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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

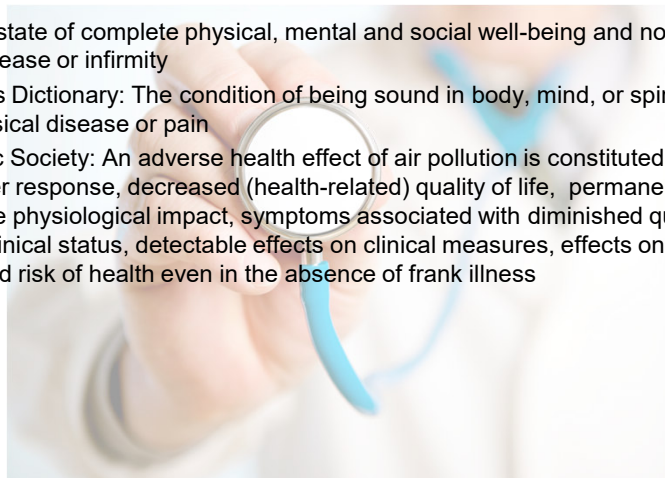
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Main theses from my 2014 presentation

- A good education system constitutes one of the fundamentals 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)

Health definitions

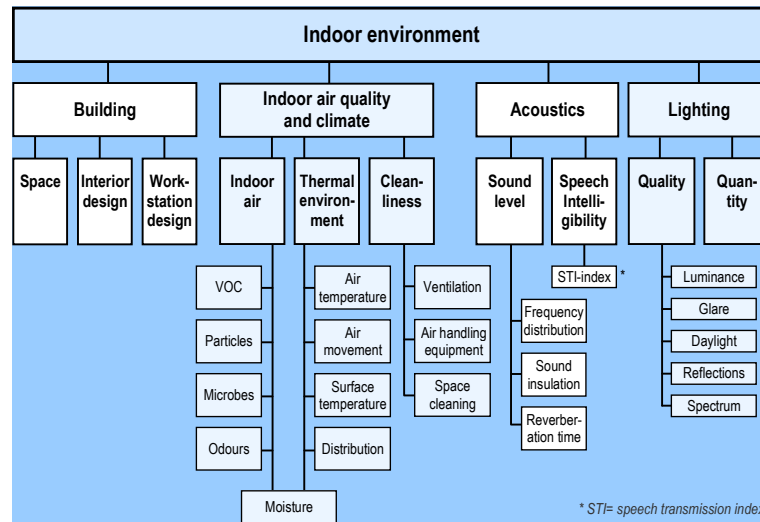
- WHO: Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity
- Merriam Webster's Dictionary: The condition of being sound in body, mind, or spirit, esp. freedom from physical disease or pain
- American Thoracic Society: An adverse health 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)



**Academic
achievements
(attainment)**

Cognitive skills

**Learning
performance**

**Academic
behavior
(engagement)**

**Attitudes
(mood &
motivation)**

Well-being and health

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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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

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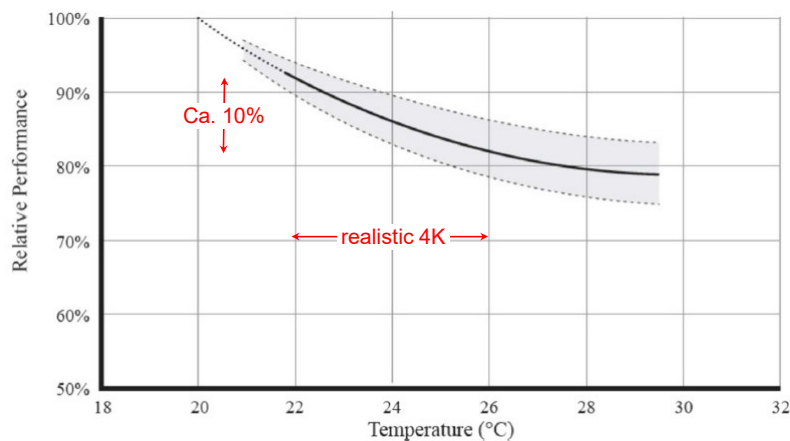
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Cognitive performance
Elementary schools
Temperature
Thermal environment

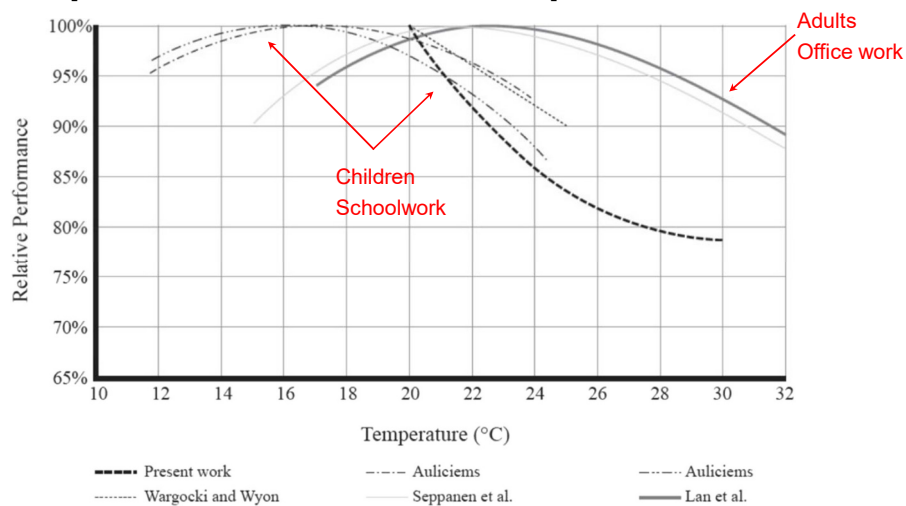
ABSTRACT

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.

Performance of schoolwork as a function of classroom temperature

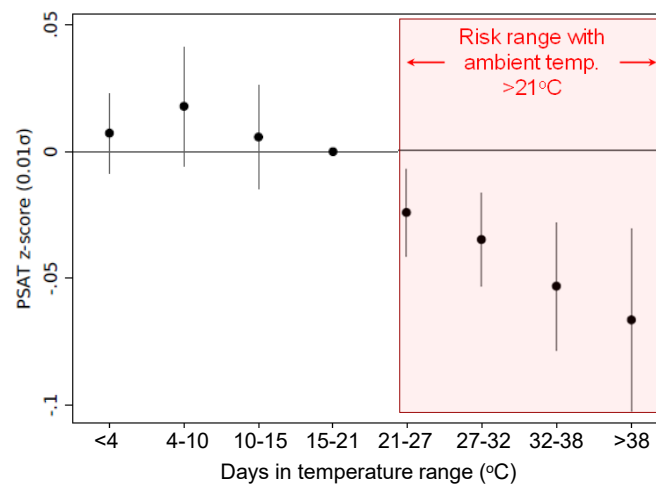


Comparison of the relationships



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



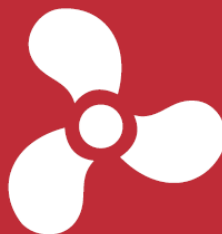
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Thermal environment – research based evidence and the need for new research

- 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

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 CO₂ 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 CO₂ 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.

CO₂ 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.
	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.
	Human neutrophils - ex vivo	Significant increase in inflammatory cytokines generation at 1,000 ppm and higher, above background levels.	No data.



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

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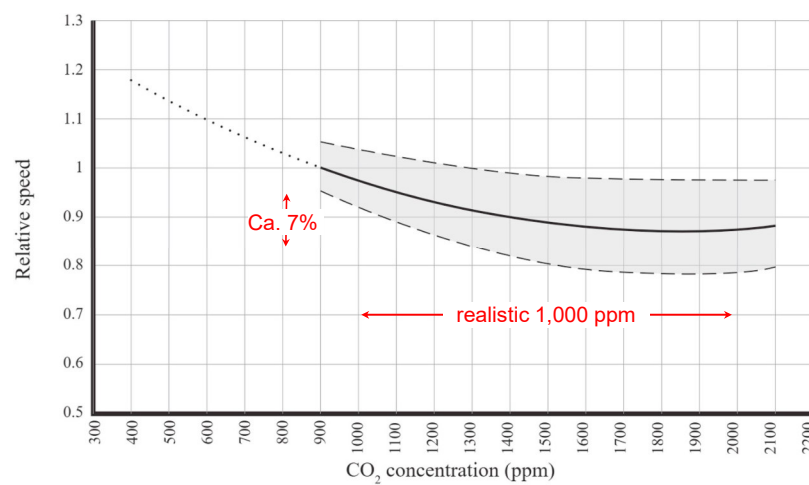
Keywords:

Children
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Elementary schools
Carbon dioxide

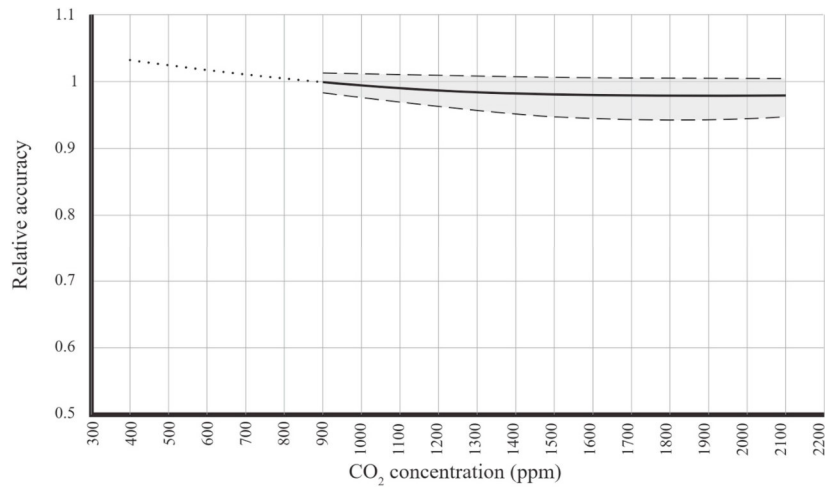
ABSTRACT

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 (CO₂). For psychological tests and school tasks, fractional changes in performance were regressed against the average concentrations of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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.

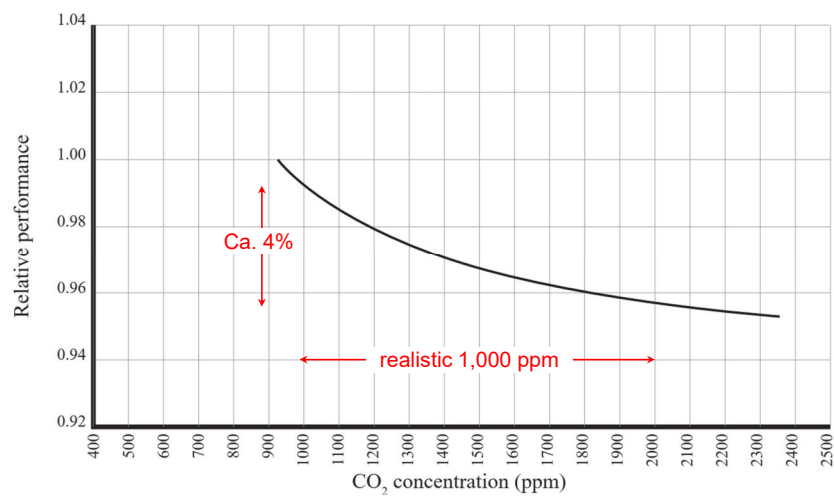
Performance of schoolwork (speed or reaction time) as a function of classroom CO₂ concentration



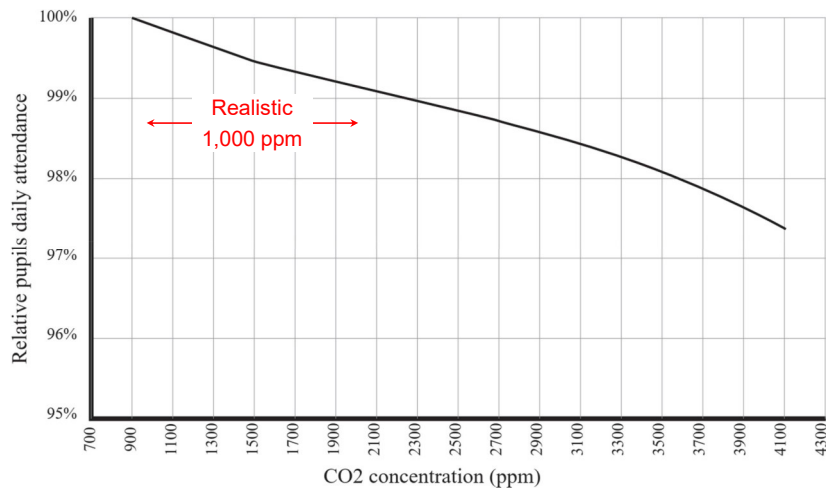
Performance of schoolwork (accuracy) as a function of classroom CO₂ concentration



Performance of national and aptitude tests and exams as a function of classroom CO₂ concentration



Pupils' daily attendance as a function of classroom CO₂ 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



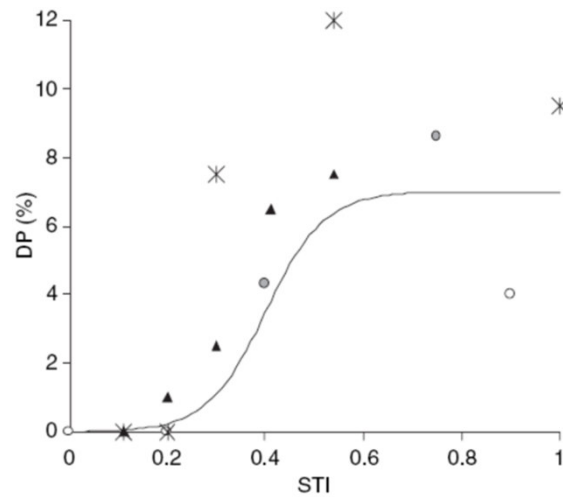
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Acoustic environment – research based evidence and the need for new research

- 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 \times (G5 v G3)	-0.64	0.55	-0.36
SNR \times (G8 v G3)	0.22	0.67	0.09
SNR \times (G11 v G3)	-1.35 ^a	0.41	-0.58

^a $p < 0.01$.

^b $p < 0.05$.

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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



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.

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.

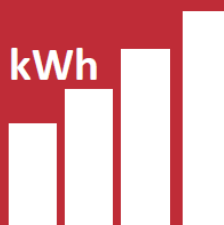
Visual environment – research based evidence and the need for new research

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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
- Maintaining temperatures that are optimal for cognitive performance will avoid rebound effect in energy

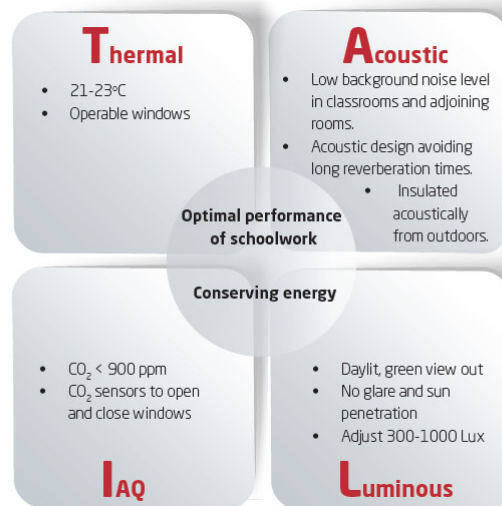
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Research-based
recommendations for
achieving high indoor
environmental quality
in classrooms to
promote learning

Summary

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



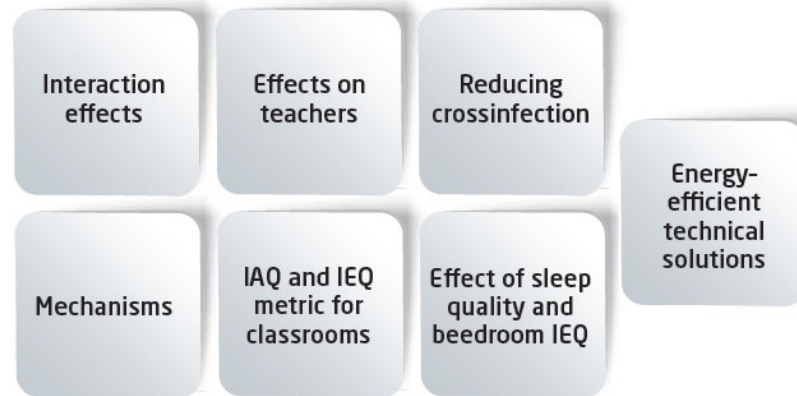
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Priorities for future research



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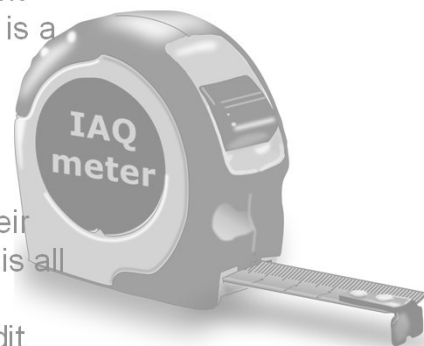
Future research and development needs



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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

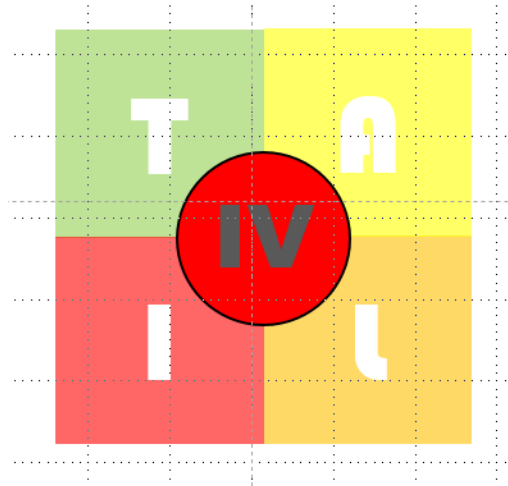


Development of a new method for IEQ rating using TAIL index

Four components:

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

Overall IEQ:



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^c, Carlos Espigares-Correa^d, Christophe Gerard^e, Olivier Greslou^b, Mathieu Rivallain^b, Marta Maria Sesana^c, Bjarne W. Olesen^a, Johann Zirngibl^b, Corinne Mandin^b

^aInternational Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark (DTU), Denmark

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ABSTRACT

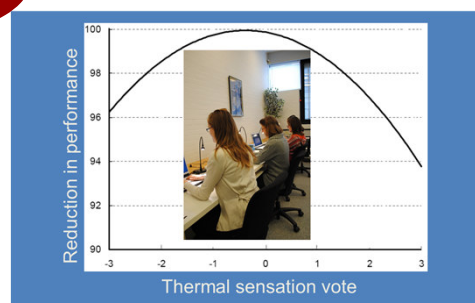
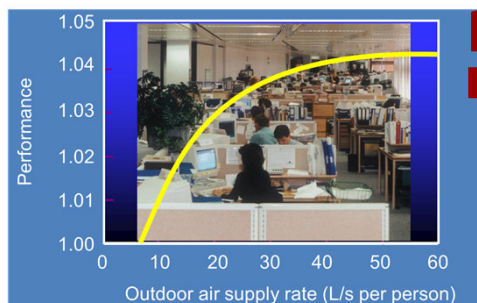
To avoid health risks and discomfort, the European Energy Performance for Building Directive (EPBD) mandates that "Member States should support energy performance upgrades of existing buildings that contribute to achieving a healthy indoor environment." There is, however, no widely accepted method for 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.

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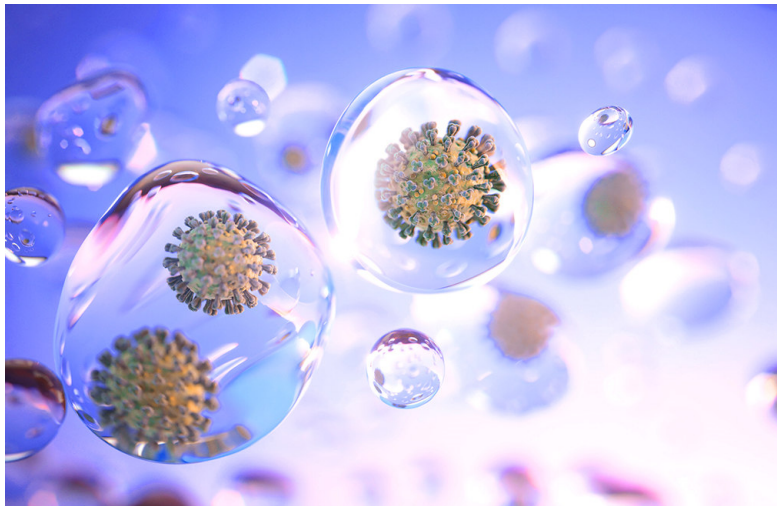
Selected parameters defining TAIL components

	IEQ parameter	Measured	Modelled	Visual inspection
I	Indoor temperature (°C)	✗	(✗)	
A	Noise level (dB(A))	✗		
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)			✗
L	Daylight factor (%)		✗	
	Illuminance (lux)	✗		

WHAT ABOUT TEACHERS?



COVID-19 and other respiratory infections with airborne pathogens



Two seminal papers

POLICY FORUM

INFECTIOUS DISEASE

A paradigm shift to combat indoor respiratory infection

Building ventilation systems must get much better

by Lilla Moravcsik, Joseph Allen, William Bushnell, Philomena M. Ekoyan, Aron Boersma, Giorgio Buonanno, José Cár, Stephanie J. Dancer, Andrew Flata, Francesco Franchini, Saba Greenhalgh, Charles Howarth, Jaap Hoogstra, Christina Isakov, José L. Jimenez, Jank Kurnik, Yugo J. Marcel Loomans, Guy Marks, Linsey C. Marr, Liva Mazurkova, Aron Krieger Moller, Shelly Miller, Donald L. Miller, Willem Naasari, Peter V. Nielsen, Catherine Nickles, Jordan Peckis, Kim Probst, Xavier Querol, Chandan Sekhar, Olli Seppänen, Shih-ichi Tanabe, Julian W. Tang, Raymond Teller, Leela Wilk, Thana, Pavel Wargocki, Aneta Wierzbicka, Manohar Yoo

There is great disparity in the way we think about and address different sources of environmental infection. Governments have for decades promulgated a large amount of legislation and invested heavily in food safety, sanitation, and drinking water for public health purposes. By contrast, airborne pathogens and respiratory infections, whether seasonal influenza or COVID-19, are addressed fairly weakly. If at all, in terms of regulations, standards, and building design and operation, pertaining to the air we breathe. We suggest that the rapid growth in our understanding of the mechanisms behind respiratory infection transmission should drive a paradigm shift in how we view and address the transmission of respiratory infections to protect against unnecessary suffering and economic losses. It starts with a recognition that preventing respiratory infection, like reducing waterborne or foodborne disease, is a tractable problem.

Two factors in particular may contribute to our relatively weak approach to fighting airborne transmission of infectious diseases compared to waterborne and foodborne transmission. First, it is much harder to trace airborne infections. Food and water contamination nearly always come from an easily identifiable point source with a discrete reservoir, such as a pipe, well, or package of food. Its impact on human health is easy if not immediate in terms of characteristic signs and symptoms, so that diligent epidemiology can track and identify the source relatively easily. Over the years, this has led to the current public health structures in well-resourced countries. Standards

of pathogens, with morbidity and mortality risk now well established. By contrast, airborne studies are much more difficult to conduct because air as a contagion medium is nebulous, widespread, not owned by anybody, and uncontrollable. Buildings and their air flows are complicated, and measurement methods for such studies are complex and not generally standardized. Second, a long-standing misunderstanding and lack of research into airborne transmission of pathogens has negatively affected recognition of the importance of this route of infection. For example, building construction has occurred subsequent to a decline in the belief that airborne pathogens are important. Therefore, the design and construction of modern buildings make few if any modifications for this airborne risk (other than for specialized medical, research, or manufacturing facilities, for example). Respiratory outbreaks have been repeatedly "explained away" by invoking droplet transmission or inadequate hand hygiene. For decades, the focus of architects and building engineers

was on thermal comfort, odor control, perceived air quality, initial investment cost, energy use, and other performance issues, whereas infection control was neglected. This could in part be based on the lack of perceived risk or on the assumption that there are more important ways to control infectious disease, despite ample evidence that healthy indoor environments with a substantially reduced pathogen count are essential for public health.

It is now known that respiratory infections are caused by pathogens emitted through the nose or mouth of an infected person and transported to a susceptible host. The pathogens are enclosed in fluid-based particles aerosolized from sputum in the respiratory tract during respiratory activities such as breathing, speaking, sneezing, and coughing. The particles encompass a wide size range, with most in the range of submicrometers to a few micrometers (1). Although the highest exposure for an individual is when they are in close proximity, community outbreaks for COVID-19 infection in particular most frequently occur at larger distances through inhalation of airborne virus-laden particles in indoor spaces shared with infected individuals (2). Such airborne transmission is potentially the dominant mode of transmission of numerous respiratory infections. There is also strong evidence on disease transmission—for example, in restaurants, ships, and schools—suggesting that the way buildings are designed, operated, and maintained influences transmission.

Yet, before COVID-19, to the best of our knowledge, almost no engineering-based measures to limit community respiratory infection transmission had been employed in public buildings (excluding health care facilities) or transport infrastructure anywhere in the world, despite the frequency of such infections and the large health burden and economic losses they cause (3). The key engineering measure is ventilation, supported by air filtration and air disinfection (4). In this context, ventilation includes a minimum amount of outdoor air combined with recirculated air that is cleaned using effective filtration and disinfection.

VENTILATION OF THE FUTURE There are ventilation guidelines, standards, and regulations to which architects and building engineers must adhere. Their objectives are to address the issues of odor, and occupant-generated bioeffluents (indicated by the concentrations of occupant-generated carbon dioxide (CO₂)), by specifying minimum ventilation rates and other measures to provide an acceptable indoor air quality (IAQ) for most occupants

RESEARCH

REVIEW SUMMARY

CORONAVIRUS

Airborne transmission of respiratory viruses

Chia C. Wang*, Kimberly A. Potter*, Josiah Smithman, Jose L. Jimenez, Seema S. Lakshminarayana, Zeynep Turkoz, Linsey C. Marr

BACKGROUND: Exposure to droplets produced in the coughs and sneezes of infected individuals or contact with droplet-contaminated surfaces (fomites) have been widely proposed as the dominant transmission modes for respiratory pathogens. Airborne transmission is traditionally defined as involving the inhalation of infectious aerosols or "droplet nuclei" smaller than 5 µm and usually at a distance of 1 to 2 m away from the infected individual, and such transmission has been thought to be relevant only for "unusual" diseases. However, there is robust evidence supporting the airborne transmission of many respiratory viruses, including severe acute respiratory syndrome coronavirus (SARS-CoV-2), Middle East respiratory syndrome (MERS-CoV), influenza virus, human rhinovirus, and respiratory syncytial virus (RSV). The limitations of traditional views of droplet, fomite, and airborne transmission were illuminated during the COVID-19 pandemic. Droplet and fomite transmission of SARS-CoV-2 alone cannot account for the numerous super-spreading events and differences in transmission between indoor and outdoor environments observed during the COVID-19 pandemic. Consensus regarding how COVID-19 is transmitted and what interventions are needed to control the pandemic has revealed a critical need to better understand the airborne transmission pathway of respiratory viruses, which will allow for better-informed strategies to mitigate the transmission of respiratory infections.

ADVANCES: Respiratory droplets and aerosols can be generated by various respiratory activities. Advances in aerosol measurement techniques, such as aerodynamic and scanning mobility particle sizing, have shown that the majority of exhaled aerosols are smaller than 5 µm, and a large fraction are <1 µm for most respiratory activities, including those produced during breathing, talking, and coughing. Exhaled aerosols occur in multiple size modes that are associated with different generation sites and production mechanisms in the respiratory tract. Although 5 µm has been used historically to distinguish aerosols from droplets, the size distinction between aerosols and droplets should be 100 µm, which represents the largest particle size that can remain suspended in still air for more than 5 s from a height of 1.5 m, typically reach a distance of 1 to 2 m from the emitter (depending on the velocity of airflow carrying the aerosols), and can be inhaled. Aerosols produced by an infected individual may contain infectious viruses, and studies have shown that viruses are restricted to small aerosols (<5 µm). The transport of exhaled aerosols is affected by the physicochemical properties of aerosols themselves and environmental factors, including temperature, relative humidity, ultraviolet radiation, airflow, and ventilation. Once inhaled, virus-laden aerosols can deposit in different parts of the respiratory tract. Larger aerosols tend to be deposited in the upper airway, whereas smaller

aerosols, although they can also be deposited there, can penetrate deep into the alveolar region of the lungs. The strong effect of ventilation on transmission, the distinct difference between indoor and outdoor transmission, well-documented long-range transmission, the observed transmission of SARS-CoV-2 despite the use of masks and eye protection, the high frequency of indoor super-spreading events of SARS-CoV-2, animal experiments, and airflow simulations provide strong and unequivocal evidence for airborne transmission. Fomite transmission of SARS-CoV-2 has been found to be far less efficient, and droplets are only dominant where individuals are within 0.2 m of each other when talking. Although both aerosols and droplets can be produced by infected individuals during respiratory activities, droplets fall quickly to the ground or surface within seconds, leaving an enrichment of aerosols over droplets. The airborne pathway likely contributes to the spread of other respiratory viruses whose transmission was previously characterized as droplet driven. The World Health Organization (WHO) and the US Centers for Disease Control and Prevention (CDC) have officially acknowledged the inhalation of virus-laden aerosols as a main transmission mode in spreading COVID-19 at both short and long ranges in 2021.

OUTLOOK: Airborne transmission of pathogens has been variably underappreciated, mostly because of an insufficient understanding about the airborne behavior of aerosols and at best partially because of the misinterpretation of aerosol observations. Given the lack of evidence for droplet and fomite transmission and the increasingly strong evidence for aerosols in transmitting numerous respiratory viruses, we must acknowledge that airborne transmission is much more prevalent than previously recognized. Given all that we have learned about SARS-CoV-2 infection, the aerosol transmission pathway needs to be reevaluated for all respiratory infectious diseases. Additional precautionary measures must be implemented for mitigating aerosol transmission at both short and long ranges, with particular attention to ventilation, airflow, air filtration, UV disinfection, and mask fit. These interventions are critical tools for ending the current pandemic and preventing future outbreaks.

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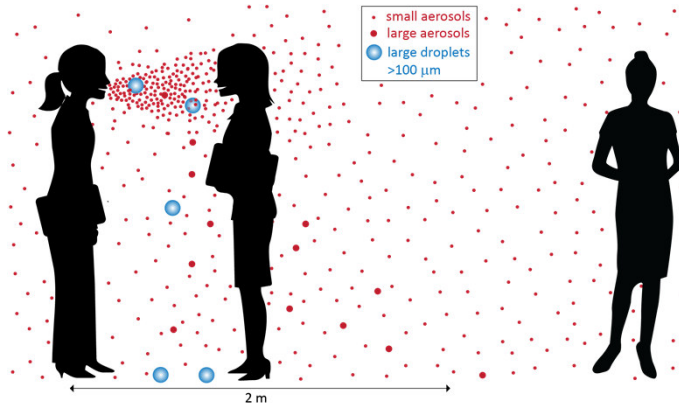
READ THE FULL ARTICLE AT
<https://doi.org/10.1016/j.science.2021.04.044>

Abbreviations are listed in the supplementary materials. Email: linmarr@mit.edu.

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Droplets



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

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Background. Multiple severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) superspreading events have been reported, suggesting that aerosols play an important role in driving the coronavirus disease 2019 (COVID-19) pandemic. To better understand the role of aerosols in SARS-CoV-2 transmission, we sought to determine viral loads within coarse- and fine-particle aerosols emitted by patients with COVID-19 while breathing, talking, and singing.

Methods. Using a G-II enhanced breath collection, we measured viral loads in coarse- and fine-particle aerosols emitted by 19 patients with COVID-19 during 30 minutes of breathing, 15 minutes of talking, and 15 minutes of singing. We also measured viral loads in aerosols emitted by 19 healthy controls during the same activities.

Results. Thirteen participants (59%) emitted detectable SARS-CoV-2 RNA in their coarse-particle aerosols, including 3 asymptomatic and 1 presymptomatic patient. Viral loads in coarse-particle aerosols were significantly higher in patients with COVID-19 than in healthy controls. Two participants, sampled on the 3rd of illness, accounted for 52% of total SARS-CoV-2 RNA copies emitted by talking and singing. Interestingly, 7 participants emitted detectable SARS-CoV-2 RNA in their fine-particle aerosols while singing. Overall, fine aerosols constituted 85% of the viral load detected in our study.

Conclusions. Patients with COVID-19 emit more SARS-CoV-2 copies than healthy controls, and singing contains more SARS-CoV-2 copies than coarse aerosols and may play a significant role in driving the COVID-19 pandemic. Isolating and sampling remains challenging; whether this can be more easily accomplished for emerging SARS-CoV-2 variants requires further research.

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

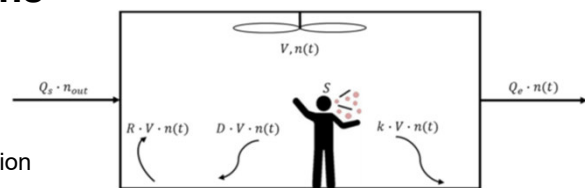
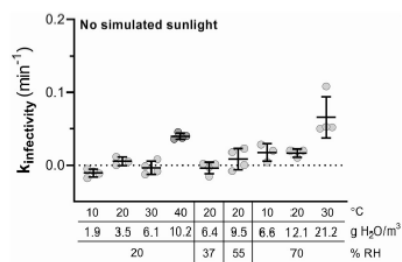
Coronavirus disease 2019 (COVID-19) is caused by the highly transmissible severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Irrespective of symptomatology, patients with COVID-19 can harbor high viral loads of SARS-CoV-2 in their respiratory tracts [1, 2] and emit SARS-CoV-2 RNA into the air [3–6], which may be collectable under favorable circumstances and collection methods [5]. Although virus emissions from talking and singing have not been measured, these respiratory 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 underserved 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

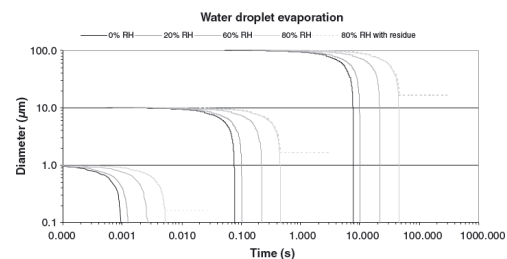
SARS-CoV-2 in Respiratory Aerosols • CID 2020;XX (XXXXX) • 1

Origin of recommendations

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



- Droplet deposition

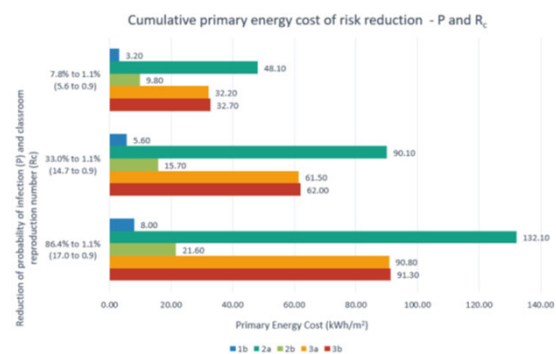
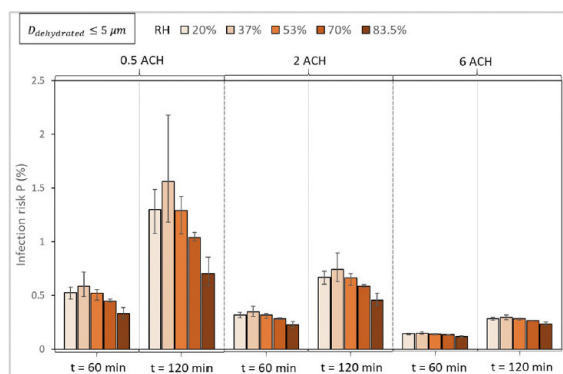


Current recommendations – non-infectious air delivery rate equivalent or outdoor air and CO₂

- Ventilate with outdoor air (5-6 ach)
- Use particle air cleaners with the similar effect
- Keep CO₂ levels below 800 ppm (900 ppm)
- Reduce the length of the lesson (intermittent occupation)
- Nothing in relation to RH/T

	Ideal (6 ACH)
	Excellent (5-6 ACH)
	Good (4-5 ACH)
	Bare minimum (3-4 ACH)
	Low (<3 ACH)

Impact of RH and air cleaning



Questions?



Thank you

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