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

The full report

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Supported by **Realdania**

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Summary

This report summarises published research on how children's performance of schoolwork in primary and secondary schools and their subsequent educational attainments are affected by classroom temperature, air quality, noise, and lighting.

The main conclusions (Items 1-20) are set out below as unequivocal statements that are validated by the findings of the detailed reviews of research published that form the bulk of the report, or by the findings of research published since those reviews were written and in some cases published. Bibliographic references to the original research reports are to be found in each detailed review or in the list that appears below.

To each statement has been added brief comments based on other relevant findings noted in the reviews.

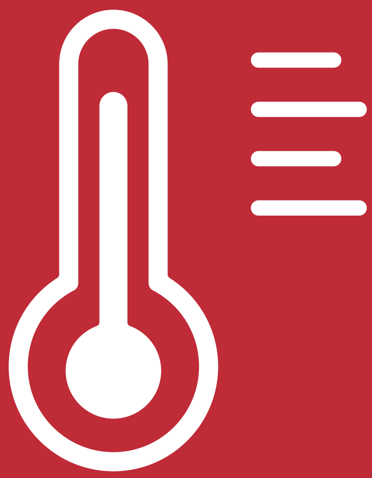
A short list of what is NOT yet known about the effects of each indoor climate factor is then appended (Items 5, 10, 15, and 20), the implications for energy conservation (Items 21-25) and priorities for future research in this area (Items 26-30) are suggested.

This report's summary is provided separately with the current recommendations and requirements of indoor environmental quality conditions in schools.

Four appendixes contain detailed reviews based on which the present report was prepared.

Thermal environment in classrooms

Raised classroom temperatures have progressively negative effects on children (Appendix 1)



Research evidence

1

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 10°K (Wargocki et al., 2019)

Children were shown to perform schoolwork less well at raised temperatures. It was assumed that this would affect how much they learned in school. This was tested in two large independent field studies, one in NY (Park, 2016) and one in CA (Goodman et al., 2018), which found that end-of-year examination results assessing what had been learned over time decreased by 0.4-0.5%, respectively, for each 1°K increase in outdoor temperature (which was assumed to have raised classroom temperatures). This demonstrates that effects on schoolwork performance, however, caused, do predict overall effects on learning.

2

Raised temperatures have twice the negative effect on schoolwork as on office work (Wargocki and Wyon, 2013; 2017)

Although this finding suggests that children are more sensitive than adults to thermal stress, the difference may be due to negative effects of raised temperatures on teachers as well as on children, or to the fact that office workers perform well-practiced tasks for which they have been trained, while all learning is by definition new. Thermal stress affects the ability to concentrate and to think clearly, skills that are universally required in schoolwork and learning, so the performance of all types of schoolwork is affected. Accuracy is affected if speed is imposed, but in free working children consciously or unconsciously attempt to maintain an acceptable level of accuracy by reducing their speed of performing schoolwork. This then becomes the most common thermal effect observed.

3

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 (Wargocki and Wyon, 2017)

This may be because children have a higher basal metabolism and also sit still for shorter periods so that their average metabolic heat production is higher than that of adults. In a field study in which classroom temperature and air quality were manipulated in the range 21-26°C (Wyon & Wargocki, 2008), window-opening behavior increased with each small increase in classroom temperature within this range of temperatures, and although this did not succeed in preventing classroom temperature from increasing it shows that thermal discomfort is clearly perceived and disliked by both children and teachers. It was found that window-opening behavior did not increase in response to poor indoor air quality, although it is generally assumed that it does.

4

In Denmark, the optimum classroom temperature appears to be below 23°C (Wargocki and Wyon, 2007)

No plausible mechanism for the negative effects of moderate heat stress has been proven. The distraction of thermal discomfort has been assumed by many to be a sufficient explanation, but it has very recently been shown that the negative effects of warmth on cognition occur even when reduced clothing insulation has eliminated thermal discomfort (Lan et al. 2020). It is believed that some aspects of the physiological response to heat are responsible for the effect.

Potential future research

5

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 (Appendix 2)

Research evidence

6

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 (Wargocki et al., 2020)

Children were shown to perform tasks typical of schoolwork less well in poor air quality. Because it is emitted at a known rate by every occupant, measured CO_2 levels are often used as a convenient indicator of the outdoor air supply rate. In experiments on adult subjects, pure CO_2 did have negative effects on the performance of a complex management decision simulation performed under time-stress, but no effects of pure CO_2 on children or the performance of tasks resembling schoolwork have ever been shown (Satish et al., 2012; Allen et al., 2016; Fisk et al., 2019). For tasks resembling office work performed by adults, pure CO_2 has been found to have no effect (Zhang et al., 2017).

7

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 (Haverinnen-Shaughnessy et al., 2011; Wargocki et al., 2020)

This demonstrates that the effects of classroom air quality on the performance of schoolwork do predict its effects on examination results, as it was shown under Point 1 above to do in the case of classroom temperature, although for indoor air quality as well the magnitude of the effect is only half as large. There is good experimental evidence that gas-phase pollutants in classroom air, not airborne particles, cause the observed negative effects on cognition (Wargocki et al., 2008; Wargocki and Wyon, 2016). The bioeffluents exhaled and emitted by other occupants and emissions from building and furnishing materials all negatively affect cognition (Wargocki et al., 2000). Neither the active molecules nor the mechanism for their negative effects have been identified, so their removal and dilution by an adequate supply of outdoor air of good quality is currently the only available means of mitigation.

8

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 (Haverinnen-Shaughnessy et al., 2011, Mendell et al., 2016; Wargocki et al., 2020)

This shows that classroom air quality effects on school test and examination results do predict national test results, widely regarded as the most reliable indicator of overall learning. It is logical that negative classroom air quality effects, if any, on teachers, on sickness absence, on pre-existing conditions such as asthma, and motivation may all contribute to this result.

9

Absenteeism is 1.5% higher with a 2 L/s/p outdoor air supply rate than with 7.5 l/s/p (Mendell et al., 2013; Wargocki et al., 2020)

This suggests an increased outdoor air supply rate can reduce cross-infection between children or mitigate pre-existing conditions that cause absenteeism. An increased outdoor air supply rate removes and dilutes airborne pathogens as well as gas-phase air pollutants and other airborne particles (Li et al., 2007), and to the extent that absenteeism is due to children staying home while sick, this must be presumed to be the mechanism for the observed effect on absenteeism. Therefore, to reduce the impact of future pandemics on learning in school, maintaining a high outdoor air supply rate must be viewed as a viable strategy. However, recirculation through filters that remove very fine particles from indoor air may remove some pathogens. Even recirculation through coarser filters will benefit pupils suffering from allergies during the season when pollen is present in classroom air (ASHRAE Guideline, 2020).

Potential future research

10

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 (Shriram et al. 2019), 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.

Classroom noise and acoustic treatment

Classroom noise has progressively negative effects on speech intelligibility (Appendix 3)

Research evidence

11 **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 (Astolfi et al., 2012; Appendix 3)**

Children's understanding of spoken information was found to be reduced when classroom noise was present. The noise that distracts attention, such as traffic and aircraft noise or background speech, can have this effect even at low dB levels, Children's interactions with teachers are to a large extent verbal, but although it is logical that reduced speech intelligibility must affect teaching and therefore learning, the magnitude of the overall effect has not been demonstrated.

12 **Younger children are more affected than older children or adults (Jamieson, 2004; Appendix 3)**

The presence of classroom noise was found to have more negative effects on speech comprehension the younger the children. Older children and adults are at a later stage of learning the language, so they are more able to guess what unintelligible words were intended to convey. Communication then becomes more robust to classroom noise.

13 **Children with hearing or attentional difficulties and children being taught in their second language are more negatively affected (Geffner et al., 1996; Hurting et al., 2016; Appendix 3)**

Children who find it difficult to hear speech, attend to speech, or understand the language of the speaker did less well than others in the presence of classroom noise. Chronic exposure to aircraft noise in school leads over time to reduced reading skills. Aircraft noise is thought to be more disruptive than continuous road traffic noise because it consists of single unpredictable events that not only might interfere with hearing but also might direct attention away from the main task. Several studies have shown that schools should preferably not be built in areas with high environmental noise exposure, so if they must be sited there, appropriate noise insulation should be used to protect classrooms from external noise.

14 **Longer reverberation times exacerbate the negative effects of classroom noise (Klatte et al., 2010; Ljung et al., 2009; Appendix 3).**

The speech comprehension of children was worse the longer the reverberation time of the classroom. Acoustic treatment of classrooms – increasing the area of sound-absorbing surfaces – can easily reduce reverberation times. This is standard practice in lecture rooms and meeting rooms where speech intelligibility is vital. However, the best and cheapest solution would be to somehow reduce the noise level generated by the children themselves because raised levels of classroom noise have been shown to cause damage to teachers' vocal cords, either directly or by obliging them to raise their voice to be heard. One way to do this would be to have noise level monitors in classrooms that can signal when the noise level is too high, just as CO_2 level monitors in classrooms can signal when it is time to open a window. Another approach is the "quiet bell" used by Montessori-trained teachers, which any child can ring to ask for quiet when they personally feel it would help them.

Potential future research

15 **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.

Classroom daylighting, view-out, and artificial lighting

Daylight, a green view-out, and good artificial lighting can improve children’s performance (Appendix 4)

Research evidence

16 Daylight in itself has beneficial effects on children in classrooms (Gentile et al., 2017; Studer et al., 2019; Appendix 4)

A delay was observed in the diurnal rise in the cortisol levels in the morning urine of 88 children aged 8-9 who were experimentally assigned at random to classrooms without windows (Gentile et al., 2017). In a cross-sectional survey of schools, better academic achievement was associated with the presence of daylight in classrooms, and when 28 children aged 11-17 were briefly exposed (for <1 hour) in the morning to either red-enriched lighting (900 lux) or blue-enriched lighting (1000 lux), the blue-enriched light exposure improved attention in two of three tasks, leading to better performance in maths tests and reduced reaction time variability in a computerized attention test (Studer et al., 2019). This supports the traditional belief that being exposed to the (naturally blue-enriched) daylight that enters classrooms through windows may have similar benefits for the performance of schoolwork. The cortisol evidence suggests a plausible mechanism (cortisol is a stress-related hormone that changes seasonally and diurnally and is known to be affected by exposure to daylight).

17 A green view-out has measurably beneficial effects on the performance of schoolwork (Matsuoka, 2010; Appendix 4)

Recognizing that the presence of a" green" view-out (a view onto grass, plants, and trees) in classrooms would be confounded with numerous potentially positive factors in any survey of differences between schools, researchers conducted an experiment in which children were assigned at random to classrooms with and without green views (Li and Sullivan, 2016). Subjects in the green window view-out condition scored significantly higher on tests of attentional functioning (13% higher) and recovered significantly faster from a stressful experience than their peers who were assigned to rooms without views to green spaces. It is worth noting here that a similarly well-conducted experiment demonstrated over 30 years ago that a green view-out reduced the duration of hospital care and the pain medication of post-operative adult patients (Ulrich, 1984).

18 Bright artificial lighting of good quality can improve concentration (Appendix 4)

Classroom lighting intensity was varied in a field intervention experiment in 4 classrooms (Barkmann et al., 2012). The average student in the intervention group made 20.8% fewer errors of omission in a task requiring concentration under the "Concentrate" lighting (>1000 lux) compared with under the "Standard" lighting (300 lux). In an intervention experiment that randomly assigned lighting conditions to 4 comparable classrooms, "Focus" lighting (1000 lux) led to a higher percentage increase in oral reading fluency performance (36%) than was observed with Normal (500 lux) lighting (17%) (Mott et al., 2012). Increasing the level of illumination (lux) and the color temperature of the lighting were both found to influence student gains in reading (Mott et al., 2012, Hviid et al., 2020). Furthermore, in a survey of classroom lighting, variables describing window glare, sun penetration, and lack of visual control were associated with negative performance (Heschong Mahone, 2003).

19 Reading speed is only decreased by extremely dim lighting (Veitch, 1990)

When 100 students aged 17-20 performed a reading task at three levels of illuminance (200, 400, or 600 lux), no influence of illumination level on reading speed could be shown (Veitch, 1990). As it is clearly impossible to read in the dark and there were no negative effects at 200 lux, any negative effects of illuminance on reading speed must therefore take place at illuminance levels below those recommended for classrooms (300 lux).

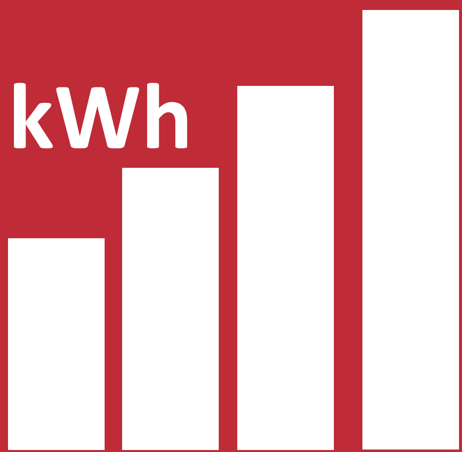
Potential future research

20 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.

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



21 Gains in energy efficiency increase energy consumption (Alcott, 2005)

Formulated in 1865, when it was found that increasing the efficiency of steam engines led to more coal being used, not less as had been confidently expected, the Jevons Paradox states that gains in energy efficiency increase energy consumption (Alcott, 2005). This happens because when the cost of whatever benefit is obtained from energy use becomes less, it becomes economically possible to use more of it. The similar effect is expected in classrooms, which become energy-efficient, leading to a rebound effect. A "rebound" above expected energy use occurs when more efficient airplane engines lead to more air travel, more efficient cars are driven longer distances and efficient LED lighting is left switched on for many more hours.

22 Energy efficiency causes a rebound in energy use

A rebound in the energy used for heating and lighting school classrooms might be expected, similar to what was observed after installing energy-efficient space heating in dwellings in Denmark (Gram-Hanssen & Hansen 2016). This intervention led to higher indoor temperatures that halved the expected gains in energy conservation. Danish householders preferred to wear light summer clothing all year.

23 Thermal convenience used up half the energy that could have been saved

The reason Danish householders preferred to wear light summer clothing all year is that lighter clothing permits a wider range of activity levels without causing people to become too hot or too cold, as noted by Wyon et al. (1975), with no need to adjust clothing insulation.

24 Classrooms should be cool, not warm, to optimize cognitive performance

It has now been shown that cognitive performance decreases at the warmer, more lightly clothed end of the comfort range created by adapting clothing insulation (Lan et al. 2020). Moderately raised temperatures have thus been shown to negatively affect cognitive performance even if thermal neutrality has been achieved by clothing adjustment. The widely held assumption that cognitive performance is unaffected unless there are complaints of thermal discomfort is consequently not true, and keeping the classroom cool, as indicated by the current research evidence, is recommended to optimize cognitive performance (Wargocki et al., 2019).

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

Children learn more and are also comfortable in cool, energy-efficient classrooms (Wargocki et al., 2019; Appendix 1). The rebound in energy use predicted by the Jevons Paradox is therefore unlikely to occur if classroom temperature and lighting are optimized for cognitive performance. Installing energy-efficient space heating and lighting in classrooms will therefore conserve energy without the rebound in energy use seen in the energy used for the space heating of dwellings.

Priorities for future research

26 Reducing risk for cross-infection

In a pandemic, and to reduce absenteeism due to illness generally (Mendell et al., 2013), alternatives to an impractically large increase in classroom air change rates must be found. Improved air distribution systems for classrooms should be developed for this purpose (Melikov, 2020). The relative efficacy of the source control that is achieved by insisting that all occupants must always leave the classroom during breaks, the duration, and timing of such breaks, and other measures such as additional cleaning of surfaces, the operation of free-standing air cleaners, and UV treatment of indoor air must have first priority. These actions will be effective for any communicable disease for which airborne transmission is expected, including Influenza.

27 Physiological mechanisms of air quality effects

Discovering exactly how different airborne pollutants affect gas-exchange in the lungs, how this affects blood-gas levels and thus has negative effects on cognition would provide insights that might revolutionize emission control, air cleaning technology, and ventilation practice (Shririam et al., 2019; Bako-Biro et al., 2005; Wargocki and Wyon, 2016). These potential practical benefits raise the priority of what might otherwise seem to be academic research, as they would identify the pollutants of concern and so make it possible to define a rational indoor air quality metric (Salis et al., 2017).

28 Direct thermal effects on cognition

By including the Adaptive Thermal Comfort (ATC) model as an alternative to rational models of human heat balance, Danish and international standards for thermal comfort are currently assuming that cognition will be optimum if subjective complaints of thermal discomfort are absent. Recent research (Lan et al. 2020) has shown that this is not so – warmth was shown to negatively affect cognition within the comfort zone. Further research to validate or refute this finding is required, as classroom temperatures will otherwise tend to increase over time, and the rebound of energy consumption predicted by the Jevons Paradox will cancel out any gains in energy efficiency.

29 Effects of environmental conditions in classrooms on teachers

Negative effects of raised temperature, poor air quality, and noise have been shown for adults working in offices (Seppanen and Fisk, 2006) and for children attending school (Wargocki and Wyon, 2016), but effects of the quality of classroom environment on teachers working in schools have not been investigated to the same extent. Research on how teachers' health, well-being, and teaching skills are affected by working conditions in classrooms and how this affects children's educational attainments is urgently required.

30 Optimizing the use of resources in classrooms

The building, equipping, heating, ventilating, staffing, and cleaning a country's classrooms incur massive first costs, running costs, and energy costs (Wargocki and Seppannen, 2006). They are justified by the educational attainments of the children who are educated in them (Madsen et al., 2020; Slotsholm, 2012). Research on how to improve the overall cost-benefit ratio by applying the findings set out in the present report would be amply justified. It shall be examined how the different parameters defining various aspects of classroom environmental quality interact and how these interactions affect cognitive performance. So far, the research on this topic has been scarce, especially when interactions of different modalities were examined (Hviid et al., 2020). With some additional assumptions, numerical modeling of how increased investment in thermal, air quality, noise reduction, and lighting improvements in classrooms would be expected to benefit educational attainment is now possible and should be the first step in setting research priorities for addressing the gaps in knowledge identified in this report to validate the assumptions made in the modeling.

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