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Pawel Wargocki
Technical University of Denmark

Healthy Indoor Climate in Schools

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Q1: How to achieve optimal learning environment and low health risk and energy use?
Q2: How to reduce the infection risk from exposure to airborne pathogens?

Healthy Indoor Climate in Schools

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Main theses from my 2014 presentation

- 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 to conserve energy
- IEQ in many schools worldwide is inadequate
- Poor IEQ 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)

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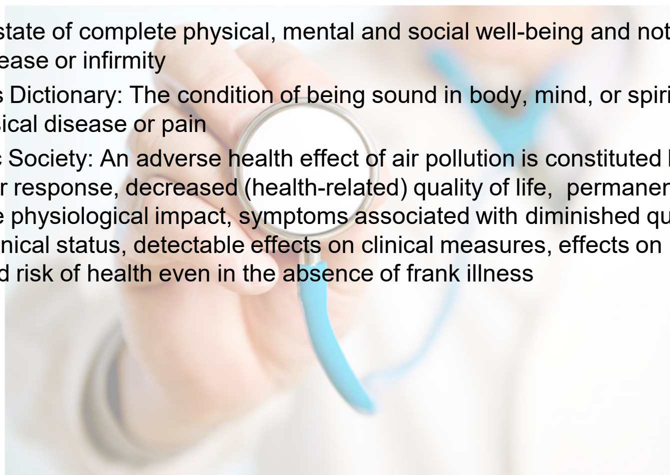
Health definitions

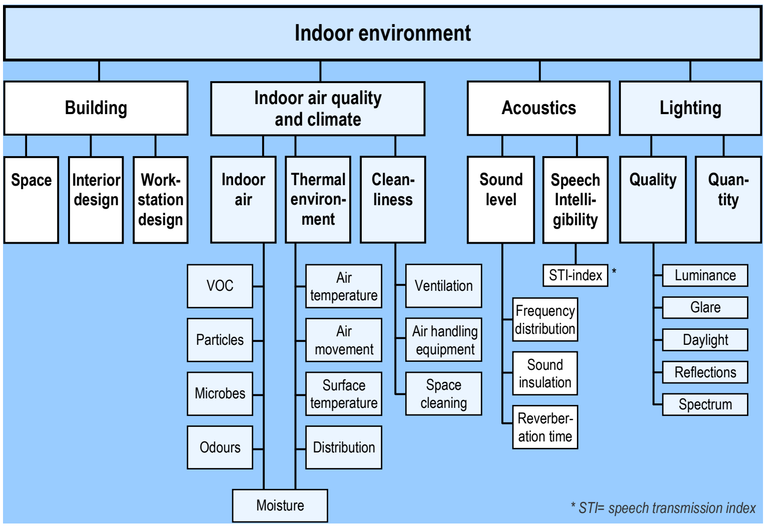
- WHO: Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity
- Merriam Webster's Dictionary: The condition of being sound in body, mind, or spirit, esp. freedom from physical disease or pain
- American Thoracic Society: An adverse health effect of air pollution is constituted by any of these: biomarker response, decreased (health-related) quality of life, permanent detectable adverse physiological impact, symptoms associated with diminished quality of life or change in clinical status, detectable effects on clinical measures, effects on mortality, increased risk of health even in the absence of frank illness

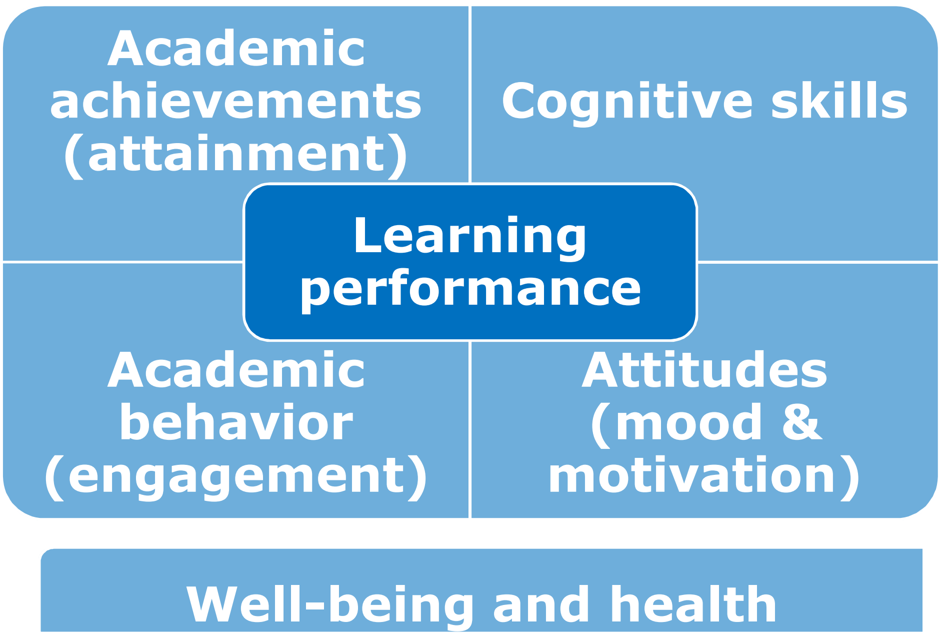


Healthy indoor climate in schools= promoting learning, avoiding absence

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

Indoor environment (IEQ)





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Thermal environment in classrooms

Raised classroom temperatures have progressively negative effects on children

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Thermal environment – research based evidence and the need for new research

- 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°C

- 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

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ELSEVIER

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

Pawel Wargocki[a,*], Jose Ali Porras-Salazar[a,b,c], Sergio Contreras-Espinoza[d]

[a] *International Centre for Indoor Environment and Energy, DTU Civil Engineering, Technical University of Denmark, Kongens Lyngby, Denmark*
[b] *School of Architecture, University of Costa Rica, San Pedro de Montes de Oca, Costa Rica*
[c] *Department of Design and Theory of Architecture, University of Bio-Bio, Bio-Bio, Chile*
[d] *Department of Statistics, University of Bio- Bio, Bio-Bio, Chile*

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Keywords:
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Temperature
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ABSTRACT

The present paper reports a meta-analysis of published evidence on the effects of temperature in school classrooms on children's performance in school. The data from 18 studies were used to construct a relationship between thermal conditions in classrooms and children's performance in school. Psychological tests measuring cognitive abilities and skills, school tasks including mathematical and language-based tasks, rating schemes, and tests used to assess progress in learning including end-of-year grades and the examination results were considered as indicators of children's performance Due to the lack of complete measurements, thermal conditions were characterized by measured classroom temperatures. To create the relationship, the fractional change in performance of psychological tests and school tasks was regressed against the average temperature at which the change was recorded; all published data were used regardless of whether the change in learning outcome changed significantly with temperature. For other learning outcomes, no relationship was created because the data were insufficient. The relationship derived in the analysis shows that the performance of psychological tests and school tasks can be expected to increase on average by 20% if classroom temperatures are lowered from 30 °C to 20 °C and that the temperature for optimal performance is lower than 22 °C. The relationship is valid only for temperate climates. It requires verification for other climates and extensions to temperatures lower than 20 °C and higher than 30 °C.

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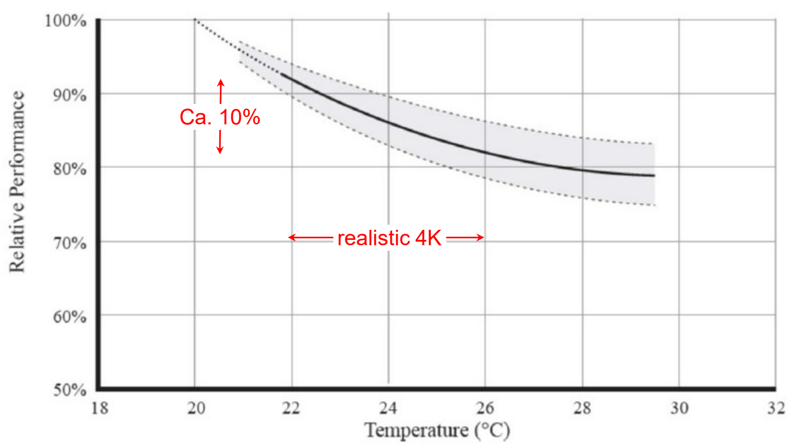
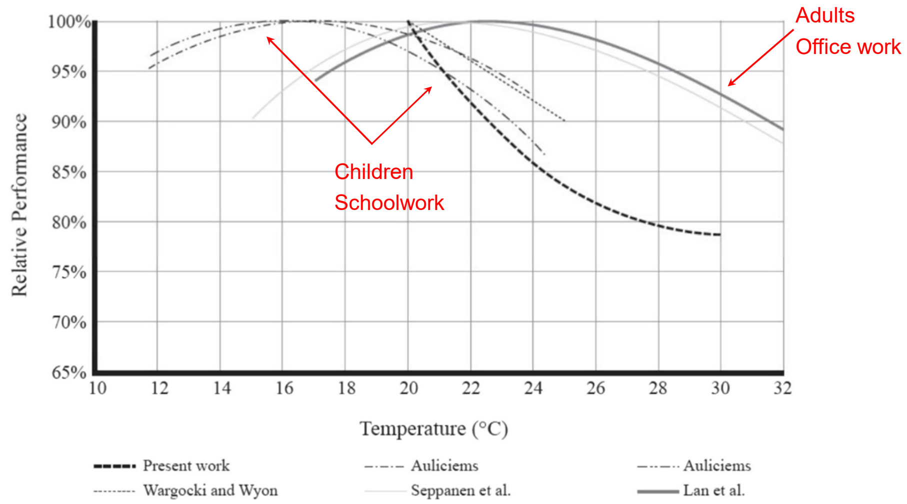
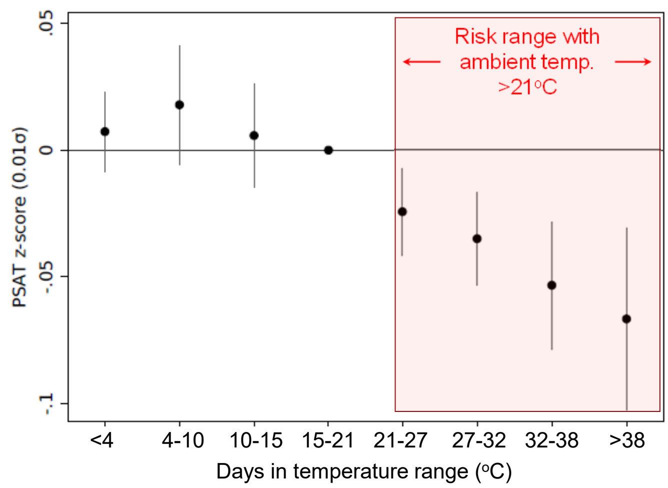
Performance of schoolwork as a function of classroom temperature



Comparison of the relationships



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



Thermal environment – research based evidence and the need for new research

- 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°C

- 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

Air quality – research based evidence and the need for new research

- 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

- 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. If they were known, they might make it possible to identify the airborne molecules responsible for these negative effects and somehow eliminate them from indoor air.

CO_2 effects on humans – marker of outdoor air supply rate (air quality)

		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.

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

Pawel Wargocki[a,*], Jose Ali Porras-Salazar[b], Sergio Contreras-Espinoza[c], William Bahnfleth[d]

[a] International Centre for Indoor Environment and Energy, DTU Civil Engineering, Technical University of Denmark, Kongens Lyngby, Denmark
[b] School of Architecture, University of Costa Rica, San Pedro de Montes de Oca, Costa Rica
[c] Department of Statistics, University of Bio- Bio, Bio-Bio, Chile
[d] Department of Architectural Engineering, Pennsylvania State University, PA, United States

ARTICLE INFO

Keywords:
Children
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Carbon dioxide

ABSTRACT

The data from published studies were used to derive systematic relationships between learning outcomes and air quality in classrooms. Psychological tests measuring cognitive abilities and skills, school tasks including mathematical and language-based tasks, rating schemes, and tests used to assess progress in learning including end-of-year grades and exam scores were used to quantify learning outcomes. Short-term sick leave was also included because it may influence progress in learning. Classroom indoor air quality was characterized by the concentration of carbon dioxide (CO_2). For psychological tests and school tasks, fractional changes in performance were regressed against the average concentrations of CO_2 at which they occurred; all data reported in studies meeting the inclusion criteria were used to derive the relationship, regardless of whether the change in performance was statistically significant at the examined levels of classroom air quality. The analysis predicts that reducing CO_2 concentration from 2,100 ppm to 900 ppm would improve the performance of psychological tests and school tasks by 12% with respect to the speed at which the tasks are performed and by 2% with respect to errors made. For other learning outcomes and short-term sick leave, only the relationships published in the original studies were available. They were therefore used to make predictions. These relationships show that reducing the CO_2 concentration from 2,300 ppm to 900 ppm would improve performance on the tests used to assess progress in learning by 5% and that reducing CO_2 from 4,100 ppm to 1,000 ppm would increase daily attendance by 2.5%. These results suggest that increasing the ventilation rate in classrooms in the range from 2 L/s-person to 10 L/s-person can bring significant benefits in terms of learning performance and pupil attendance; no data are available for higher rates. The results provide a strong incentive for improving classroom air quality and can be used in cost-benefit analyses.

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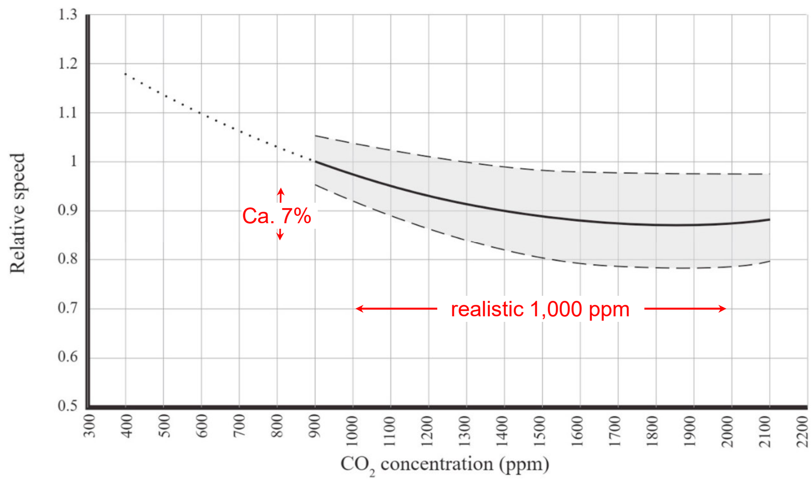
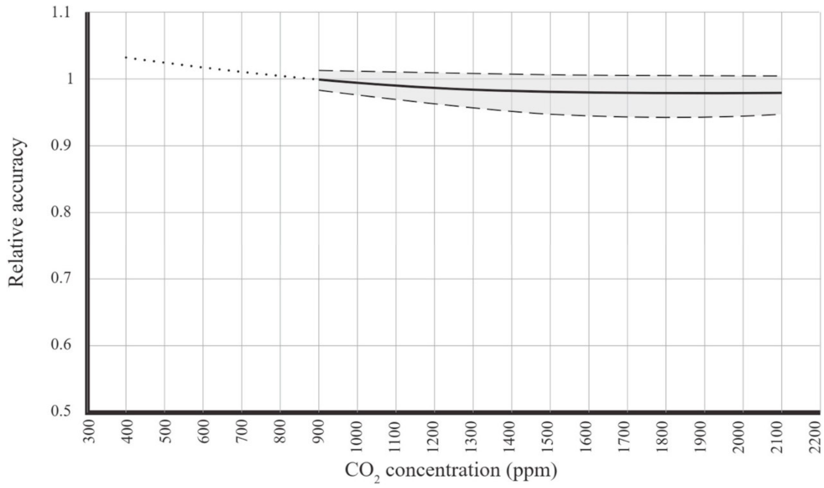
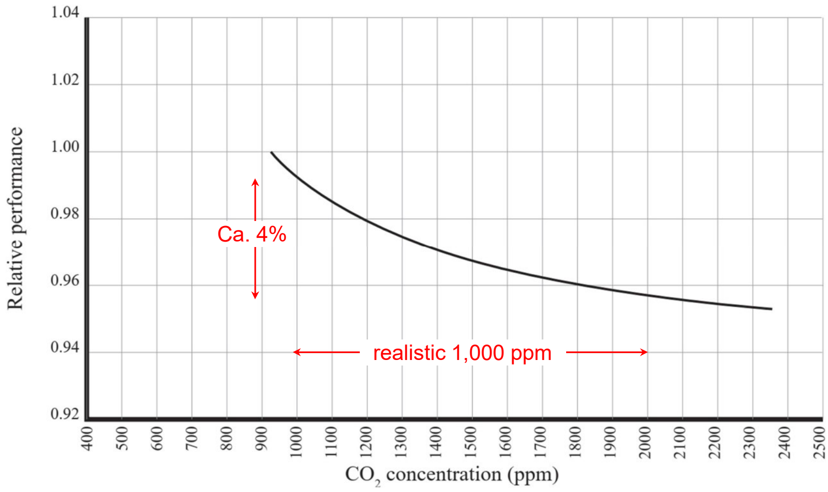
Performance of schoolwork (speed or reation time) as a function of classroom CO_2 concentration



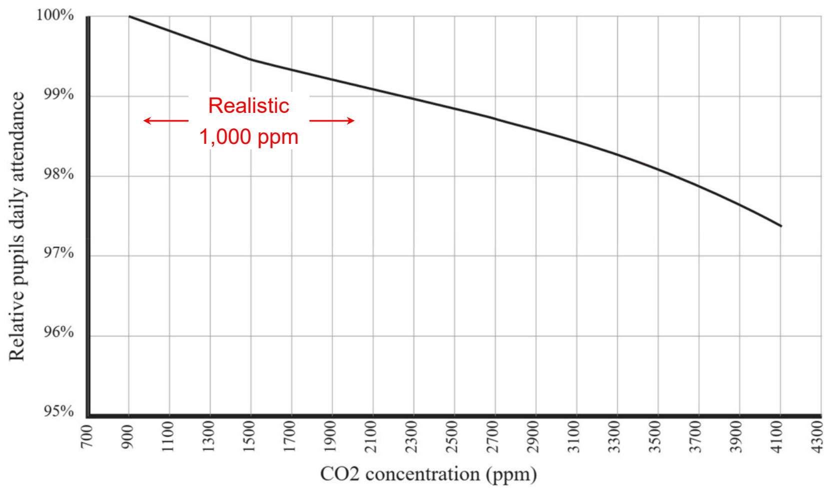
Performance of schoolwork (accuracy) as a function of classroom CO_2 concentration



Performance of national and aptitude tests and exams as a function of classroom CO_2 concentration



Pupils' daily attendance as a function of classroom CO_2 concentration



Air quality – research based evidence and the need for new research

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Classroom noise and acoustic treatment

Classroom noise has progressively negative effects on speech intelligibility

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Acoustic environment – research based evidence and the need for new research

- 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.

- What is NOT yet known: 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. The sensitivity of different pedagogical methods to noise was beyond the scope of this review.

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Speech intelligibility, adults

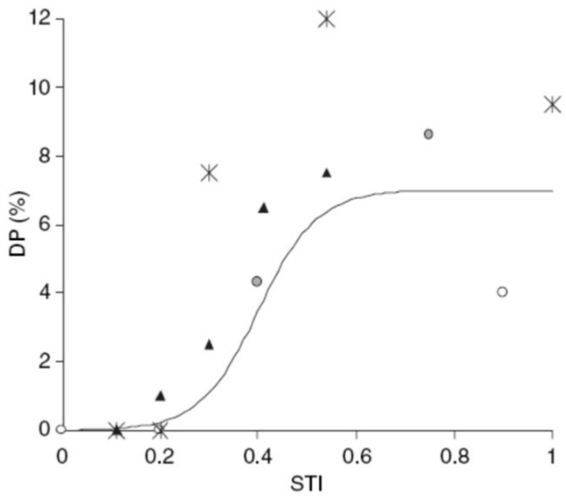

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TABLE 4 | Results from the multivariate regression model (N = 178) with acoustic metrics as predictors, classroom demographic variables as covariates, and math test scores as outcomes. Grade results shown are against grade 3.

	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] $p < 0.05$.

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Acoustic environment – research based evidence and the need for new research

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Classroom daylighting, view-out, and artificial lighting

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

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Visual environment – research based evidence and the need for new research

- 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

- 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.

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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.

Visual environment – research based evidence and the need for new research

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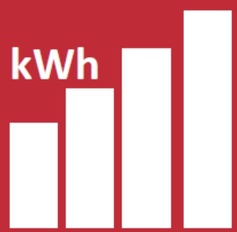
Energy conservation and cognitive performance

Securing cognitive performance will secure energy conservation in classrooms so both goals can be achieved at the same time in classrooms



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Energy and cognitive performance

- Gains in energy efficiency increase energy consumption
- Energy efficiency causes a rebound in energy use
- Thermal convenience can use up half the energy that could have been saved
- Classrooms should be cool, not warm, to optimize cognitive performance
- <u>Maintaining temperatures that are optimal for cognitive performance will avoid rebound effect in energy</u>

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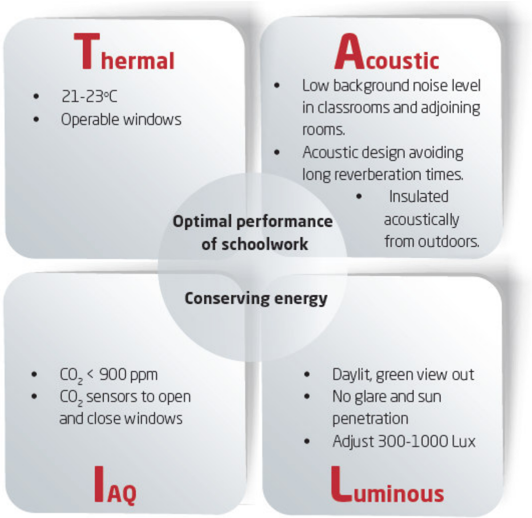
Classroom conditions securing optimal performance of schoolwork (and conservation of energy)



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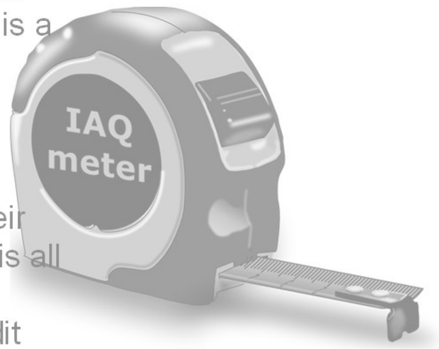
Priorities for future research

Future research and development needs

- Interaction effects
- Effects on teachers
- Reducing crossinfection
- Energy-efficient technical solutions
- Mechanisms
- IAQ and IEQ metric for classrooms
- Effect of sleep quality and beedroom IEQ

Necessity for IAQ/IEQ metric

- Lack of IAQ metric or disagreement what should constitute IAQ metric is a significant barrier holding back innovation of IAQ conducive technologies, emergence of undocumented methods of measurements of IAQ claiming their high efficiency and authenticity, this all resulting in undervaluing the importance of IAQ in different credit schemes and compliance metrics related to built environment

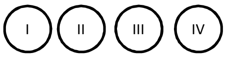


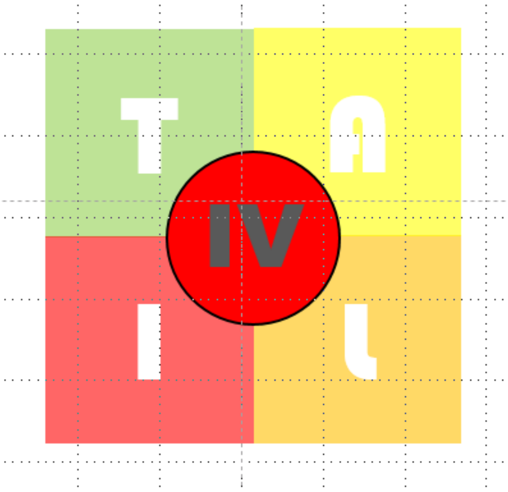
Development of a new method for IEQ rating using TAIL index

Four components:

- **T**hermal environment
- **A**coustic environment
- **I**ndoor air quality
- **L**ight – Luminous (visual) environment

Overall IEQ:

- 



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

Pawel Wargocki [a,*], Wenjuan Wei [b], Jana Bendžalová [e], Carlos Espigares-Correa [d], Christophe Gerard [f], Olivier Greslou [b], Mathieu Rivallain [b], Marta Maria Sesana [c], Bjarne W. Olesen [a], Johann Zirngibl [b], Corinne Mandin [b]

[a] International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark (DTU), Denmark
[b] University of Paris-Est, Scientific and Technical Centre for Building (CSTB), Health and Comfort Department, French Indoor Air Quality Observatory (OQAI), France
[c] Politecnico di Milano, Polo Territoriale di Lecco, Italy
[d] Valencia Institute of Building (IVE), Spain
[e] Environment and Building Energy Efficiency (ENBEE), Slovakia
[f] Certivea, Scientific and Technical Direction, France

A R T I C L E   I N F O

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Assessment scheme
Energy renovation
Public buildings

A B S T R A C T

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

	IEQ parameter	Measured	Modelled	Visual inspection
T	Indoor temperature (ºC)	×	(×)	
A	Noise level (dB(A))	×		
I	CO_2 (ppm)	×	(×)	
	Ventilation rate (L/s)	×	(×)	
	Formaldehyde (μg/m³)	×		
	Benzene (μg/m³)	×		
	$PM_{2.5}$ (μg/m³)	×		
	Radon (Bq/m³)	×		
	Indoor air relative humidity (%)	×	(×)	
	Visible mold (cm²)			×
L	Daylight factor (%)		×	
	Illuminance (lux)	×		

WHAT ABOUT TEACHERS?

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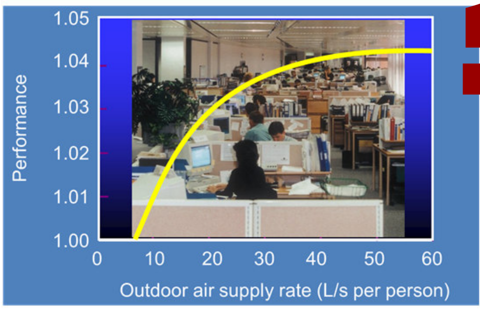

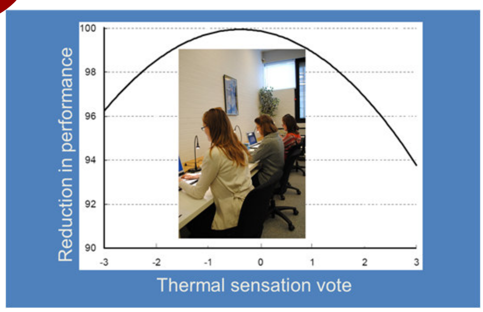

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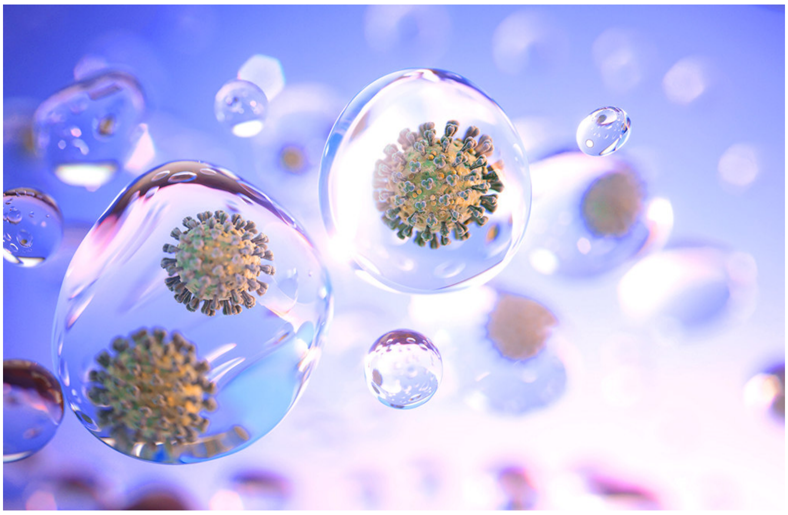
COVID-19 and other respiratory infections with airborne pathogens



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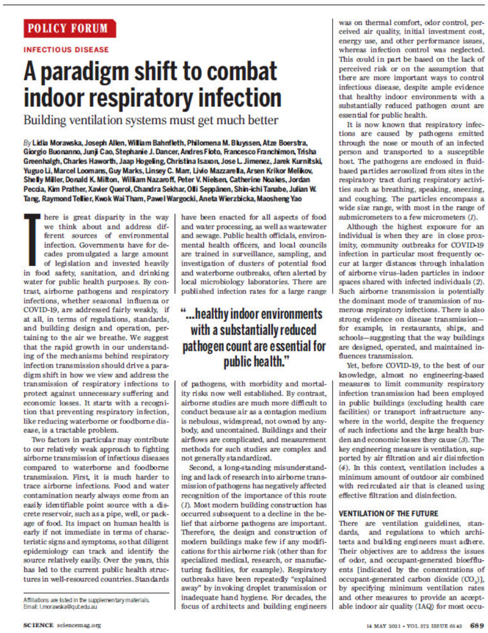
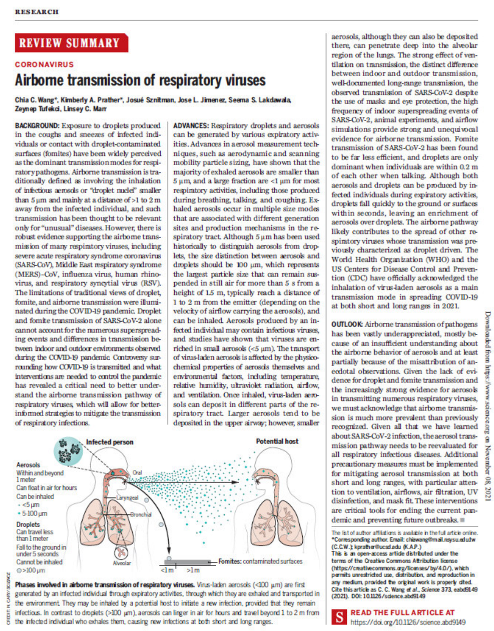
Two seminal papers





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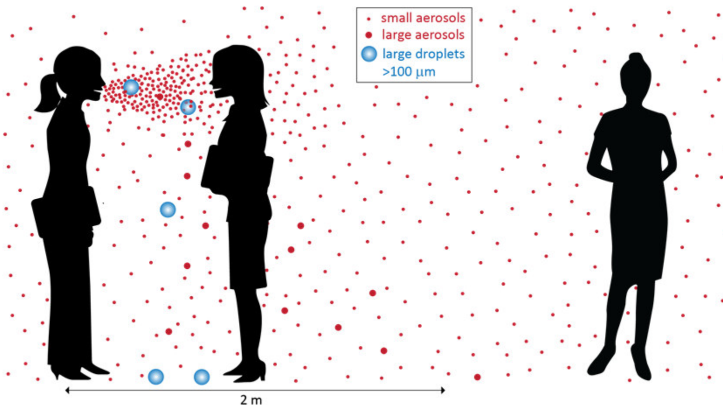
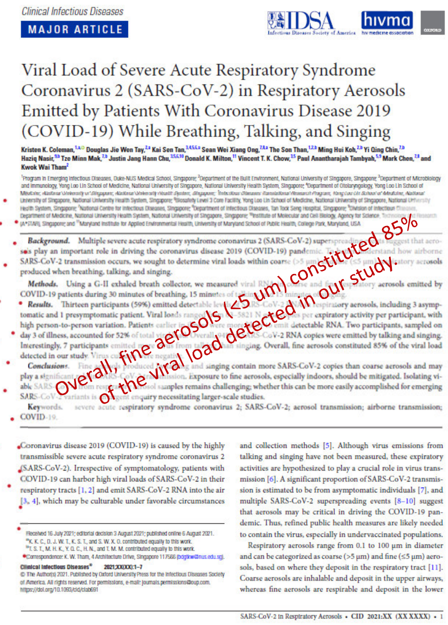
Droplets





Clinical Infectious Diseases
MAJOR ARTICLE

Viral Load of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) in Respiratory Aerosols Emitted by Patients With Coronavirus Disease 2019 (COVID-19) While Breathing, Talking, and Singing

Kristen K. Coleman,[1,a] Douglas Jie Wen Tay,[2,a] Kai Sen Tan,[3,4,5,6,a] Sean Wei Xiang Ong,[7,8,a] The Son Than,[1,2,b] Ming Hui Koh,[2,b] Yi Qing Chin,[7,b] Haziq Nasir,[9,b] Tze Minn Mak,[7,b] Justin Jang Hann Chu,[3,5,6,10] Donald K. Milton,[11] Vincent T. K. Chow,[3,5] Paul Anantharajah Tambyah,[5,9] Mark Chen,[7,8] and Kwok Wai Tham[2]

Background. Multiple severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) superspreading events suggest that aerosols play an important role in driving the coronavirus disease 2019 (COVID-19) pandemic. To better understand how airborne SARS-CoV-2 transmission occurs, we sought to determine viral loads within coarse (>5 µm) and fine (≤5 µm) respiratory aerosols produced when breathing, talking, and singing.

Methods. Using a G-II exhaled breath collector, we measured viral RNA in coarse and fine respiratory aerosols emitted by COVID-19 patients during 30 minutes of breathing, 15 minutes of talking, and 15 minutes of singing.

Results. Thirteen participants (59%) emitted detectable levels of SARS-CoV-2 RNA in respiratory aerosols, including 3 asymptomatic and 1 presymptomatic patient. ... per expiratory activity per participant, with high person-to-person variation. Patients earlier in illness were more likely to emit detectable RNA. Two participants, sampled on day 3 of illness, accounted for 52% of total viral load. ... SARS-CoV-2 RNA copies were emitted by talking and singing. Interestingly, 7 participants emitted more virus from talking than singing. Overall, fine aerosols constituted 85% of the viral load detected in our study. Virus cultures were negative.

Conclusions. Fine aerosols produced by talking and singing contain more SARS-CoV-2 copies than coarse aerosols and may play a significant role in SARS-CoV-2 transmission. Exposure to fine aerosols, especially indoors, should be mitigated. Isolating viable SARS-CoV-2 from respiratory aerosol samples remains challenging; whether this can be more easily accomplished for emerging SARS-CoV-2 variants is an urgent enquiry necessitating larger-scale studies.

Keywords. severe acute respiratory syndrome coronavirus 2; SARS-CoV-2; aerosol transmission; airborne transmission; COVID-19.

Overall, fine aerosols (<5 um) constituted 85% of the viral load detected in our study.

Coronavirus disease 2019 (COVID-19) is caused by the highly transmissible severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Irrespective of symptomatology, patients with COVID-19 can harbor high viral loads of SARS-CoV-2 in their respiratory tracts [1, 2] and emit SARS-CoV-2 RNA into the air [3, 4], which may be culturable under favorable circumstances and collection methods [5]. Although virus emissions from talking and singing have not been measured, these expiratory activities are hypothesized to play a crucial role in virus transmission [6]. A significant proportion of SARS-CoV-2 transmission is estimated to be from asymptomatic individuals [7], and multiple SARS-CoV-2 superspreading events [8–10] suggest that aerosols may be critical in driving the COVID-19 pandemic. Thus, refined public health measures are likely needed to contain the virus, especially in undervaccinated populations.

Respiratory aerosols range from 0.1 to 100 µm in diameter and can be categorized as coarse (>5 µm) and fine (≤5 µm) aerosols, based on where they deposit in the respiratory tract [11]. Coarse aerosols are inhalable and deposit in the upper airways, whereas fine aerosols are respirable and deposit in the lower

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[a]K. K. C., D. J. W. T., K. S. T., and S. W. X. O. contributed equally to this work.
[b]T. S. T., M. H. K., Y. Q. C., H. N., and T. M. M. contributed equally to this work.
Correspondence: K. W. Tham, 4 Architecture Drive, Singapore 117566 (bdgtkw@nus.edu.sg).
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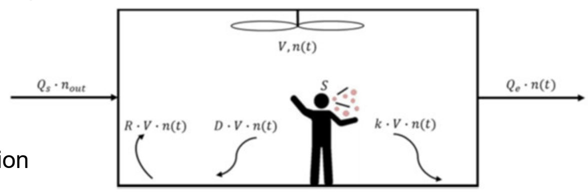
SARS-CoV-2 in Respiratory Aerosols • CID 2021:XX (XX XXXX) • 1

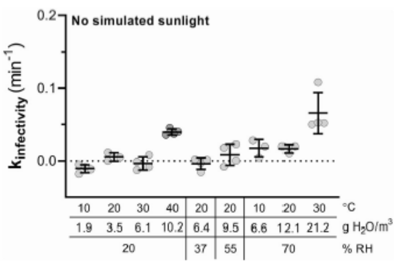
DTU

Origin of recommendations

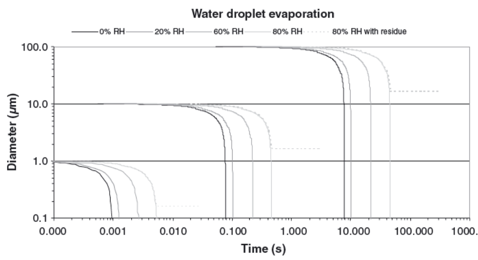
- Wells-Riley equation
  - Quanta assumption
  - Full-mixing (perfect-mixing) assumption
  - Number of people with infection assumption



- Virus inactivation



- Droplet deposition



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Current recommendations – 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)
(dark red)	Low (<3 ACH)

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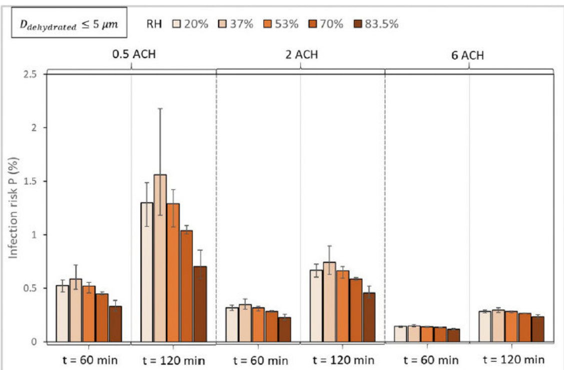
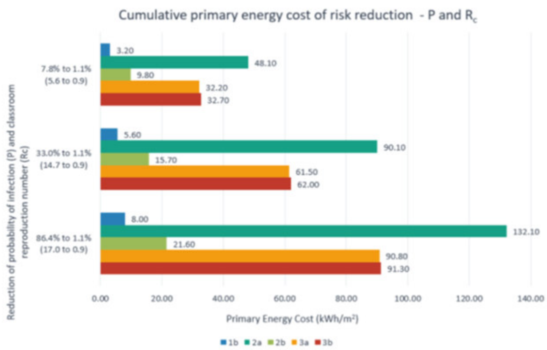
Impact of RH and air cleaning





Questions?

Thank you

Pawel Wargocki
paw@byg.dtu.dk