Bildung braucht …
Lüftungsstandards in Schulen

HEINZ TROX
STIFTUNG

AACHENER TAG DER LUFTQUALITÄT
ZUKUNFTSRAUM SCHULE STATT BILDUNGS(BAU)KRISE

Aachen, 14. September 2023

HEINZ TROX
STIFTUNG

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Introduction

The obvious facts…..

- A good education system constitutes one of the fundaments of a modern society because poor learning can have lifelong consequences for a student and for society
- Early childhood experiences impact behaviour later on in a life
- Buildings must promote health, reduce energy and be sustainable, health being a sustainability component
- The primary purpose of school building is to provide an optimal conditions for learning and then (in parallel) energy use should be minimized
- Indoor environmental quality in many schools worldwide is inadequate
- Poor indoor environmental quality in schools is linked not only to health problems but also to decreased concentration and poor test results
- All children and teachers, independent of the socio-economic status, have the right to breathe healthy air (also in schools)

OECD: countries with better test school results have higher growth rate

- The OECD new survey of Adults Skills finds that foundation skills in mathematics have a major impact on individivdual's life chances.
- The survey shows that poor mathematics skills severely limit people's access to better-paying and more rewarding jobs; at the aggregate level, inequality in the distribution of mathematics skills across populations is closely related to how wealth is shared within nations.
- Beyond that, the survey shows that people with strong skills in mathematics are also more likely to volunteer, see themselves as actors rather than objects of political processes, and are even more likely to trust others.

Objective – answers to thre questions

Q1: What is the optimal learning environment?

Q2: How to examine that learning environment is optimal?

Q3: How to advance research and implement present findings?

Q1: What is the optimal learning environment?

Research-based recommendations for achieving high indoor environmental quality in classrooms to promote learning

Thermal environment in classrooms

Raised classroom temperatures have progressively negative effects on children

- Meta-analysis of all available data shows that children's performance of tasks typical of schoolwork is reduced by 20% as the classroom air temperature is increased by 10K
- Raised temperatures have twice the negative effect on schoolwork as on office work
- The optimum temperature for schoolwork is 2-3K lower than it is for office work, and children in school subjectively prefer lower temperatures than are preferred in offices
- In Denmark, the optimum classroom temperature appears to be below 23^{o}C

Building and Environment 157 (2019) 197–204

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

ELSEVIER

The relationship between classroom temperature and children's performance in school

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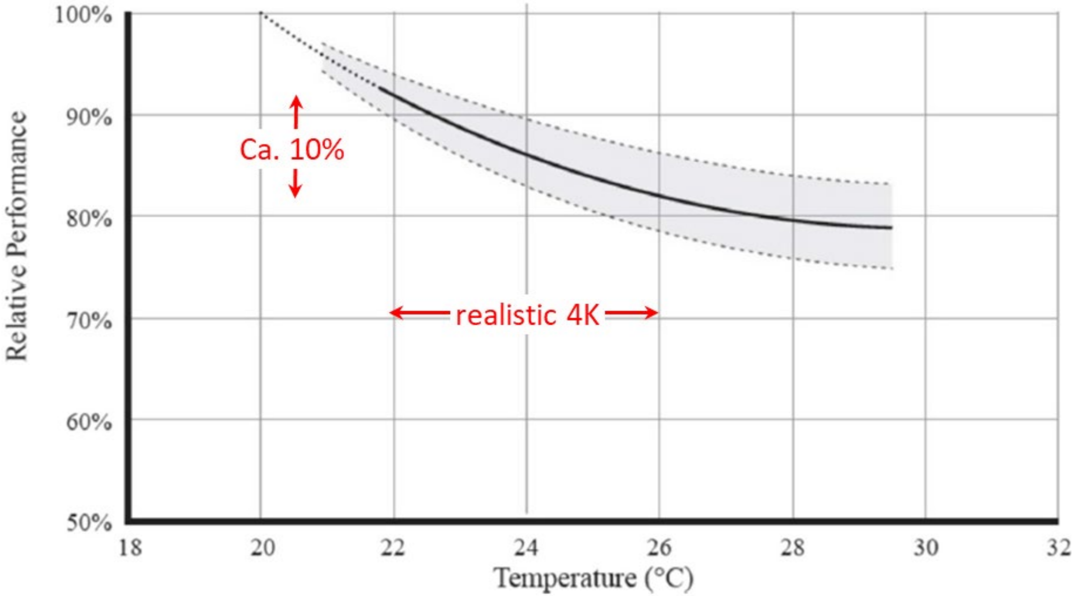
A R T I C L E I N F O

Keywords:
Children
Learning
Cognitive performance
Elementary schools
Temperature
Thermal environment

A B S T R A C T

The present paper reports a meta-analysis of published evidence on the effects ‹
rooms on children's performance in school. The data from 18 studies were us
between thermal conditions in classrooms and children's performance in school.
cognitive abilities and skills, school tasks including mathematical and language-b
tests used to assess progress in learning including end-of-year grades and the ‹
sidered as indicators of children's performance Due to the lack of complete mea
were characterized by measured classroom temperatures. To create the relatior
performance of psychological tests and school tasks was regressed against the ave
change was recorded; all published data were used regardless of whether the
changed significantly with temperature. For other learning outcomes, no relatio
data were insufficient. The relationship derived in the analysis shows that the perf
and school tasks can be expected to increase on average by 20% if classroom t
30 °C to 20 °C and that the temperature for optimal performance is lower than :
only for temperate climates. It requires verification for other climates and extensi‹
20 °C and higher than 30 °C.



NBER WORKING PAPER SERIES

HEAT AND LEARNING

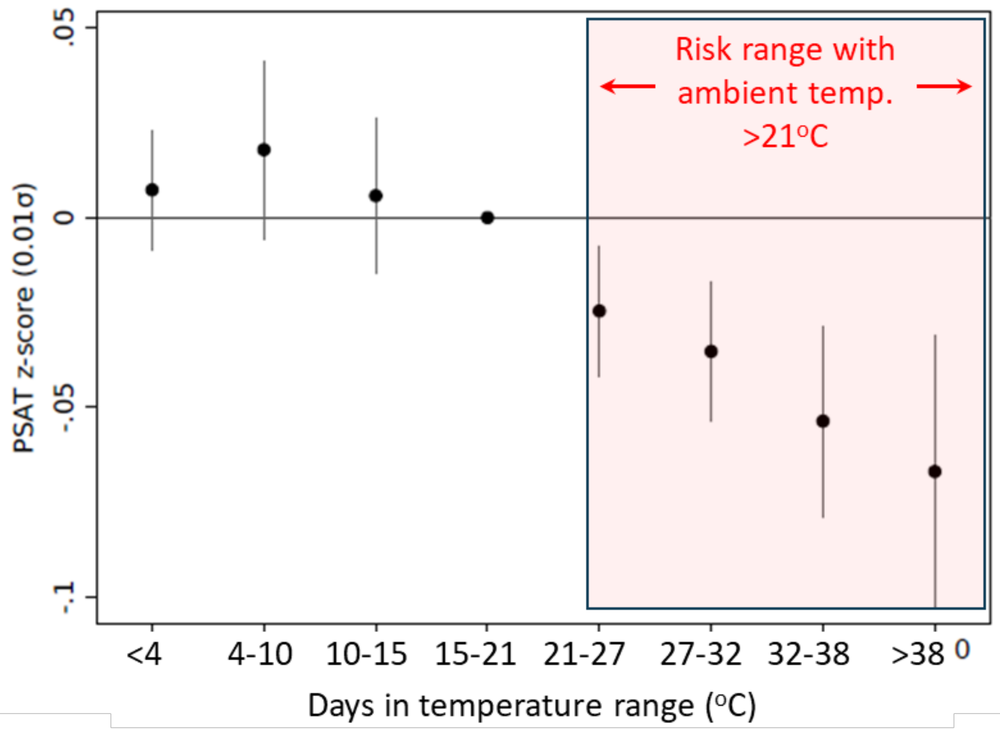
Joshua Goodman
Michael Hurwitz
Jisung Park
Jonathan Smith

Working Paper 24639
http://www.nber.org/papers/w24639

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
May 2018

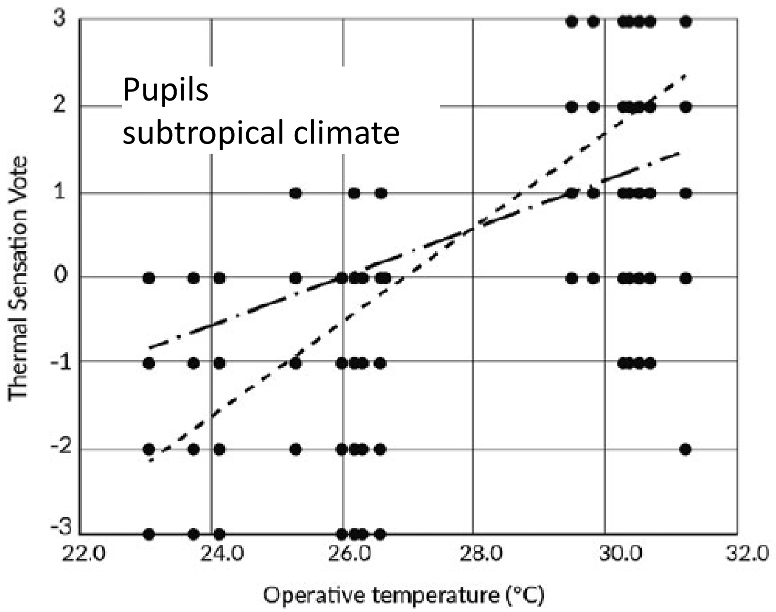
ABSTRACT

We provide the first evidence that cumulative heat exposure inhibits cognitive skill development and that school air conditioning can mitigate this effect. Student fixed effects models using 10 million PSAT-takers show that hotter school days in the year prior to the test reduce learning, with extreme heat being particularly damaging and larger effects for low income and minority students. Weekend and summer heat has little impact and the effect is not explained by pollution or local economic shocks, suggesting heat directly reduces the productivity of learning inputs. New data providing the first measures of school-level air conditioning penetration across the US suggest such infrastructure almost entirely offsets these effects. Without air conditioning, each 1° F increase in school year temperature reduces the amount learned that year by one percent. Our estimates imply that the benefits of school air conditioning likely outweigh the costs in most of the US, particularly given future predicted climate change.

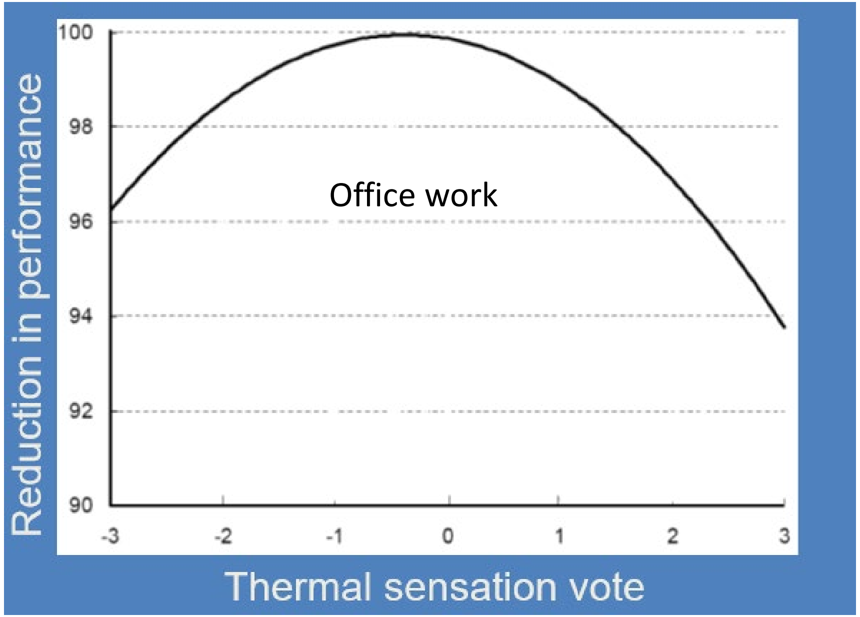


SD of the score on math and langauge exit exam (US) as a function of overheating (ambient temperature)

Temperature or thermal discomfort?



Porras-Salazar et al. (2018)



Lan et al. (2021)

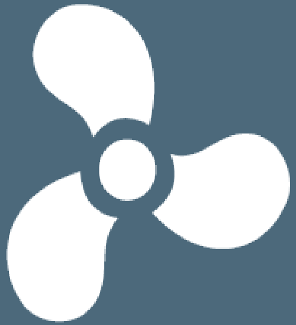
Thermal environment –the need for new research

What is NOT yet known:

- **the optimum classroom temperature range for each climatic zone,**
- **whether thermal effects on teachers affect teaching quality (since they are known to affect adults performing office work),**
- **the mechanism for thermal effects on cognition and learning,**
- **and whether IEQ factors such as noise or air quality interact with thermal effects**

Classroom air quality

Poor classroom air quality has progressively negative effects on children



- Children perform schoolwork 12% faster and 2% more accurately when the outdoor air supply rate is such that the resulting CO_2 concentration in a typical classroom is 900 ppm instead of 2100 ppm
- School test and examination results are 5% better when the outdoor air supply rate is such that the resulting CO_2 concentration in a typical classroom is 900 ppm instead of 2400 ppm
- National test results are 5% better with a 7.5 L/s/p than with a 2 L/s/p outdoor air supply rate in classrooms
- Absenteeism is 1.5% higher with a 2 L/s/p outdoor air supply rate than with 7.5 l/s/p
- This suggests an increased outdoor air supply rate can reduce cross-infection between children or mitigate pre-existing conditions

Building and Environment 173 (2020) 106749

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

The relationships between classroom air quality and children's performance in school

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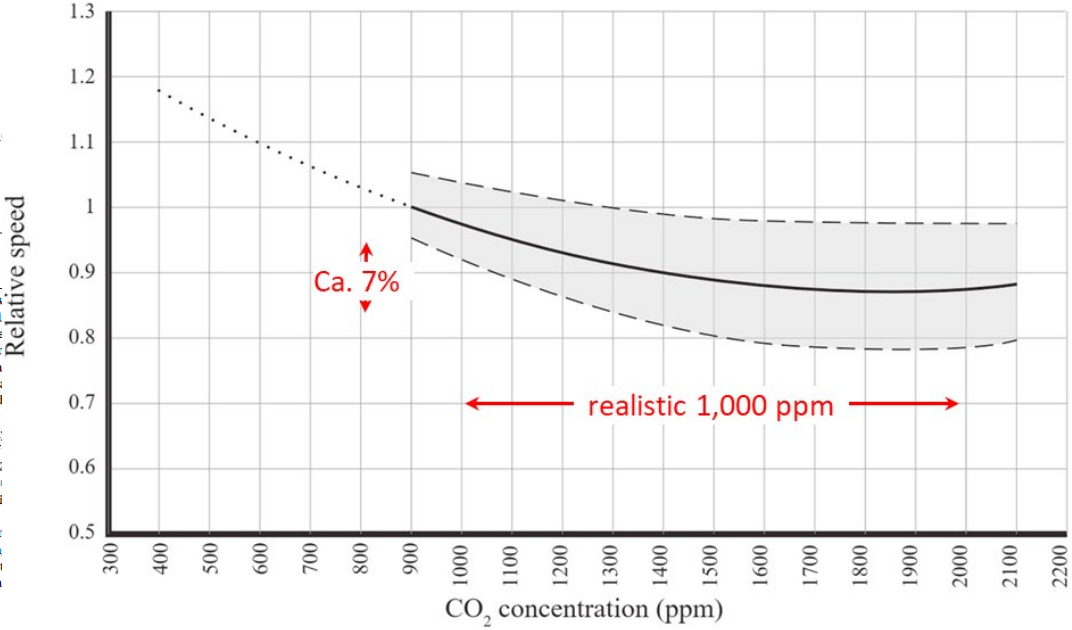
ARTICLE INFO

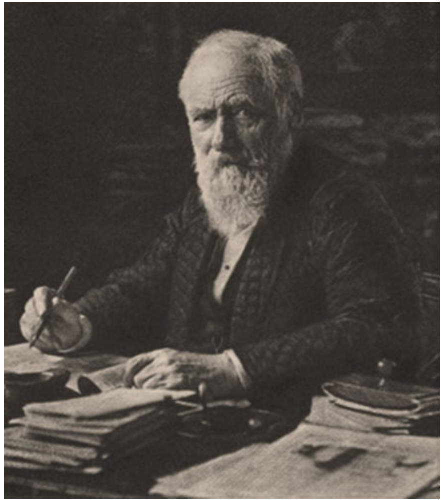
Keywords:
Children
Learning
Cognitive performance
Elementary schools
Carbon dioxide

ABSTRACT

The data from published studies were used to derive systematic relationships betv quality in classrooms. Psychological tests measuring cognitive abilities and skill ematical and language-based tasks, rating schemes, and tests used to assess progre year grades and exam scores were used to quantify learning outcomes. Short-ter because it may influence progress in learning. Classroom indoor air quality wa tration of carbon dioxide (CO_2). For psychological tests and school tasks, fraction regressed against the average concentrations of CO_2 at which they occurred; all d the inclusion criteria were used to derive the relationship, regardless of whether statistically significant at the examined levels of classroom air quality. The anal concentration from 2,100 ppm to 900 ppm would improve the performance of tasks by 12% with respect to the speed at which the tasks are performed and by 2 For other learning outcomes and short-term sick leave, only the relationships p were available. They were therefore used to make predictions. These relationshi concentration from 2,300 ppm to 900 ppm would improve performance on the learning by 5% and that reducing CO_2 from 4,100 ppm to 1,000 ppm would incr These results suggest that increasing the ventilation rate in classrooms in the ran person can bring significant benefits in terms of learning performance and pupil a for higher rates. The results provide a strong incentive for improving classroom cost-benefit analyses.



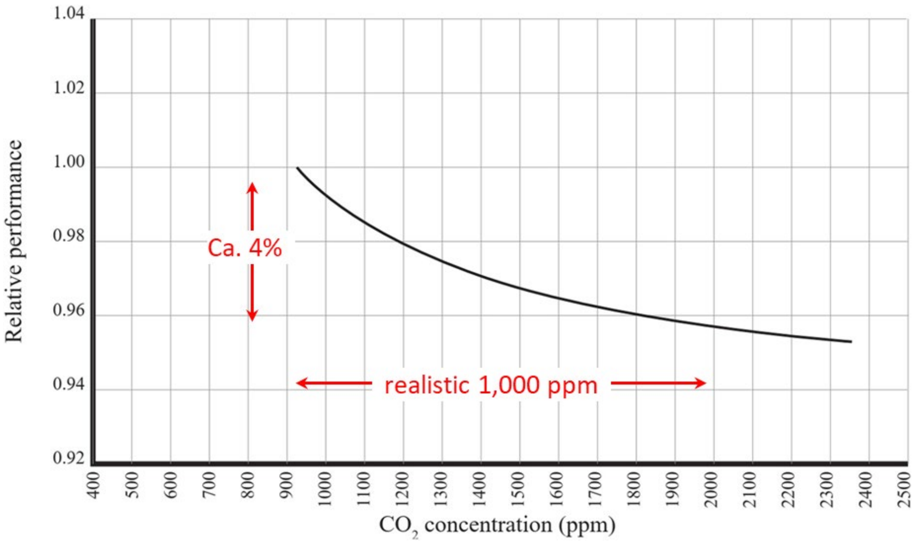
CO_2 a marker of outdoor air supply rate (air quality)

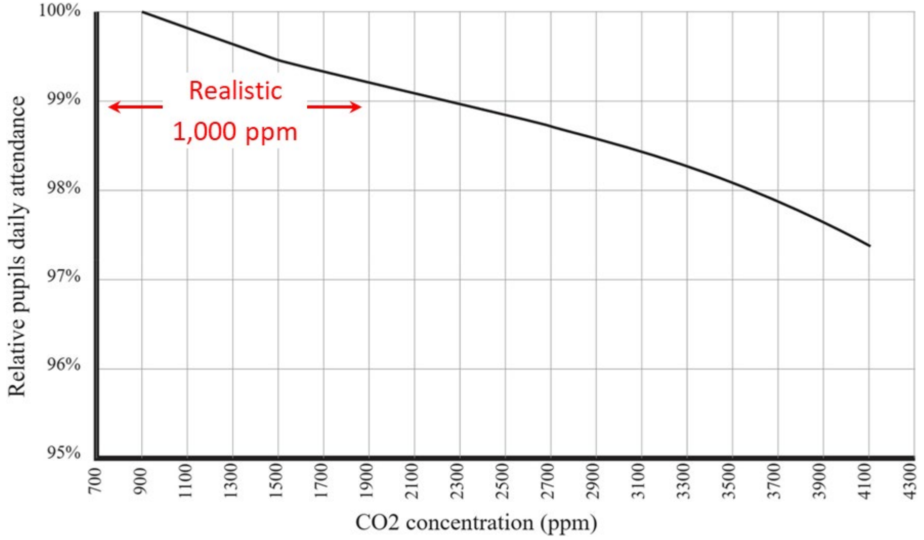


"The corruption of the air is not caused solely by the carbon dioxide content, we simply use this as a benchmark from which we can then also estimate a higher or lower content of other (pollutant) substances..."

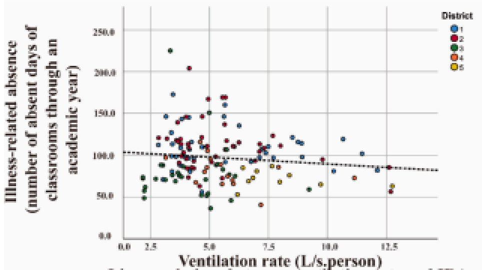
		Pure CO_2	CO_2 with other bioeffluents
Cognitive impacts	Office-like tasks	No adverse effects until 20,000 ppm, possibly higher. Incidental effects at 1,200 ppm and 3,000 ppm.	Adverse effects over 1,600 ppm.
Cognitive impacts	Highly demanding tasks	Adverse effects at and over 1,000 ppm, but inconsistent.	Adverse effects at 950 ppm and over.
Physiological impacts	End-tidal CO_2	Hypercapnic levels reached between 15,000 to 25,000 ppm and over.	Hypercapnic levels at 2,700 ppm.
Physiological impacts	Human neutrophils - *ex vivo*	Significant increase in inflammatory cytokines generation at 1,000 ppm and higher, above background levels.	No data.

Performance of national and aptitude tests and exams and daily attendance rates as a function of classroom CO_2 concentration (a marker of ventilation with outdoor air)



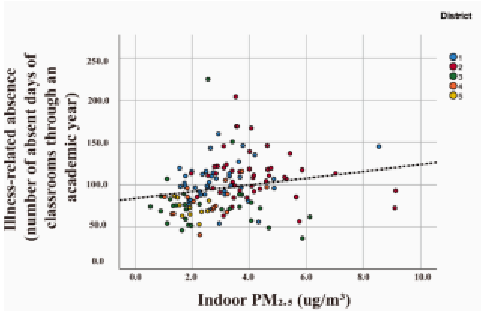


Not a CO_2 (a new study from the US)



a: Linear relations between ventilation rate and IRA

Every 1 L/s per person increase in ventilation rate was associated with a 5.59 decrease in days with absences per year.
This corresponds to a 0.15% increase in the annual daily attendance rate.



b: Linear relations between indoor $PM_{2.5}$ and IRA

Every additional 1 μg/m^3 of indoor PM2.5 was associated with a 7.37 increase in days with absences per year.
This corresponds to a 0.19% decrease in the annual daily attendance rate.

Environment International 176 (2023) 107944

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

ELSEVIER

Full length article

Associations between illness-related absences and ventilation and indoor $PM_{2.5}$ in elementary schools of the Midwestern United States

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ARTICLE INFO

Handling Editor: Hanna Boogaard

Keywords:
Classroom
Indoor air quality
Pupils
Attendance
Particulate matter
Ventilation

ABSTRACT

This study monitored indoor environmental data in 144 classrooms in 31 schools in the Midwestern United States for two consecutive days every fall, winter, and spring during a two-year period; 3,105 pupils attended classrooms where the measurements were conducted. All classrooms were ventilated with mechanical systems that had recirculation; there were no operable exterior windows or doors. The daily absence rate at the student level and demographic data at the classroom level were collected. The overall mean ventilation rate, using outdoor air, was 5.5 L/s per person (the corresponding mean carbon dioxide concentrations were < 2,000 ppm), and the mean indoor $PM_{2.5}$ was 3.6 μg/m^3. The annual illness-related absence rate at the classroom level was extracted from the student-level absence data and regressed on measured indoor environmental parameters. Significant associations were found. Every 1 L/s per person increase in ventilation rate was associated with a 5.59 decrease in days with absences per year. This corresponds to a 0.15% increase in the annual daily attendance rate. Every additional 1 μg/m^3 of indoor $PM_{2.5}$ was associated with a 7.37 increase in days with absences per year. This corresponds to a 0.19% decrease in the annual daily attendance rate. No other relationships were significant. Present results agree with the previously demonstrated benefits of reduced absence rates when classroom ventilation is improved and provide additional evidence on the potential benefits of reducing indoor inhalable particles. Overall, reduced absence rates are expected to provide socioeconomic benefits and benefits for academic achievements, while higher ventilation rates and reduced particle levels will also contribute to reduced health risks, including those related to airborne respiratory pathogens.

1. Introduction

The indoor environment of elementary schools has been identified as a major environmental concern and risk factor (Daisey et al., 2003; Mendell and Heath, 2005). Children spend 8 to 10 h per day and approximately 200 days a year in elementary schools, and many children are more vulnerable to adverse indoor environmental conditions because (a) children have higher breathing rates than adults and (b) their bodies are still growing and many organs are developing (Chen et al., 2015). An adverse classroom environment could lead to aggravated health conditions and decreased academic achievement (Mendell and Heath, 2005), which causes overall public concern among parents, teachers, and school officials.

Absenteeism caused by pupils missing school days because of medical conditions or illnesses that make it impossible to attend classes has been used in previous research as a proxy for pupils' health and classroom conditions. One of the leading causes of illness-related school absences has been attributed to asthma or asthma-related respiratory illnesses and symptoms (Meng et al., 2012; Tinkelman and Schwartz, 2004). Other common health problems associated with school absenteeism have been identified and incude among others allergic rhinitis (Blaiss, 2004), chronic illness and pain (Sato, 2007), influenza (Neuzil et al., 2002), obesity and sickle cell anemia (Taras and Potts-Datema, 2005), and diabetes (Kearney, 2008). Illness-related absenteeism has also been considered a risk factor for the academic performance of pupils in schools. Studies have reported that pupils with better attendance records have better grade point averages (GPA) and perform better on standardized reading and math tests (Gottfried, 2010), mathematics

Some recommendations re. non-infectious air delivery rate equivalent or outdoor air and CO_2

Ventilate with outdoor air (5-6 ach)

Use particle air cleaners with the similar effect

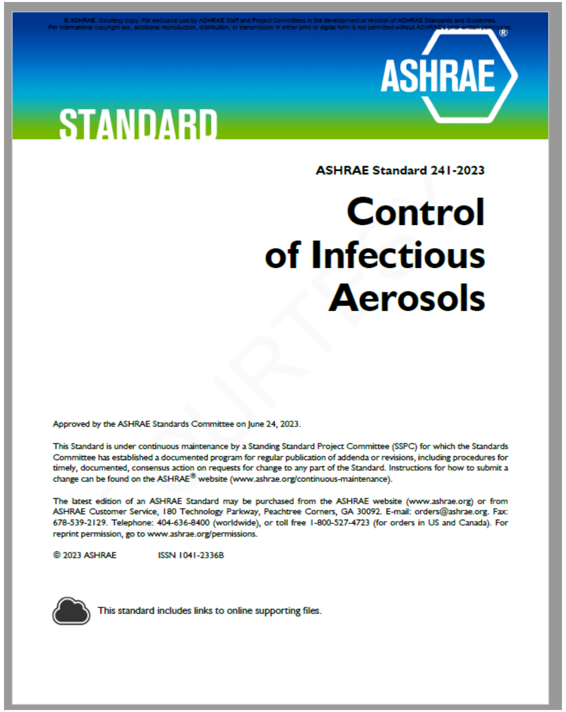
Keep CO_2 levels below 800 ppm (900 ppm)

Reduce the length of the lesson (intermittent occupation)

Nothing in relation to RH/T

(green)	Ideal (6 ACH)
(light green)	Excellent (5-6 ACH)
(yellow)	Good (4-5 ACH)
(pink)	Bare minimum (3-4 ACH)
(red)	Low (<3 ACH)

ASHRAE 241 (2023)



ASHRAE®

STANDARD

ASHRAE Standard 241-2023

Control of Infectious Aerosols

Approved by the ASHRAE Standards Committee on June 24, 2023.

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This standard includes links to online supporting files.

Table 5-1 Minimum Equivalent Clean Airflow per Person in Breathing Zone in IRMM

Occupancy Category	ECAi cfm/person	ECAi L/s/person
Correctional Facilities		
Cell	30	15
Dayroom	40	20
Commercial/Retail		
Food and beverage facilities	60	30
Gym	80	40
Office	30	15
Retail	40	20
Transportation waiting	60	30
Educational Facilities		
Classroom	40	20
Lecture hall	50	25
Industrial		
Manufacturing	50	25
Sorting, packing, light assembly	20	10
Warehouse	20	10
Health Care		
Exam room	40	20
Group treatment area	70	35
Patient room	70	35
Resident room	50	25
Waiting room	90	45
Public Assembly/Sports and Entertainment		
Auditorium	50	25
Place of religious worship	50	25
Museum	60	30
Convention	60	30
Spectator area	50	25
Lobbies	50	25
Residential		
Common space	50	25
Dwelling unit	30	15

ca. 5-6 h^{-1}

Air quality – the need for new research

What is NOT yet known:

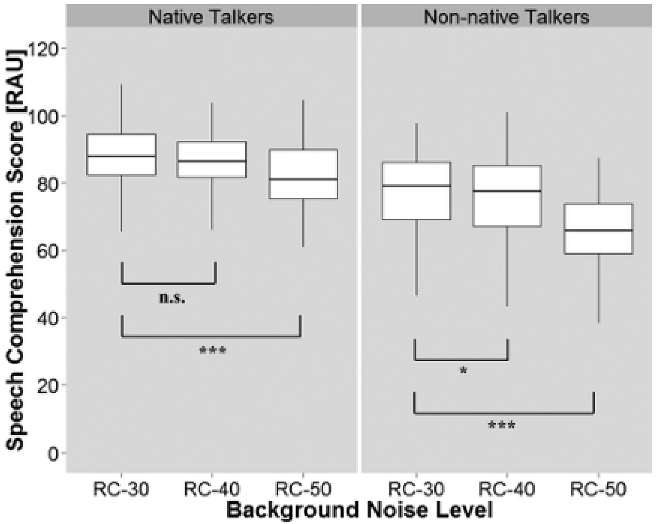
- The extent to which classroom occupant density and a low outdoor air supply rate affect cross-infection,
- whether there are any negative indoor air quality effects on teachers that affect teaching quality,
- whether thermal effects interact with the effects of air quality,
- and the mechanism for the negative effects of air quality on cognition: although it has been shown that lung capacity is temporarily reduced by exposure to poor indoor air quality, the physiological processes by which this occurs and how this affects cognition are not known.

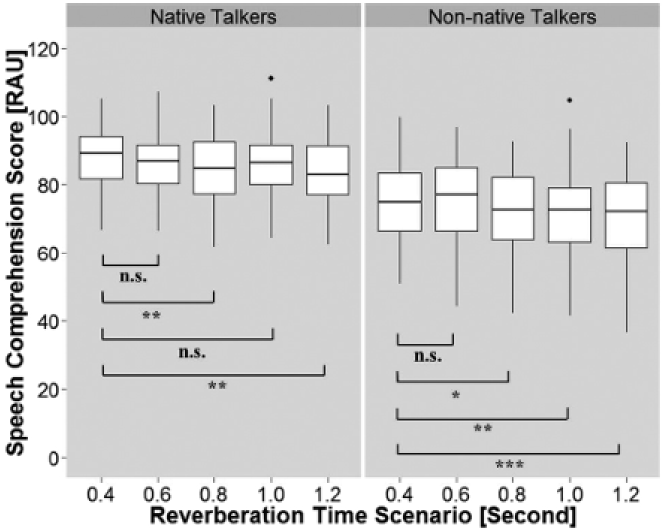
Classroom noise and acoustic treatment

Classroom noise has progressively negative effects on speech intelligibility

- Classroom noise negatively affects speech intelligibility, comprehension, and memory, but there is little evidence that it affects non-verbal tasks such as reading, writing, or mathematics
- Younger children are more affected than older children or adults
- Children with hearing or attentional difficulties and children being taught in their second language are more negatively affected
- Longer reverberation times exacerbate the negative effects of classroom noise.

Speech comprehension





Peng and Wang (2016)

Non-speech levels and learning performance

Math	Estimate B	Standard error	β
%FRL	–0.26[a]	0.03	–0.52
%Gifted	0.58[a]	0.05	0.54
%SPED	–0.31[a]	0.09	–0.19
G5 v G3	8.01	10.35	0.25
G8 v G3	–3.39	10.52	–0.08
G11 v G3	18.63[b]	7.28	0.49
L_{AeqN}	–0.87[b]	0.35	–0.17
SNR	–0.42	0.30	–0.09
$T20_m$	–0.22	7.65	–0.00
SNR × (G5 v G3)	–0.64	0.55	–0.36
SNR × (G8 v G3)	0.22	0.67	0.09
SNR × (G11 v G3)	–1.35[a]	0.41	–0.58

[a]*p < 0.01.*
[b]*p < 0.05.*

Language	Estimate B	Standard error	β
%FRL	–0.17[a]	0.03	–0.37
%Gifted	0.61[a]	0.07	0.62
%SPED	–0.29[a]	0.09	–0.19
G5 v G3	0.75	9.90	0.03
G8 v G3	–35.98[b]	15.71	–0.94
G11 v G3	–10.90	20.08	–0.31
L_{AeqN}	–0.26	0.32	–0.06
SNR	–0.49	0.41	–0.11
$T20_m$	11.45	8.23	0.09
SNR × (G5 v G3)	–0.24	0.56	–0.15
SNR × (G8 v G3)	1.88[b]	0.81	0.85
SNR × (G11 v G3)	–0.18	1.24	–0.08

[a]*p < 0.01.*
[b]*p < 0.05.*

Brill and Wang (2021)

Keep non-speech levels < 40 dB(A)

Confirmation of ANSI S12.60-2010 Part 1 for occupied classrooms recommending RTmax=0.6 – 0.7 sec BNLmax 35 dBA

Acoustic environment –the need for new research

<u>What is NOT yet known:</u>

- **The negative effects of different kinds and levels of classroom noise on non-verbal tasks and educational attainment,**
- **how and how much it affects teachers’ health and well-being,**
- **how noise can best be mitigated by acoustic engineering measures,**
- **whether it affects teaching quality,**
- **whether windows can be opened for ventilation without admitting too much external noise,**
- **whether installation noise such as fan noise has any negative effects**
- **and whether thermal or air quality effects interact with the negative effects of noise.**

Building and Environment 236 (2023) 110194

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Indoor soundscape, speech perception, and cognition in classrooms: A systematic review on the effects of ventilation-related sounds on students

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ARTICLE INFO

Keywords:
Classroom acoustic
Classroom soundscape
Ventilation
Speech perception
Cognition
Indoor comfort

ABSTRACT

Good air quality in classrooms, achieved through natural or mechanical ventilation, is necessary for students' health and cognition, but might simultaneously expose them to challenging sound environments, affecting learning and well-being. In this work we focused on the interaction between acoustics and ventilation modality and systematically reviewed the effects of sound stimuli related to ventilation on students' speech perception, cognition, and acoustic comfort.

Adopting the PRISMA guidelines, we selected 37 studies published after 1990, including students from primary school to university and assessing the impacts either of fan noise from mechanical ventilation or of sounds intruding into the classroom when windows are opened (i.e. traffic noise, aircraft noise, railway noise, human noise, sirens and construction noise, natural sounds). By comparison with a quiet baseline condition (no noise or low sound level), the effects were categorized as positive, null or negative.

Our systematic review showed a negative effect of fan noise. However, future research should better frame the result by including an integrated approach between acoustical and ventilation requirements. Concerning anthropogenic sounds entering the classroom in natural ventilation conditions, negative or no effects were generally observed, depending on the specific task and noise characteristics. On the contrary, natural sounds from open windows were found to consistently yield a positive effect on students' learning and comfort. Therefore, ventilation can sometimes improve the indoor soundscape depending on the context. The limitations of the currently available knowledge and under-investigated areas were outlined through the systematic review, which should be addressed in future studies.

Classroom daylighting, view-out, and artificial lighting

Daylight, a green view-out, and good artificial lighting can improve children's performance

- **Daylight in itself has beneficial effects on children in classrooms**
- **A green view-out has measurably beneficial effects on the performance of schoolwork**
- **Bright artificial lighting of good quality can improve concentration (1,000 vs. 300 lux)**
- **Reading speed is only decreased by extremely dim lighting**

Daylight and school performance

Table 3. Strength and significance of the association between the continuous lighting indicators and the performance test mean score. The coefficient represents the strength of association.

Variable	Coefficient	SE	t	*p*	CI (95%)	
Window/Floor Area Ratio	23.51	3.62	6.5	<0.01	16.41	30.60
Type of Shading	6.64	0.52	12.88	<0.01	5.63	7.65
Latitude	1.18	0.08	15.11	<0.01	1.03	1.34
Percentage of Windows facing South	0.04	0.01	3.51	<0.01	0.02	0.06
Daylight Index	−0.25	0.16	−1.57	0.12	−0.57	0.06
Direct Sunlight	−0.002	0.87	0	1.00	−1.70	1.70
Glazing	3.41	0.50	6.84	<0.01	2.44	4.39
Open-able Windows	0.57	0.38	1.49	0.14	−0.18	1.32

Adjusted on age, gender, race, and maternal education.

Baloch et al. (2021)

Visual environment – the need for new research

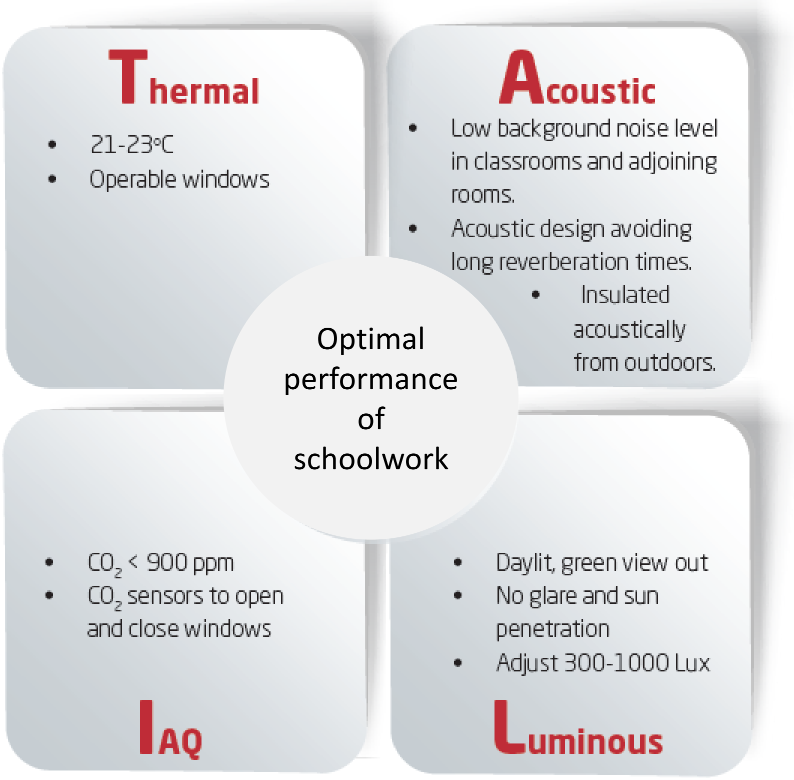
What is NOT yet known:

- **whether improving the daylight, view-out, or lighting quality of classrooms would lead to decreased absence rates, increased learning and improved end-of-year examination results,**
- **their relative importance in achieving these goals,**
- **the magnitude of the improvements,**
- **whether such effects interact with temperature, air quality or noise,**
- **how they affect teachers' health and performance**
- **and whether learning would be further enhanced if lighting could be changed by teachers to be more appropriate for different classroom activities and times of the day.**

Classroom conditions securing optimal performance of schoolwork

Summary

Research-based recommendations for achieving high indoor environmental quality in classrooms to promote learning



Q2: How to examine that learning environment is optimal?

Academic achievements (attainment)

Cognitive skills

Learning performance

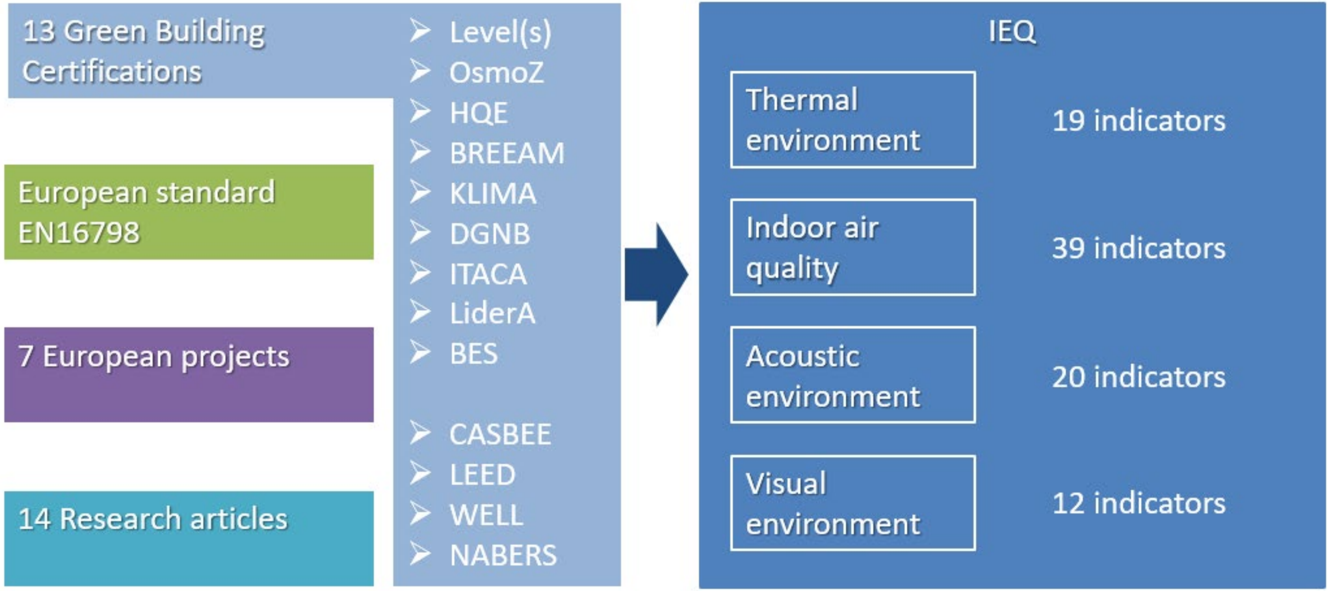
Academic behavior (engagement)

Attitudes (mood & motivation)

?

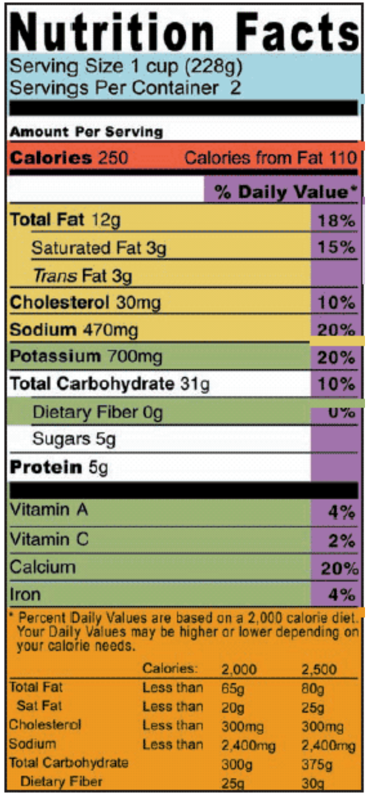
Well-being and health

Various IEQ indicators included in the current certification schemes and standards

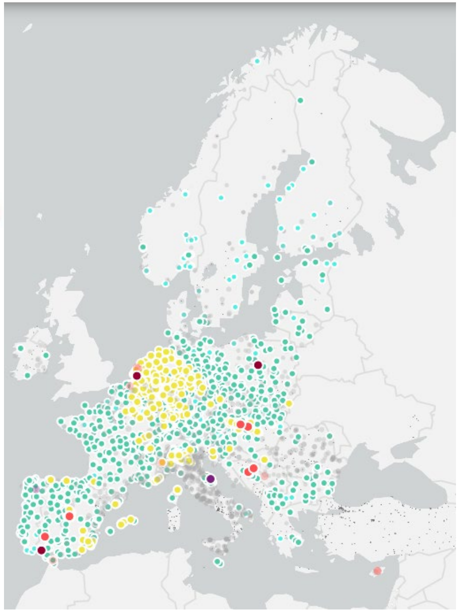


Wei et al. (2020)

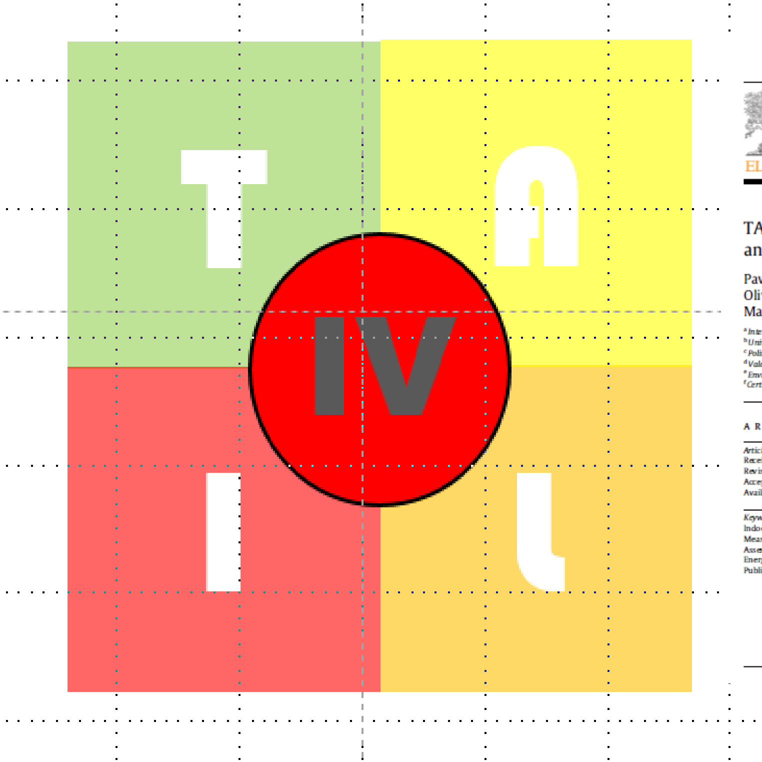
No method for rating IEQ

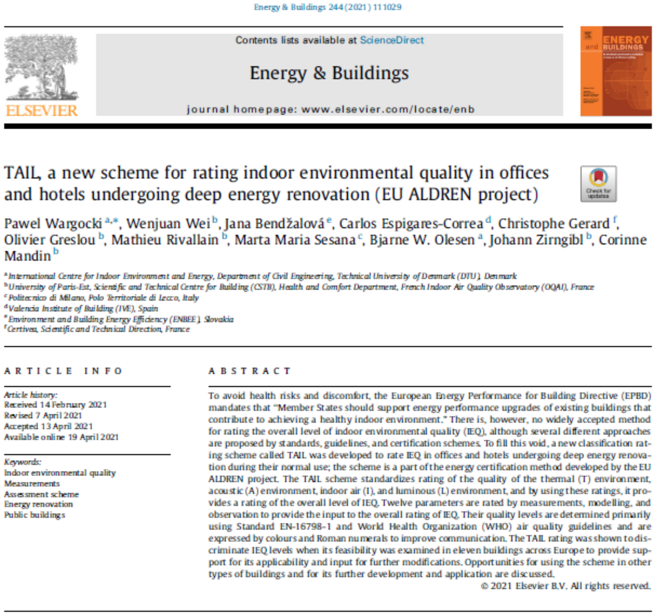


European Air Quality Index



The TAIL rating scheme





Energy & Buildings 244 (2021) 111029

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

TAIL, a new scheme for rating indoor environmental quality in offices and hotels undergoing deep energy renovation (EU ALDREN project)

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ARTICLE INFO

Article history:
Received 14 February 2021
Revised 7 April 2021
Accepted 13 April 2021
Available online 19 April 2021

Keywords:
Indoor environmental quality
Measurements
Assessment scheme
Energy renovation
Public buildings

ABSTRACT

To avoid health risks and discomfort, the European Energy Performance for Building Directive (EPBD) mandates that "Member States should support energy performance upgrades of existing buildings that contribute to achieving a healthy indoor environment." There is, however, no widely accepted method for rating the overall level of indoor environmental quality (IEQ), although several different approaches are proposed by standards, guidelines, and certification schemes. To fill this void, a new classification rating scheme called TAIL was developed to rate IEQ in offices and hotels undergoing deep energy renovation during their normal use; the scheme is a part of the energy certification method developed by the EU ALDREN project. The TAIL scheme standardizes rating of the quality of the thermal (T) environment, acoustic (A) environment, indoor air (I), and luminous (L) environment, and by using these ratings, it provides a rating of the overall level of IEQ. Twelve parameters are rated by measurements, modelling, and observation to provide the input to the overall rating of IEQ. Their quality levels are determined primarily using Standard EN-16798-1 and World Health Organization (WHO) air quality guidelines and are expressed by colours and Roman numerals to improve communication. The TAIL rating was shown to discriminate IEQ levels when its feasibility was examined in eleven buildings across Europe to provide support for its applicability and input for further modifications. Opportunities for using the scheme in other types of buildings and for its further development and application are discussed.

Selected parameters defining TAIL components incl. TAIL for schools

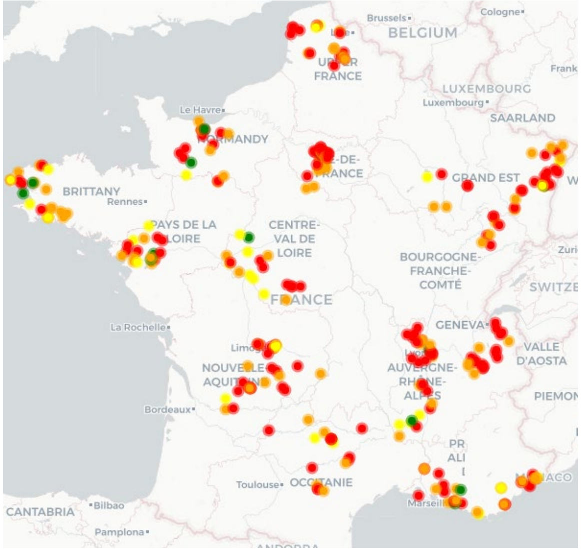
	IEQ parameter	Measured	Modelled	Visual inspection
T	Indoor temperature (°C)	×		
A	Noise level (dB(A))	×		
	Reverberation time (s)	×		
I	CO_2 (ppm)	×		
	Ventilation rate (L/s)	×		
	Formaldehyde (µg/m^3)	×		
	Benzene (µg/m^3)	×		
	$PM_{2.5}$ (µg/m^3)	×		
	Radon (Bq/m^3)	×		
	Indoor air relative humidity (%)	×		
	Visible mold (cm^2)			×
	Nitrogen dioxide (µg/m^3)	×		
L	Daylight factor (%)		×	
	Illuminance (lux)	×		

Ranges of parameters included in TAIL: IAQ

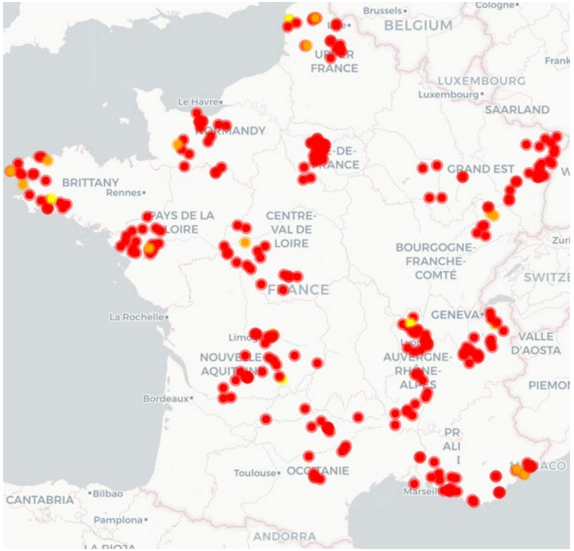
Quality of indoor air quality (I)	Green	Yellow	Orange	Red
Carbon dioxide (concentration above outdoors)[1,2]	≤550 ppm	≤800 ppm	≤1350 ppm	If other quality levels cannot be achieved
Ventilation rate[3,7]	≥(10 L/s/p + 2.0 L/s/m^{2}floor)	≥(7 L/s/p + 1.4 L/s/m^{2}floor) and <(10 L/s/p + 2.0 L/s/m^{2}floor)	≥(4 L/s/p + 0.8 L/s/m^{2}floor) and <(7 L/s/p + 1.4 L/s/m^{2}floor)	If other quality levels cannot be achieved
Relative humidity offices[2,4] hotel rooms[2,4,5]	≥30%≤50%≥ 30% and ≤50%	≥25%≤60%≥25% and ≤60%	≥20%≤70%≥20% and ≤60%	If other quality levels cannot be achieved
Visible mold[6,7]	No visible mould	Minor moisture damage, minor areas with visible mould (<400 cm^2)	Damaged interior structural component, larger areas with visible mould (<2500 cm^2)	Large areas with visible mould (≥2500 cm^2)
Benzene[7]	<2 µg/m^3	≥2 µg/m^3	no criteria	≥5 µg/m^3
Formaldehyde[7]	<30 µg/m^3	≥30 µg/m^3	no criteria	≥100 µg/m^3
Particles $PM_{2.5}$ (gravimetric)[7]	<10 µg/m^3	≥10 µg/m^3	no criteria	≥25 µg/m^3
Particles $PM_{2.5}$ (optical)[7]	<10 µg/m^3	≥10 µg/m^3	no criteria	≥25 µg/m^3
Radon[7,8]	<100 Bq/m^3	≥100 Bq/m^3	no criteria	≥300 Bq/m^3

Example of TAIL application: 308 schools in France

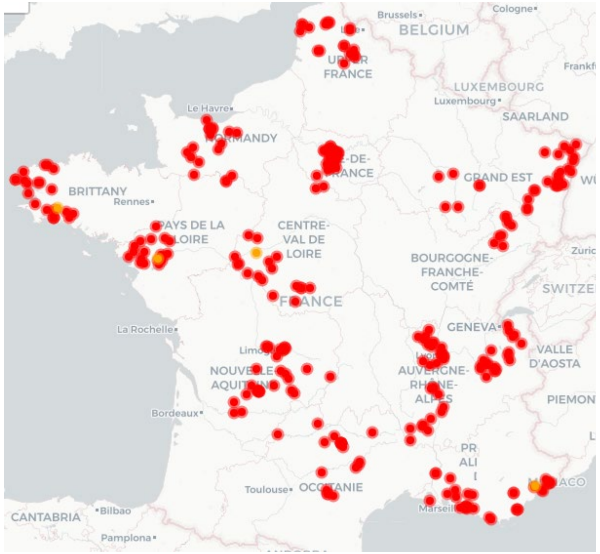
Category	Green (I)	Yellow (II)	Orange (III)	Red (IV)



Quality of thermal environment (T)



IAQ (I)



IEQ (TAIL)

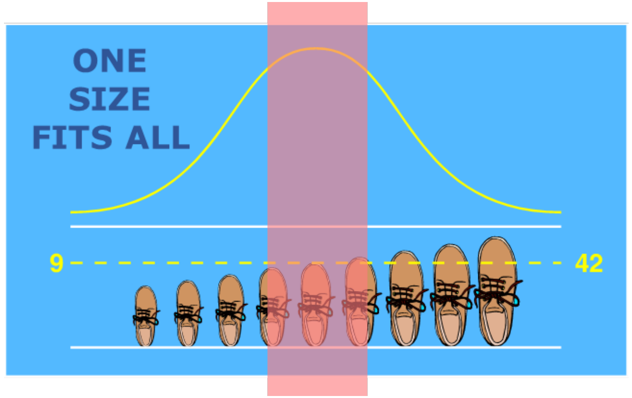
Monitoring and documentation of IEQ is of an essence

- Useful data for all building stakeholders and additional incentives for improvement of IEQ
- Create benchmark, reference, building data-base
- Monitor performance – compliance and maintenance
- Input to sustainable investments, and technological advancements
- Input to control and AI
- Input to energy simulation and reduce performance gap
- Input to economic calculations
- Demonstrate invisible - occupants feel secure (no risks)
- Raising awareness

Q3: How to advance research and implement present findings?

Requirements are not sufficiently ambitious

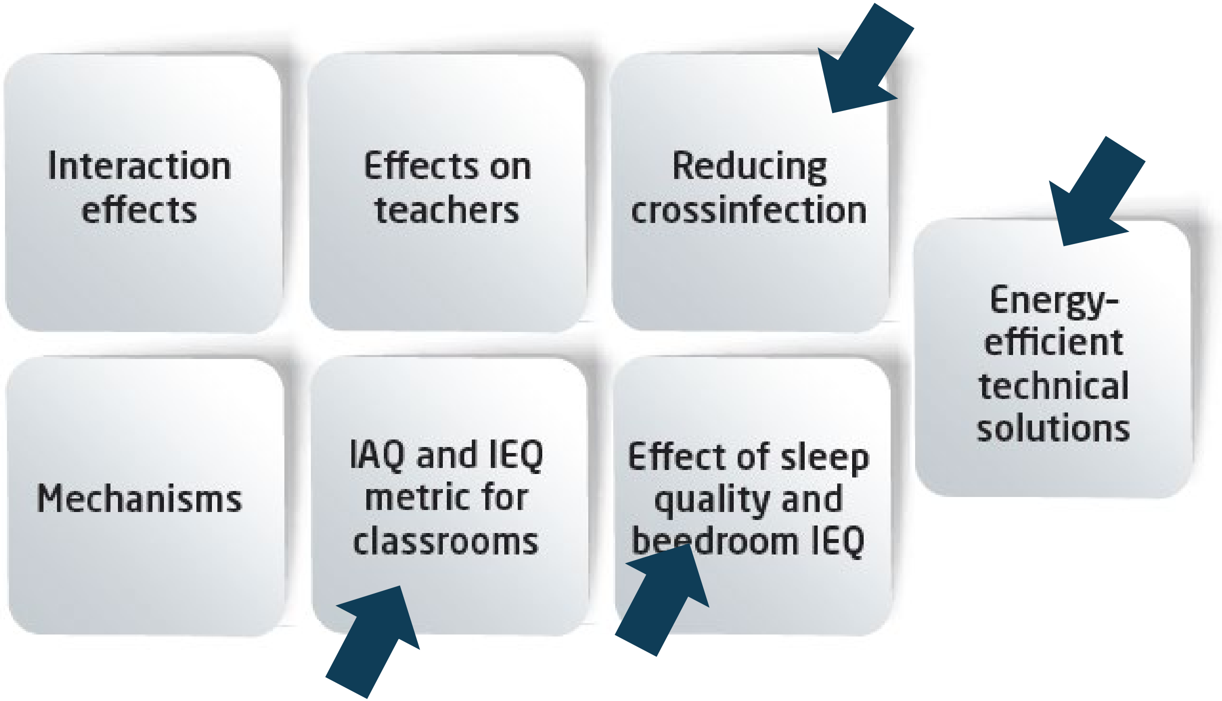
- Overdependence on the existing rather crude technological solutions and minimum standards.
- Based on population data thus addressing needs for an average person and neglecting individual preferences and differences
- Comfort (satisfaction) is the main design criteria, other outcomes not addressed sufficiently
- Addressing one aspect of IEQ not a combined effect
- There no tools to secure high IEQ at the design, operation and maintence phase
- All may be a factor limiting development and innovation.



Redefining paradigms for science and practice

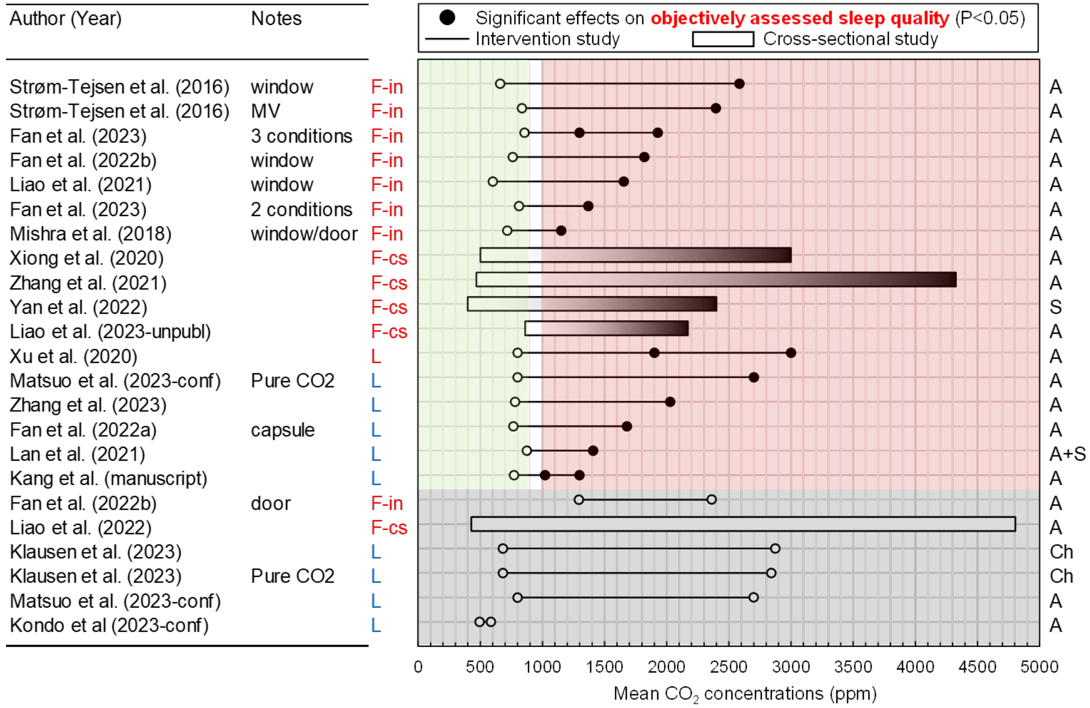
- IEQ/wellness are crucial and should be monetized on a par with other costs of running the buildings
- A paradigm shift resulting in advancement of IEQ technical solutions and regulations is needed from the ”one-size fit all” concept to all-inclusive and from minimum to aspiring
- Future demands should among others address preferences of an individual, be health related, adaptive, initiate participatory design and innovation
- Monitoring and rating schemes need to be developed and put immediately into the use
- Human responses should be used for control of IEQ together with environmental measurements
- All responses should be addressed not only comfort

Future research and development needs



Sleep is essential

- **People sleep over 20 years during their life time**
- **High quality sleep is vital for humans**
- **Sleep improves cognitive performance (memory and learning, and creativity), reduce health risks (dementia, Alzheimer's disease), regulates hunger and fullness (obesity), reduce risks for car accidents, improves concentration and next-day performance**
- **People are getting more and more deprived of sleep, length (<7,5 hrs) and quality**



Concluding remarks

An estimate of socio-economic consequences

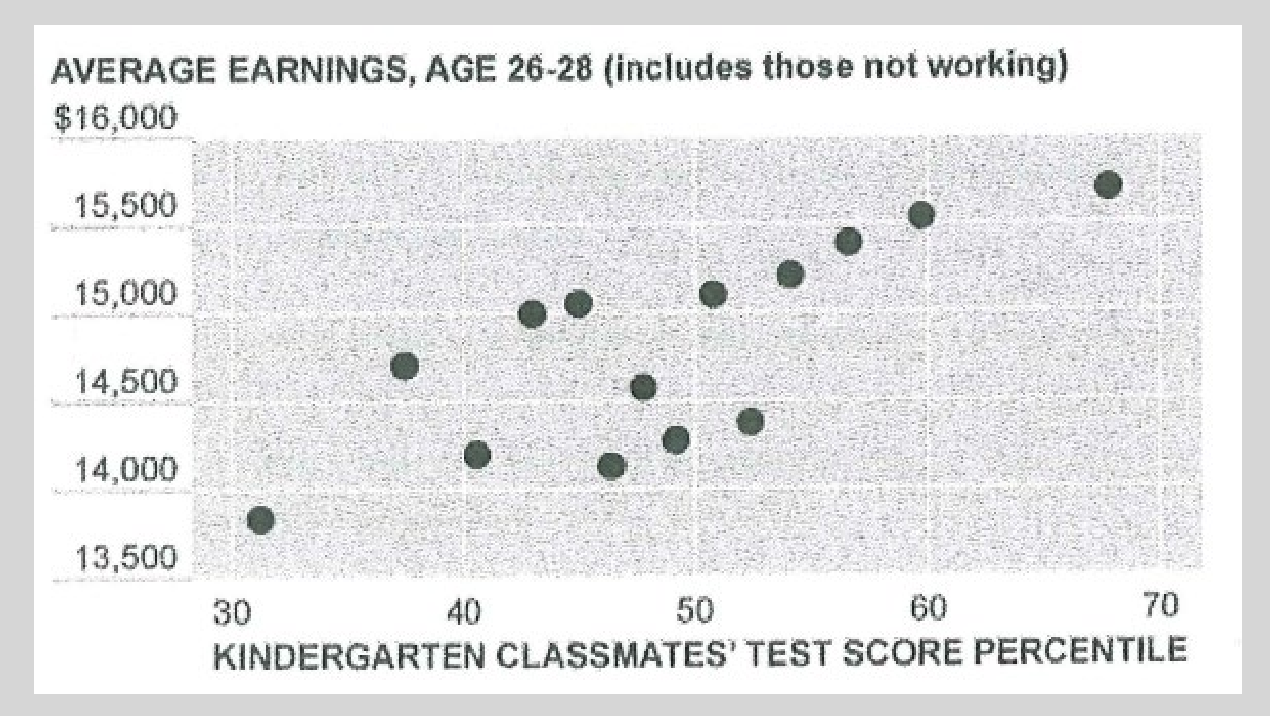
- 15% reduced performance (1/8) => 1 school year
- More time for teaching to reach the same educational targets, teacher cost => compare with the renovation costs
- Absence rates of pupils (& care takers) and teachers => cost of absenteeism
- Loss of opportunity (salary) as regards future work => socio-economic impact
- Consequences for national economy => GDP and public expenses/incomes

"It is certain that the additional expenses per pupil of the best ventilation needed not exceed the price of one or two cheap lunches."

New Hampshire School District

Ventilation Code, 1893

Potential data source for socio-economic consequences



Chetty et al., 2010

Change the mind set

"We must think of clean air as we think of clean water and fresh food. Here we do not compromise, nor should we do so with the indoor climate." @WargockiPawel

Thank you and questions

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