture Transfer Properties of Coated Gypsum
Emile Goossens

nr 73
Plybamboo Wall-Panels for Housing
Guillermo E. González-Beltrán

nr 74
The Future Site-Proceedings
Ger Maas
Frans van Gassel

nr 75
Radon transport in Autoclaved Aerated Concrete
Michel van der Pal

nr 76
The Reliability and Validity of Interactive Virtual Reality Computer Experiments
Amy Tan

nr 77
Measuring Housing Preferences Using Virtual Reality and Belief Networks
Maciej A. Orzechowski

nr 78
Computational Representations of Words and Associations in Architectural Design
Nicole Segers

nr 79
Measuring and Predicting Adaptation in Multidimensional Activity-Travel Patterns
Chang-Hyeon Joh

nr 80
Strategic Briefing
Fayez Al Hassan

nr 81
Well Being in Hospitals
Simona Di Cicco

nr 82
Solares Bauen: Implementierungs- und Umsetzungs-Aspekte in der Hochschulausbildung in Österreich
Gerhard Schuster

nr 83
Supporting Strategic Design of Workplace Environments with Case-Based Reasoning
Shauna Mallory-Hill

nr 84
ACCEL: A Tool for Supporting Concept Generation in the Early Design Phase
Maxim Ivashkov

nr 85
Brick-Mortar Interaction in Masonry under Compression
Ad Vermeltfoort

nr 86
Zelfredzaam Wonen
Guus van Vliet

nr 87
Een Ensemble met Grootstedelijke Allure
Jos Bosman Hans
Schippers

nr 88
On the Computation of Well-Structured Graphic Representations in Architectural Design
Henri Achten

nr 89
De Evolutie van een West-Afrikaanse Vernaculaire Architectuur
Wolf Schijns

nr 90
ROMBO Tactiek
Christoph Maria Ravesloot

nr 91
External Coupling between Building Energy Simulation and Computational Fluid Dynamics
Ery Djunaedy

nr 92
Design Research in the Netherlands 2005
editors: Henri Achten
Kees Dorst
Pieter Jan Stappers
Bauke de Vries

nr 93
Ein Modell zur Baulichen Transformation
Jalil H. Saber Zaimian

nr 94
Human Lighting Demands: Healthy Lighting in an Office Environment
Myriam Aries

nr 95
A Spatial Decision Support System for the Provision and Monitoring of Urban Greenspace
Claudia Pelizaro

nr 96
Leren Creëren
Adri Proveniers

nr 97
Simlandscape
Rob de Waard

nr 98
Design Team Communication
Ad den Otter

nr 99
Humaan-Ecologisch Georiënteerde Woningbouw
Juri Czabanowski

nr 100
Hambase
Martin de Wit

nr 101
Sound Transmission through Pipe Systems and into Building Structures
Susanne Bron-van der Jagt

nr 102
Het Bouwkundig Contrapunt
Jan Francis Boelen

nr 103
A Framework for a Multi-Agent Planning Support System
Dick Saarloos

nr 104
Bracing Steel Frames with Calcium Silicate Element Walls
Bright Mweene Ng'andu

nr 105
Naar een Nieuwe Houtskeletbouw
F.N.G. De Medts

nr 106 and 107
Niet gepubliceerd

nr 108
Geborgenheid
T.E.L. van Pinxteren

nr 109
Modelling Strategic Behaviour in Anticipation of Congestion
Qi Han

nr 110
Reflecties op het Woondomein
Fred Sanders

nr 111
On Assessment of Wind Comfort by Sand Erosion
Gábor Dezsö

nr 112
Bench Heating in Monumental Churches
Dionne Limpens-Neilen

nr 113
RE. Architecture
Ana Pereira Roders

nr 114
Toward Applicable Green Architecture
Usama El Fiky

nr 115
Knowledge Representation under Inherent Uncertainty in a Multi-Agent System for Land Use Planning
Liying Ma

nr 116
Integrated Heat Air and Moisture Modeling and Simulation
Jos van Schijndel

nr 117
Concrete Behaviour in Multiaxial Compression
J.P.W. Bongers

nr 118
The Image of the Urban Landscape
Ana Moya Pellitero

nr 119
The Self-Organizing City in Vietnam
Stephanie Geertman

nr 120
A Multi-Agent Planning Support System for Assessing Externalities of Urban Form Scenarios
Rachel Katoshevski-Cavari

nr 121
Den Schulbau Neu Denken, Fühlen und Wollen
Urs Christian Maurer-Dietrich

nr 122
Peter Eisenman Theories and Practices
Bernhard Kormoss

nr 123
User Simulation of Space Utilisation
Vincent Tabak

nr 125
In Search of a Complex System Model
Oswald Devisch

nr 126
Lighting at Work: Environmental Study of Direct Effects of Lighting Level and Spectrum on Psychohysiological Variables
Grazyna Górnicka

nr 127
Flanking Sound Transmission through Lightweight Framed Double Leaf Walls
Stefan Schoenwald

nr 128
Bounded Rationality and Spatio-Temporal Pedestrian Shopping Behavior
Wei Zhu

nr 129
Travel Information: Impact on Activity Travel Pattern
Zhongwei Sun

nr 130
Co-Simulation for Performance Prediction of Innovative Integrated Mechanical Energy Systems in Buildings
Marija Trčka

nr 131
Niet gepubliceerd

nr 132
Architectural Cue Model in Evacuation Simulation for Underground Space Design
Chengyu Sun

nr 133
Uncertainty and Sensitivity Analysis in Building Performance Simulation for Decision Support and Design Optimization
Christina Hopfe

nr 134
Facilitating Distributed Collaboration in the AEC/FM Sector Using Semantic Web Technologies
Jacob Beetz

nr 135
Circumferentially Adhesive Bonded Glass Panes for Bracing Steel Frame in Façades
Edwin Huveners

nr 136
Influence of Temperature on Concrete Beams Strengthened in Flexure with CFRP
Ernst-Lucas Klamer

nr 137
Sturen op Klantwaarde
Jos Smeets

nr 139
Lateral Behavior of Steel Frames with Discretely Connected Precast Concrete Infill Panels
Paul Teewen

nr 140
Integral Design Method in the Context of Sustainable Building Design
Perica Savanović

nr 141
Household Activity-Travel Behavior: Implementation of Within-Household Interactions
Renni Anggraini

nr 142
Design Research in the Netherlands 2010
Henri Achten

nr 143
Modelling Life Trajectories and Transport Mode Choice Using Bayesian Belief Networks
Marloes Verhoeven

nr 144
Assessing Construction Project Performance in Ghana
William Gyadu-Asiedu

nr 145
Empowering Seniors through Domotic Homes
Masi Mohammadi

nr 146
An Integral Design Concept for Ecological Self-Compacting Concrete
Martin Hunger

nr 147
Governing Multi-Actor Decision Processes in Dutch Industrial Area Redevelopment
Erik Blokhuis

nr 148
A Multifunctional Design Approach for Sustainable Concrete
Götz Hüsken

nr 149
Quality Monitoring in Infrastructural Design-Build Projects
Ruben Favié

nr 150
Assessment Matrix for Conservation of Valuable Timber Structures
Michael Abels

nr 151
Co-simulation of Building Energy Simulation and Computational Fluid Dynamics for Whole-Building Heat, Air and Moisture Engineering
Mohammad Mirsadeghi

nr 152
External Coupling of Building Energy Simulation and Building Element Heat, Air and Moisture Simulation
Daniel Cóstola

nr 153
Adaptive Decision Making In Multi-Stakeholder Retail Planning
Ingrid Janssen

nr 154
Landscape Generator
Kymo Slager

nr 155
Constraint Specification in Architecture
Remco Niemeijer

nr 156
A Need-Based Approach to Dynamic Activity Generation
Linda Nijland

nr 157
Modeling Office Firm Dynamics in an Agent-Based Micro Simulation Framework
Gustavo Garcia Manzato

nr 158
Lightweight Floor System for Vibration Comfort
Sander Zegers

nr 159
Aanpasbaarheid van de Draagstructuur
Roel Gijsbers

nr 160
'Village in the City' in Guangzhou, China
Yanliu Lin

nr 161
Climate Risk Assessment in Museums
Marco Martens

nr 162
Social Activity-Travel Patterns
Pauline van den Berg

nr 163
Sound Concentration Caused by Curved Surfaces
Martijn Vercammen

nr 164
Design of Environmentally Friendly Calcium Sulfate-Based Building Materials: Towards an Improved Indoor Air Quality
Qingliang Yu

nr 165
Beyond Uniform Thermal Comfort on the Effects of Non-Uniformity and Individual Physiology
Lisje Schellen

nr 166
Sustainable Residential Districts
Gaby Abdalla

nr 167
Towards a Performance Assessment Methodology using Computational Simulation for Air Distribution System Designs in Operating Rooms
Mônica do Amaral Melhado

nr 168
Strategic Decision Modeling in Brownfield Redevelopment
Brano Glumac

nr 169
Pamela: A Parking Analysis Model for Predicting Effects in Local Areas
Peter van der Waerden

nr 170
A Vision Driven Wayfinding Simulation-System Based on the Architectural Features Perceived in the Office Environment
Qunli Chen

nr 171
Measuring Mental Representations Underlying Activity-Travel Choices
Oliver Horeni

nr 172
Modelling the Effects of Social Networks on Activity and Travel Behaviour
Nicole Ronald

nr 173
Uncertainty Propagation and Sensitivity Analysis Techniques in Building Performance Simulation to Support Conceptual Building and System Design
Christian Struck

nr 174
Numerical Modeling of Micro-Scale Wind-Induced Pollutant Dispersion in the Built Environment
Pierre Gousseau

nr 175
Modeling Recreation Choices over the Family Lifecycle
Anna Beatriz Grigolon

nr 176
Experimental and Numerical Analysis of Mixing Ventilation at Laminar, Transitional and Turbulent Slot Reynolds Numbers
Twan van Hooff

nr 177
Collaborative Design Support: Workshops to Stimulate Interaction and Knowledge Exchange Between Practitioners
Emile M.C.J. Quanjel

nr 178
Future-Proof Platforms for Aging-in-Place
Michiel Brink

nr 179
Motivate:
A Context-Aware Mobile Application for Physical Activity Promotion
Yuzhong Lin

nr 180
Experience the City:
Analysis of Space-Time Behaviour and Spatial Learning
Anastasia Moiseeva

nr 181
Unbonded Post-Tensioned Shear Walls of Calcium Silicate Element Masonry
Lex van der Meer

nr 182
Construction and Demolition Waste Recycling into Innovative Building Materials for Sustainable Construction in Tanzania
Mwita M. Sabai

nr 183
Durability of Concrete
with Emphasis on Chloride Migration
Przemysław Spiesz

nr 184
Computational Modeling of Urban Wind Flow and Natural Ventilation Potential of Buildings
Rubina Ramponi

nr 185
A Distributed Dynamic Simulation Mechanism for Buildings Automation and Control Systems
Azzedine Yahiaoui

nr 186
Modeling Cognitive Learning of Urban Networks in Daily Activity-Travel Behavior
Şehnaz Cenani Durmazoğlu

nr 187
Functionality and Adaptability of Design Solutions for Public Apartment Buildings in Ghana
Stephen Agyefi-Mensah

nr 188
A Construction Waste Generation Model for Developing Countries
Lilliana Abarca-Guerrero
nr 189
Synchronizing Networks:
The Modeling of Supernetworks for Activity-Travel Behavior
Feixiong Liao

nr 190
Time and Money Allocation Decisions in Out-of-Home Leisure Activity Choices Gamze Zeynep Dane

nr 191
How to Measure Added Value of CRE and Building Design
Rianne Appel-Meulenbroek

nr 192
Secondary Materials in Cement-Based Products:
Treatment, Modeling and Environmental Interaction
Miruna Florea

nr 193
Concepts for the Robustness Improvement of Self-Compacting Concrete:
Effects of Admixtures and Mixture Components on the Rheology and Early Hydration at Varying Temperatures
Wolfram Schmidt

nr 194
Modelling and Simulation of Virtual Natural Lighting Solutions in Buildings
Rizki A. Mangkuto

nr 195
Nano-Silica Production at Low Temperatures from the Dissolution of Olivine - Synthesis, Tailoring and Modelling
Alberto Lazaro Garcia

nr 196
Building Energy Simulation Based Assessment of Industrial Halls for Design Support
Bruno Lee

nr 197
Computational Performance Prediction of the Potential of Hybrid Adaptable Thermal Storage Concepts for Lightweight Low-Energy Houses
Pieter-Jan Hoes

nr 198
Application of Nano-Silica in Concrete
George Quercia Bianchi

nr 199
Dynamics of Social Networks and Activity Travel Behaviour
Fariya Sharmeen

nr 200
Building Structural Design Generation and Optimisation including Spatial Modification
Juan Manuel Davila Delgado

nr 201
Hydration and Thermal Decomposition of Cement/Calcium-Sulphate Based Materials
Ariën de Korte

nr 202
Republiek van Beelden:
De Politieke Werkingen van het Ontwerp in Regionale Planvorming
Bart de Zwart

nr 203
Effects of Energy Price Increases on Individual Activity-Travel Repertoires and Energy Consumption
Dujuan Yang

nr 204
Geometry and Ventilation:
Evaluation of the Leeward Sawtooth Roof Potential in the Natural Ventilation of Buildings
Jorge Isaac Perén Montero

nr 205
Computational Modelling of Evaporative Cooling as a Climate Change Adaptation Measure at the Spatial Scale of Buildings and Streets
Hamid Montazeri

nr 206
Local Buckling of Aluminium Beams in Fire Conditions
Ronald van der Meulen

nr 207
Historic Urban Landscapes:
Framing the Integration of Urban and Heritage Planning in Multilevel Governance
Loes Veldpaus

nr 208
Sustainable Transformation of the Cities: Urban Design Pragmatics to Achieve a Sustainable City
Ernesto Antonio Zumelzu Scheel

nr 209
Development of Sustainable Protective Ultra-High Performance Fibre Reinforced Concrete (UHPFRC): Design, Assessment and Modeling
Rui Yu

nr 210
Uncertainty in Modeling Activity-Travel Demand in Complex Uban Systems
Soora Rasouli

nr 211
Simulation-based Performance Assessment of Climate Adaptive Greenhouse Shells
Chul-sung Lee

nr 212
Green Cities:
Modelling the Spatial Transformation of the Urban Environment using Renewable Energy Technologies
Saleh Mohammadi

nr 213
A Bounded Rationality Model of Short and Long-Term Dynamics of Activity-Travel Behavior
Ifigeneia Psarra

nr 214
Effects of Pricing Strategies on Dynamic Repertoires of Activity-Travel Behaviour
Elaheh Khademi

nr 215
Handstorm Principles for Creative and Collaborative Working
Frans van Gassel

nr 216
Light Conditions in Nursing Homes: Visual Comfort and Visual Functioning of Residents
Marianne M. Sinoo

nr 217
Woonsporen:
De Sociale en Ruimtelijke Biografie van een Stedelijk Bouwblok in de Amsterdamse Transvaalbuurt
Hüseyin Hüsnü Yegenoglu

nr 218
Studies on User Control in Ambient Intelligent Systems
Berent Willem Meerbeek

nr 219
Daily Livings in a Smart Home:
Users' Living Preference Modeling of Smart Homes
Erfaneh Allameh

nr 220
Smart Home Design:
Spatial Preference Modeling of Smart Homes
Mohammadali Heidari Jozam

nr 221
Wonen:
Discoursen, Praktijken, Perspectieven
Jos Smeets

nr 222
Personal Control over Indoor Climate in Offices:
Impact on Comfort, Health and Productivity
Atze Christiaan Boerstra

nr 223
Personalized Route Finding in Multimodal Transportation Networks
Jianwe Zhang

nr 224
The Design of an Adaptive Healing Room for Stroke Patients
Elke Daemen

nr 225
Experimental and Numerical Analysis of Climate Change Induced Risks to Historic Buildings and Collections
Zara Huijbregts

nr 226
Wind Flow Modeling in Urban Areas Through Experimental and Numerical Techniques
Alessio Ricci

nr 227
Clever Climate Control for Culture:
Energy Efficient Indoor Climate Control Strategies for Museums Respecting Collection Preservation and Thermal Comfort of Visitors
Rick Kramer

nr 228
Fatigue Life Estimation of Metal Structures Based on Damage Modeling
Sarmediran Silitonga

nr 229
A multi-agents and occupancy based strategy for energy management and process control on the room-level
Timilehin Moses Labeodan

nr 230
Environmental assessment of Building Integrated Photovoltaics: Numerical and Experimental Carrying Capacity Based Approach
Michiel Ritzen

nr 231
Performance of Admixture and Secondary Minerals in Alkali Activated Concrete: Sustaining a Concrete Future
Arno Keulen

nr 232
World Heritage Cities and Sustainable Urban Development: Bridging Global and Local Levels in Monitoring the Sustainable Urban Development of World Heritage Cities
Paloma C. Guzman Molina

nr 233
Stage Acoustics and Sound Exposure in Performance and Rehearsal Spaces for Orchestras: Methods for Physical Measurements
Remy Wenmaekers

nr 234
Municipal Solid Waste Incineration (MSWI) Bottom Ash: From Waste to Value Characterization, Treatments and Application
Pei Tang

nr 235
Large Eddy Simulations Applied to Wind Loading and Pollutant Dispersion
Mattia Ricci

nr 236
Alkali Activated Slag-Fly Ash Binders: Design, Modeling and Application
Xu Gao

nr 237
Sodium Carbonate Activated Slag: Reaction Analysis, Microstructural Modification & Engineering Application
Bo Yuan

nr 238
Shopping Behavior in Malls
Widiyani

nr 239
Smart Grid-Building Energy Interactions: Demand Side Power Flexibility in Office Buildings
Kennedy Otieno Aduda

nr 240
Modeling Taxis Dynamic Behavior in Uncertain Urban Environments
Zheng Zhong

nr 241
Gap-Theoretical Analyses of Residential Satisfaction and Intention to Move
Wen Jiang

nr 242
Travel Satisfaction and Subjective Well-Being: A Behavioral Modeling Perspective
Yanan Gao

nr 243
Building Energy Modelling to Support the Commissioning of Holistic Data Centre Operation
Vojtech Zavrel

nr 244
Regret-Based Travel Behavior Modeling: An Extended Framework
Sunghoon Jang

nr 245
Towards Robust Low-Energy Houses: A Computational Approach for Performance Robustness Assessment using Scenario Analysis
Rajesh Reddy Kotireddy

nr 246
Development of sustainable and functionalized inorganic binder-biofiber composites
Guillaume Doudart de la Grée

nr 247
A Multiscale Analysis of the Urban Heat Island Effect: From City Averaged Temperatures to the Energy Demand of Individual Buildings
Yasin Toparlar

nr 248
Design Method for Adaptive Daylight Systems for buildings covered by large (span) roofs
Florian Heinzelmann

nr 249
Hardening, high-temperature resistance and acid resistance of one-part geopolymers
Patrick Sturm

nr 250
Effects of the built environment on dynamic repertoires of activity-travel behaviour
Aida Pontes de Aquino

nr 251
Modeling for auralization of urban environments: Incorporation of directivity in sound propagation and analysis of a frame- work for auralizing a car pass-by
Fotis Georgiou

nr 252
Wind Loads on Heliostats and Photovoltaic Trackers
Andreas Pfahl

nr 253
Approaches for computational performance optimization of innovative adaptive façade concepts
Roel Loonen

nr 254
Multi-scale FEM-DEM Model for Granular Materials: Micro-scale boundary conditions, Statics, and Dynamics
Jiadun Liu

nr 255
Bending Moment - Shear Force Interaction of Rolled I-Shaped Steel Sections
Rianne Willie Adriana Dekker

nr 256
Paralympic tandem cycling and hand- cycling: Computational and wind tunnel analysis of aerodynamic performance
Paul Fionn Mannion

nr 257
Experimental characterization and numerical modelling of 3D printed concrete: Controlling structural behaviour in the fresh and hardened state
Robert Johannes Maria Wolfs

nr 258
Requirement checking in the building indus- try: Enabling modularized and extensible requirement checking systems based on semantic web technologies
Chi Zhang

nr 259
A Sustainable Industrial Site Redevelopment Planning Support System
Tong Wang

nr 260
Efficient storage and retrieval of detailed building models: Multi-disciplinary and long-term use of geometric and semantic construction information
Thomas Ferdinand Krijnen

nr 261
The users' value of business center concepts for knowledge sharing and networking behavior within and between organizations
Minou Weijs-Perrée

nr 262
Characterization and improvement of aerodynamic performance of vertical axis wind turbines using computational fluid dynamics (CFD)
Abdolrahim Rezaeiha

nr 263
In-situ characterization of the acoustic impedance of vegetated roofs
Chang Liu

nr 264
Occupancy-based lighting control: Developing an energy saving strategy that ensures office workers' comfort
Christel de Bakker

nr 265
Stakeholders-Oriented Spatial Decision Support System
Cahyono Susetyo

nr 266
Climate-induced damage in oak museum objects
Rianne Aleida Luimes

nr 267
Towards individual thermal comfort: Model predictive personalized control of heating systems
Katarina Katic

nr 268
Modelling and Measuring Quality of Urban Life: Housing, Neighborhood, Transport and Job
Lida Aminian

nr 269
Optimization of an aquifer thermal energy storage system through integrated modelling of aquifer, HVAC systems and building
Basar Bozkaya

nr 270
Numerical modeling for urban sound propagation: developments in wave-based and energy-based methods
Raúl Pagán Muñoz

nr 271
Lighting in multi-user office environments: improving employee wellbeing through personal control
Sanae van der Vleuten-Chraibi

nr 272
A strategy for fit-for-purpose occupant behavior modelling in building energy and comfort performance simulation
Isabella I. Gaetani dell'Aquila d'Aragona

nr 273
Een architectuurhistorische waardestelling van naoorlogse woonwijken in Nederland: Het voorbeeld van de Westelijke Tuinsteden in Amsterdam
Eleonore Henriette Marie Mens

nr 274
Job-Housing Co-Dependent Mobility Decisions in Life Trajectories
Jia Guo

nr 275
A user-oriented focus to create healthcare facilities: decision making on strategic values
Emilia Rosalia Catharina Maria Huisman

nr 276
Dynamics of plane impinging jets at moderate Reynolds numbers – with applications to air curtains
Adelya Khayrullina

nr 277
Valorization of Municipal Solid Waste Incineration Bottom Ash - Chemical Nature, Leachability and Treatments of Hazardous Elements
Qadeer Alam

nr 278
Treatments and valorization of MSWI bottom ash - application in cement-based materials
Veronica Caprai

nr 279
Personal lighting conditions of office workers - input for intelligent systems to optimize subjective alertness
Juliëtte van Duijnhoven

nr 280
Social influence effects in tourism travel: air trip itinerary and destination choices Xiaofeng Pan

nr 281
Advancing Post-War Housing: Integrating Heritage Impact, Environmental Impact, Hygrothermal Risk and Costs in Renovation Design Decisions
Lisanne Claartje Havinga

nr 282
Impact resistant ultra-high performance fibre reinforced concrete: materials, components and properties
Peipeng Li

nr 283
Demand-driven Science Parks: The Perceived Benefits and Trade-offs of Tenant Firms with regard to Science Park Attributes Wei Keat Benny Ng

nr 284
Raise the lantern; how light can help to maintain a healthy and safe hospital environment focusing on nurses
Maria Petronella Johanna Aarts

nr 285
Modelling Learning and Dynamic Route and Parking Choice Behaviour under Uncertainty
Elaine Cristina Schneider de Carvalho

nr 286
Identifying indoor local microclimates for safekeeping of cultural heritage
Karin Kompatscher

nr 287
Probabilistic modeling of fatigue resistance for welded and riveted bridge details. Resistance models and estimation of uncertainty.
Davide Leonetti

nr 288
Performance of Layered UHPFRC under Static and Dynamic Loads: Effects of steel fibers, coarse aggregates and layered structures
Yangyueye Cao

nr 289
Photocatalytic abatement of the nitrogen oxide pollution: synthesis, application and long-term evaluation of titania-silica composites
Yuri Hendrix

nr 290
Assessing knowledge adoption in post- disaster reconstruction: Understanding the impact of hazard-resistant construction knowledge on reconstruction processes of self-recovering communities in Nepal and the Philippines
Eefje Hendriks

nr 291
Locating electric vehicle charging stations: A multi-agent based dynamic simulation
Seheon Kim

nr 292
De invloed van Lean Management op de beheersing van het bouwproces
Wim van den Bouwhuijsen

nr 293
Neighborhood Environment and Physical Activity of Older Adults
Zhengying Liu

nr 294
Practical and continuous luminance distribution measurements for lighting quality
Thijs Willem Kruisselbrink

nr 295
Auditory Distraction in Open-Plan Study Environments in Higher Education
Pieternella Elizabeth Braat-Eggen

nr 296
Exploring the effect of the sound environment on nurses' task performance: an applied approach focusing on prospective memory
Jikke Reinten

nr 297
Design and performance of water resist- ant cementitious materials– Mechanisms, evaluation and applications
Zhengyao Qu

nr 298
Design Optimization of Seasonal Thermal Energy Storage Integrated District Heating and Cooling System: A Modeling and Simulation Approach
Luyi Xu

nr 299
Land use and transport: Integrated approaches for planning and management
Zhongqi Wang

nr 300
Multi-disciplinary optimization of building spatial designs: co-evolutionary design process simulations, evolutionary algorithms, hybrid approaches
Sjonnie Boonstra

nr 301
Modeling the spatial and temporal relation between urban land use, temperature, and energy demand
Hung-Chu Chen

nr 302
Seismic retrofitting of masonry walls with flexible deep mounted CFRP strips
Ömer Serhat Türkmen

nr 303
Coupled Aerostructural Shape and Topology Optimization of Horizontal-Axis Wind Turbine Rotor Blades
Zhijun Wang

nr 304
Valorization of Recycled Waste Glass and Converter Steel Slag as Ingredients for Building Materials: Hydration and Carbonation Studies
Gang Liu

nr 305
Low-Carbon City Development based on Land Use Planning
Gengzhe Wang

nr 306
Sustainable energy transition scenario analysis for buildings and neighborhoods - Data driven optimization
Shalika Saubhagya Wickramarachchi Walker

nr 307
In-between living and manufactured: an exploratory study on biobuilding components for building design
Berrak Kirbas Akyurek

nr 308
Development of alternative cementitious binders and functionalized materials: design, performance and durability
Anna Monika Kaja

nr 309
Development a morphological approach for interactive kinetic façade design: Improving multiple occupants’ visual comfort
Seyed Morteza Hosseini

nr 310
PV in urban context: modeling and simulation strategies for analyzing the performance of shaded PV systems
Ádám Bognár

nr 311
Life Trajectory, Household Car Ownership Dynamics and Home Renewable Energy Equipment Adoption
Gaofeng Gu

nr 312
Impact of Street-Scale Built Environment on Walking/Cycling around Metro Stations
Yanan Liu

nr 313
Advances in Urban Traffic Network Equilibrium Models and Algorithms
Dong Wang

nr 314
Development of an uncertainty analysis framework for model-based consequential life cycle assessment: application to activity-based modelling and life cycle assessment of multimodal mobility
Paul Martin Baustert

nr 315
Variable stiffness and damping structural joints for semi-active vibration control Qinyu Wang

nr 316
Understanding Carsharing-Facilitating Neighborhood Preferences
Juan Wang

nr 317
Dynamic alignment of Corporate Real Estate to business strategies: An empirical analysis using historical data and in-depth modelling of decision making
Howard Cooke

nr 318
Local People Matter: Towards participatory governance of cultural heritage in China
Ji Li

nr 319
Walkability and Walkable Healthy Neighborhoods
Bojing Liao

nr 320
Light directionality in design of healthy offices: exploration of two methods
Parisa Khademagha

nr 321
Room acoustic modeling with the time- domain discontinuous Galerkin method
Huiqing Wang

nr 322
Sustainable insulating lightweight materials for enhancing indoor building performance: miscanthus, aerogel and nano-silica
Yuxuan Chen

nr 323
Computational analysis of the impact of façade geometrical details on wind flow and pollutant dispersion
Xing Zheng

nr 324
Analysis of urban wind energy potential around high-rise buildings in close proximity using computational fluid dynamics
Yu-Hsuan Jang

nr 325
A new approach to automated energy performance and fault detection and diagnosis of HVAC systems: Development of the 4S3F method
Arie Taal

nr 326
Innovative Admixtures for Modifying Viscosity and Volume Change of Cement Composites
Hossein Karimi

nr 327
Towards houses with low grid dependency: A simulation-based design optimization approach
Zahra Mohammadi

nr 328
Activation of demand flexibility for heating systems in buildings: Real-life demonstration of optimal control for power-to-heat and thermal energy storage
Christian Finck

nr 329
A computational framework for analysis and optimisation of automated solar shading systems
Samuel B. de Vries

nr 330
Challenges and potential solutions for cultural heritage adaptive reuse: a comparative study employing the Historic Urban Landscape approach
Nadia Pintossi

nr 331
Shared control in office lighting systems
Tatiana Aleksandrovna Lashina

nr 332
Comfort in Urban Public Spaces
You Peng

nr 333
Numerical modelling of metal soap formation in historical oil paintings Gerardus Johannes Anna Maria Eumelen

nr 334
A transdisciplinary decision-making approach to food-water-energy nexus: A guide towards sustainable development
Maryam Ghodsvali

nr 335
Numerical modelling of transient low- frequency sound propagation and vibration in buildings
Indra Sihar

nr 336
Characterization of impact sound from lightweight joist floors
Yi Qin

nr 337
Cities for Children: Supporting Children and Caregivers in Participatory Urban Planning
Özlemnur Ataol

nr 338
Engaging the unengaged: Exploring citizen participation in nature-based solutions in China
Li Dai

nr 339
Municipal Solid Waste Incineration Residues: analysis, treatments, and applications
Ekaterina Loginova

nr 340
Enhancing the Uptake of Nature-Based Solutions in Urban Settings: An Information Systems Approach
Shahryar Ershad Sarabi

nr 341
Work Schedule Arrangements in Two-Adult Households with Children
Bilin Han

nr 342

Increasing awareness of urban cultural heritage using digital technologies: empirical design and analysis of a new multi-media web platform

Benshuo Wang

nr 343

Mechanical and physical properties of fibre-cement composites using alternative natural fibres

Katerina Kochova

nr 344

Numerical and experimental investigation of urban microclimate in a real compact heterogeneous urban area

Nestoras Antoniou

The indoor environmental quality in schools for higher education is far from optimal. Improvement of the indoor environment should be one of the top priorities of school management. It is their responsibility to create optimal teaching and learning conditions for lecturers and students.

To achieve evidence-based improvements of the indoor environmental quality (IEQ) for the advancement of teaching and learning quality of higher education learning environments, this research aimed at developing input for creating optimal indoor environmental conditions to facilitate in-class activities. This consisted of four stages.

First, a systematic literature review was conducted to reveal the effect of IEQ in classrooms in higher education on the quality of teaching, the quality of learning, and students' academic performance. Next, a systematic approach was developed to examine the effect of all four IEQ parameters: indoor air quality and thermal conditions, lighting conditions, and acoustic conditions in classrooms. Furthermore, a field experiment was conducted to explore the effect of multiple indoor environmental parameters on students and their academic performance. Finally, a qualitative case study described lecturers and students' perceptions related to the IEQ and how they interact with this environment to maintain an acceptable indoor environment quality.

Application of the composed framework in higher education classrooms revealed that there is no 'on-size fits all' indoor environmental quality for students. Students perform at their best in different IEQ conditions, and these conditions are task dependent, suggesting that classrooms which provide multiple IEQ classroom conditions facilitate different learning tasks optimally. When school management succeeds in creating optimal indoor environmental quality conditions in classrooms, this will positively contribute to lecturers and students' academic performance and subsequently to a more positive school climate.

DEPARTMENT OF THE BUILT ENVIRONMENT

TU/e EINDHOVEN
UNIVERSITY OF
TECHNOLOGY