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The Effects of Thermal Conditions and Indoor Air Quality on Health, Comfort and Cognitive Performance of Students

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About the authors

UCL is ranked fourth in the world's top ten universities by the QS World University Rankings (2012). More than 4,000 academic and research staff at UCL are dedicated to research and teaching of the highest standards. Nobel prizes have been awarded to 21 former academics and graduates. In the last 2008 Research Assessment Exercise (RAE), UCL was rated the best research university in London, and third in the UK overall, for the number of its submissions which were considered of 'world-leading quality'. UCL is one of the most successful UK universities at attracting funding, with an income of nearly £900 million in 2012, when we received: (a) 3^{rd} highest allocation of Research Council UK funding, and (b) 3^{rd} highest allocation of European Research Council Starting Grants. More than 40% of the almost 27,000-strong student community is engaged in graduate studies, with more than a third of these graduate students pursuing research degrees.

The Institute of Education has a reputation as the UK's premier institution for the education and training of teachers and for the conduct of educational and social research. Originally founded in October 1902 as the London Day Training College, in 1987 the award of a Royal Charter confirmed its status as an independent college and school of the University of London. Over the last one hundred years the Institute has seen a broadening of responsibilities, and it is now the largest university centre of education research in the UK – undertaking around a quarter of the education research carried out in UK universities – as well as being one of the largest UK centres of social science – as the second highest recipient of social science research funding among higher education institutions. In any one year, staff at the IOE are engaged in over 250 research projects funded by research councils, charities, government departments and international agencies.

Professor Julie Dockrell

Julie is Professor of Psychology and Special Needs at the Institute of Education, University of London, and a Visiting Professor at the University of Umea in Sweden. She has also acted as an advisor or consultant to the Department for Education, the National Children's Bureau, Open University and the Qualifications and Curriculum Authority, amongst others. She has expertise and an extensive publications record in language development and difficulties; the wider impacts of experiencing a language problem; lexical development and semantic representation; assessment of language and cognition; developmental difficulties; impact of acoustic environments on language and learning; and interventions to enhance oral language skills.

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Dejan is a building scientist with a background in heating, ventilation and air conditioning engineering and the extensive experience of monitoring and modelling work in the field of the built environment. Dejan is a Professor of Building Performance Analysis at the UCL Institute for Environmental Design and Engineering. He is a member of the Education Funding Agency Steering Committees on Building Performance Evaluation and Ventilation Design. Dejan is a co founder and long standing board member of CIBSE School Design Group (5,700 members, 2013). He co-authored and edited DCLG's Ventilation Design in Schools and forthcoming CIBSE's TM on Integrated School Design.

Lia Chatzidiakou

Lia is a doctoral researcher in healthy buildings at the UCL Institute for Environmental Design and Engineering. She has been working on a large EU Commission project School Indoor Pollution and Health: Observatory Network In Europe (SINPHONIE) which aims to improve indoor air quality in schools by establishing indoor air quality benchmarks for schools and assessing effects of indoor air quality on health of primary school children. Lia is a postgraduate teaching assistant on MSc in Environmental Design and Engineering.

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Built Offsite preface

Built Offsite Ltd is an education construction specialist operating across the UK and is very aware of its responsibility to create optimum learning environments for the benefit of the students making use of these new school facilities.

Since its inception Built Offsite has been committed to reducing the energy demand and environmental impact in its design and specification of the school buildings it constructs. As a result of this continued development focus on sustainability the Company routinely provides schools that can achieve a peak heating demands of less than 10 W/m^2 *which is in line with the best Passivhaus standards.*

However the Company has increasingly become aware that the drive towards energy efficiency could be to the detriment of indoor air quality, with consequential negative impacts on learning performance for the school.

Built Offsite has now focussed its R&D efforts towards developing classroom environments that seek to optimise Indoor Air Quality (IAQ) and energy demand to create sustainable school buildings that have a positive impact on learning performance.

Built Offsite believed it was essential to establish if there were clear, unequivocal quantitative links between air quality in the classroom and cognitive performance to support this development objective. With this in mind Built Offsite commissioned the internationally respected authorities in this field, University College London (UCL) and the Institute of Education (IoE), to work together to undertake an independent and systematic review of the published research in this area to determine the evidence base for this link.

Executive summary

The present review evaluates the strength and consistency of current evidence indicating that there is an association between indoor pollutants and thermal conditions in schools on students' performance. Moreover, the report examines evidence that air pollution and thermal conditions may have acute and adverse effects on students' health which can indirectly affect performance, through impaired attendance and discomfort. Current guidelines ensuring adequate IAQ in UK school classrooms have been framed around CO_2 levels, and do not consider specific pollutants, as there is no direct evidence linking exposure to indoor microbial and chemical pollutants in classrooms with reduced performance. Main **findings** include:

1. There is evidence that lower temperatures in the range between 25°C to 20°C improved student performance by 2% to 4% for every 1°C reduction. Whilst the current guidance in BB101 permits classroom temperatures above 25°C there is evidence that maintaining classroom temperatures substantially below these DfE guidelines could have significant benefits both in terms of student performance and well being.

2. Low outdoor air ventilation rates and thus high indoor concentrations of CO_2 impairs attention span and increases concentration loss and tiredness . There is evidence that increasing ventilation rates from 5 L/s-p to 15 L/s-p was associated with a 7% improvement in academic performance. Further there is evidence that cognitive performance may be affected at CO_2 levels as low as 1000 ppm.

3. Higher indoor CO_2 levels have been associated with increased probability of communicable infection, asthmatic symptoms, absenteeism, and impaired academic performance of children. Every decrease of indoor CO_2 levels by 1000 ppm was associated with at least 1.0% to 2.5% relative decrease in illness absence of students.

4. Currently there is no evidence on the effect of VOC levels on cognitive performance of students. Higher levels of Total Volatile Organic Compounds (TVOCs) were associated with Sick Building Syndrome (SBS) symptoms and dissatisfaction with IAQ. Control of indoor sources together with CO_2 levels below 1300 ppm (95%CI[1]: 1200 to 1400 ppm) may result to TVOCs levels below 200 $\mu g/m^3$, that is the lowest threshold for discomfort in some countries. Currently, there are no guidelines on indoor TVOCs concentrations in UK for non-industrial environments.

5. Increased ventilation rates can reduce indoor mould concentrations (an increase of 1 CFU/m^3 of microbial concentrations for every 1 ppm increase in CO_2); however thresholds for mould concentrations are not well defined. Sufficient evidence associates high microbial concentrations with general and respiratory symptoms in children. There were no studies on the effect of biological concentrations on cognitive performance of students.

6. Traffic related pollutants, such as Particulate Matter, ozone and carbon monoxide were linked to increased illness-related absenteeism and asthma incidence. Exposure to nitrogen dioxide was related to asthma incidence and asthma exacerbations. Indoor levels of traffic related pollutants shall be considered separately because low CO_2 levels do not guarantee a healthy environment, although they provide a first indication of exposure.

[1] **Confidence Interval:** for a given statistic calculated for a sample of observations, the confidence interval is a range of values around that statistic that are believed to contain, with a certain probability (eg 95%), the true value of that statistic.

Based on the available evidence, engineering **recommendations** for healthy, comfortable school environments conducive to knowledge have been proposed:

1. Schools should not allow temperatures to drift above the recommended range of 20 to 22 °C in the winter season and 22 to 24 °C in the summer. While current guidelines allow temperatures in the range of 25 °C to 32 °C, evidence suggests that temperatures in this range may impact on cognitive performance and comfort of the students.

2. Overall evidence suggests limiting average indoor CO_2 concentrations in all teaching and learning spaces to an average of 1000 ppm (a minimum fresh air supply rate of 8 L/s-p) during a teaching day, which is below current guidelines.

3. Construction and cleaning materials used in the classrooms should not be used if they impact on IAQ. Materials can be screened based upon both content and actual measured emissions. VOC content refers to the amount of chemicals in the product that are VOCs and, as such, can potentially off gas from the product during installation or use. VOC emissions refer to the gases released by the product during installation or use. With serious debate about the applicability of emissions tests for other chemicals of concern, screening by content is currently the most reliable way to avoid problematic exposures. Project teams should communicate directly with manufacturers' representatives to obtain information about chemicals of concern.

4. Filtration of outdoor air can deal effectively with airborne particles but not with other chemicals while it introduces further challenges (increased running costs, source of contamination if filters are poorly maintained). Location of school buildings should be considered in relation to outdoor pollution sources. More broadly, policy should be directed towards citywide level planning, such as urban greening programmes around school buildings, which are likely to decrease outdoor pollution levels reducing prevalence of respiratory illness. Monitoring of indoor concentrations of chemicals known in respect of their hazardousness to health, should be performed routinely in school buildings. Indoor concentrations shall comply with guidelines of the World Health Organisation, which provide a scientific basis for legally enforceable standards for the indoor environment.

Overall, this report found indicative evidence that CO_2 levels in classrooms lower than those recommended in current guidelines could improve academic performance, health and comfort of the occupants. However, carefully designed studies, controlling for potential confounding factors, are required to extend and elaborate the findings outlined in this report.

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Nomenclature

σ	standard deviation
μm	micrometre
ΔCO_2	indoor minus outdoor CO_2 levels
95%CI	95% **C**onfidence **I**nterval
ASHRAE	**A**merican **S**ociety of **H**eating, **R**efrigeration, and **A**ir-Conditioning **E**ngineers
BB101	**B**uilding **B**ulletin 101
CFU/m^3	**C**olony **F**orming **U**nit per cubic meter of air
CO	Carbon Monoxide
CO_2	Carbon Dioxide
ISAAC	The **I**nternational **S**tudy of **A**sthma and **A**llergies in **C**hildhood
L/s-p	litres per second per person
N_s	Number of schools
N_c	Number of children
NO	Nitrogen Monoxide
NO_2	Nitrogen Dioxide
NV	**N**atural **V**entilation
MM	**M**ixed-**M**ode Ventilation
MV	**M**echanical **V**entilation
O_3	Ozone
OR	**O**dds **R**atio
meta-**OR**	meta-analytic **O**dds **R**atio
PM	**P**articulate **M**atter
$PM_{2.5}$	Airborne particles with a diameter less than or equal to 2.5 μm
PM_{10}	Airborne particles with a diameter less than or equal to 10 μm
PMV	**P**redicted **M**ean **V**ote
PPD	**P**redicted **P**ercentage **D**issatisfied
ppm	**P**arts **P**er **M**illion
RH	**R**elative **H**umidity
SBS	**S**ick **B**uilding **S**yndrome
TVOCs	**T**otal **V**olatile **O**rganic **C**ompounds
VOC	**V**olatile **O**rganic **C**ompound

1 Introduction

School buildings are complex spaces to design as they need to perform well in all aspects of environmental conditions, including, but not limited to, air quality and acoustic levels [1], while needing to accommodate periods with very high occupant densities. The typical classroom has on average four times as many occupants per square metre as the typical office building. According to Eurostat (2011) [2], the average primary class size in European countries and the US was 21 (σ: 2) pupils corresponding to a density ranging from 2 to 3.1 m^2 per person. The high occupancy densities in school classrooms result in high internal heat gains, high carbon dioxide (CO_2) levels, emissions of body odours together with various indoor pollutants (physical, chemical and microbial).

Former meta-analytic reviews [3], [4], [5] offer a comprehensive picture of air quality and thermal conditions in school settings, emphasising that reduced ventilation rates and elevated indoor temperatures in schools are common, frequently much worse than in office buildings [6]. Children are more vulnerable to airborne pollutants than adults because their developing lungs breathe more air compared to the relative size of their bodies, and they have an underdeveloped ability to communicate concerns in response to pollutant levels. Children spend most of their time indoors while at school [2]. School authorities have a particular duty of care for their pupils in ensuring that appropriate conditions in the indoor environment are maintained. In this context, thermal comfort levels and Indoor Air Quality (IAQ) have a crucial role to play in producing an environment that supports optimal educational and health outcomes.

Health symptoms and irritations in indoor environments are reported with different frequency; one group of frequent symptoms has been identified as Sick Building Syndrome (SBS). Presently, it is not clear if SBS consists of symptoms correlated to an exposure or reflects an accumulation of effects of several unrelated indoor exposures.

The UK has one of the highest prevalence rates of childhood asthma among European countries, with almost 10% of children (1.1 million) suffering from symptoms [7]. In many countries a significant increase in asthma hospital admissions among asthmatic children peak in September, and coincide closely with their return to the school environment [8], [9], [10]. These studies indicate that a sub-population of school-aged children with asthma receive challenges when returning back to school that trigger their asthma, such as viral infections and exposure to allergens. Rising respiratory disease has led to an increasing research focus on IAQ in schools and the need for worldwide epidemiological campaigns, such as the International Study of Asthma and Allergies in Childhood (ISAAC) involving more than 100 countries and nearly 2 million children [11].

While other variables, such as socio-economic factors, diet, special educational needs and pedagogy, affect health and educational outcomes [12], the present review evaluates the strength and consistency of current evidence that indoor pollutants and thermal conditions in schools may influence students' performance or attendance. Additionally, this review briefly presents evidence that school exposure may have health and comfort implications on school occupants, which may impair performance indirectly. For example, exposure to indoor pollutants may exacerbate diseases, such as asthma, resulting in health symptoms or absenteeism that in turn impairs performance indirectly through effects on attendance.

2 Regulatory framework and empirical evidence on indoor levels in school settings

This section presents current regulatory frameworks developed to ensure acceptable thermal conditions and adequate IAQ in educational settings and other non-industrial environments. Moreover, current evidence on thermal conditions and indoor pollution levels in classrooms is summarised.

2.1 Thermal conditions

There has been an extensive research on thermal comfort over several decades, which has led to two main approaches, the thermo-physiological and the adaptive comfort approach. Both approaches form the basis for existing thermal comfort standards, which include ISO 7730 [13], ASHRAE Standard 55 [14], and at the European level EN 15251 [15]. The thermo-physiological model was developed by Fanger [16] based on extensive American and European experiments which involved over 1000 subjects exposed to well-controlled environments. The model equation developed is presented in ISO 7730, and can be used to calculate Predicted Mean Vote (PMV). This predicted thermal sensation can be transferred to the predicted thermal comfort in the form of Predicted Percentage Dissatisfied (PPD), which is the predicted percentage of people in a large group that will be dissatisfied at a PMV value. The calculation of PMV takes into account the thermo-physiological properties of humans and their balance with the environment. On a personal level this includes the activity level and clothing insulation. The thermal environment is determined by the variables air temperature, mean radiant temperature, relative humidity and air velocity. The recommended temperature range lies between 20 °C ± 1 to 24.5 °C ± 2.5 depending on season.

Latest versions of the standards ASHRAE 55 2010 [14], ISO 7730 [13] and EN 15251 [15] include also an adaptive thermal comfort diagram in the evaluation of thermal comfort of a not fully conditioned indoor environment allowing for a wider band of temperatures and corresponding energy savings. The required operative temperature is estimated as a function of a weighted running mean of the exterior temperature. Adaptive models have been developed through fieldwork and state that thermal preferences depend on the way people interact with their environment, modifying their own behaviour and adapting their expectations to match the thermal environment.

Based on the above standards [14], [13], [15], the UK Building Bulletin 101 (BB101) recommendation focuses on preventing overheating in the non-heating season [17]. More specifically, BB101 recommends that air temperature in UK classrooms during the occupied period of the non-heating season, should not exceed 32 °C and there should be no more than 120 hours when the air temperature in the classroom rises above 28 °C . Moreover, the average internal to external temperature difference should not exceed 5 °C . The revised BB101 performance criteria [18] suggests that when the external air temperature is 22 °C, or higher, the internal operative temperature should not exceed the external air temperature by more than 3 °C. Regarding the heating season, regulatory framework focuses on minimum indoor temperatures in the workplace of 16 °C [19].

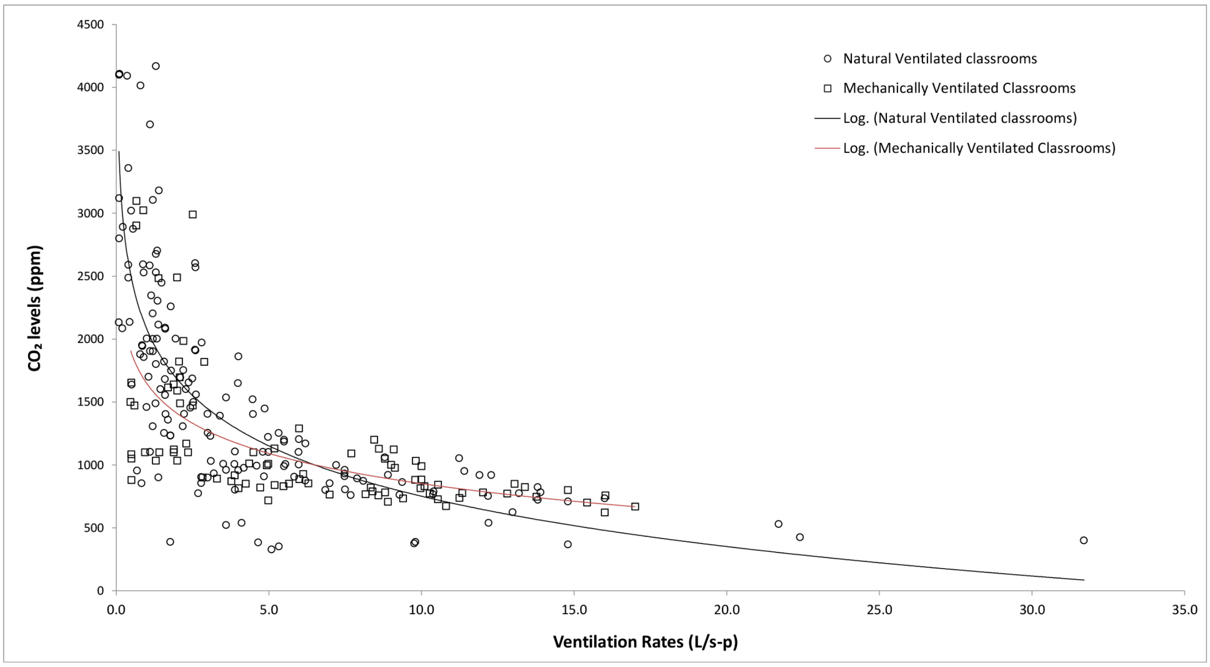

Figure 1: Correlation between indoor CO_2 levels and ventilation rates in naturally and mechanically ventilated classrooms synthesised in a meta-analytic study [3]

2.2 Ventilation rates and CO_2 levels

Ventilation is the process of exchanging indoor polluted air with outdoor (presumably) fresh and clean air. Indoor CO_2 levels produced by metabolic breathing of the occupants are a reliable indicator of ventilation rates, as increased outdoor airflow dilutes indoor concentrations (Figure 1). CO_2 levels and corresponding ventilation rates are therefore a good indicator of pollutants with indoor sources (such as bio-effluents); however they are poor indicators of traffic related pollutants. The relationship between CO_2 levels and ventilation rates is described by an exponential curve (Figure 1). The large number of studies clustered in Figure 1 towards the lower end of the range of ventilation rates suggests that low ventilation rates, and high CO_2 levels in schools are common.

In North America and some other countries minimum ventilation rates are regulated by ASHRAE 62.1-2010 [20] and are dependent on strength of indoor pollution sources and occupancy. In the UK, BB101 [17] and the updated version "Facilities Output Specification for School Buildings" [18] provide guidelines on maximum CO_2 levels and minimum ventilation rates to ensure adequate IAQ in classrooms. The recommended ventilation performance standards for naturally ventilated classrooms can be summarised as follows:

- Average indoor CO_2 levels during a typical teaching day shall not exceed 1500 ppm, and average ventilation rates shall be above 5 L/s-p.

- At any occupied time the occupants should be able to reduce the concentration of CO_2 to 1000 ppm, and ventilation rates above 8 L/s-p shall be easily achieved by the occupants.

- Minimum ventilation rates shall not fall below 3 L/s-p. According to BB101 [17], maximum CO_2 concentration levels during a typical teaching day, should not exceed 5000 ppm, while the revised version [18] sets stricter limits and requires that CO_2 levels shall not exceed 2000 ppm for more than 20 minutes at a time.

2.3 Guideline values for indoor pollutants

Building regulatory frameworks for the provision of adequate IAQ has been framed around CO_2 levels and corresponding ventilation rates rather than specific pollutants (see previous section). WHO guidelines provide a scientific basis for legally enforceable standards [21],[22]. Guidelines focus on chemicals that are often found indoors in concentrations of health concern. WHO 2006 and 2010 guideline values of the traffic-related pollutants investigated in this review, are presented in Table 1.

Table 1: WHO guidelines [21],[22] of maximum acceptable levels of indoor pollutants

Pollutant	**Units**	**Short-term Exposure**	**Annual Average Exposure**
$PM_{2.5}$	($\mu g/m^3$)	25 (24-h mean)	10
PM_{10}	($\mu g/m^3$)	50 (24-h mean)	20
NO_2	($\mu g/m^3$)	200 (1-h mean)	40
O_3	($\mu g/m^3$)	100 (8-h mean)	
CO	(mg/m^3)	100 (15 minutes)	
		35 (1-h)	
		10 (8-h)	
		7 (24-h)	

A recent meta-analytic study on indoor concentrations of pollutants in school settings [3] found that concentrations often exceeded recommended guidelines. Daily mean concentrations of PM_{10} in European classrooms ranged from 43 to 169 $\mu g/m^3$, median daily concentration of $PM_{2.5}$ was 20 $\mu g/m^3$ and indoor NO_2 levels ranged from 8.3 to 77 $\mu g/mm^3$. NO_2 is often adopted in epidemiological studies as an indicator of traffic intensity as it is primarily produced by motor-vehicle emissions and depends on proximity to pollution sources. Children attending schools in proximity to streets with high traffic intensity were exposed to three to four-fold higher nitrogen dioxide levels compared with children attending urban background schools. Indoor O_3 levels in six European countries in 46 classrooms in 21 schools were on average 10.4 $\mu g/m^3$ (range of median values: 3.0-15.1 $\mu g/m^3$).

Indoor environments with high occupancy density, such as schools, have high indoor microbial concentrations [23]. Environmental factors, such as water leakage, age of the building and construction materials may affect indoor microbial concentrations. Interior finishing in the classroom, such as furnishings and textiles, may act as significant reservoirs of irritants and allergens, that impact on the school IAQ [24], [25], [26], [27]. Upholstery seats [28] and wall-to wall carpet significantly increased fungi and allergen concentrations [29]. Allergen concentrations were 10-fold higher in carpeted classrooms compared with hard floor [26]. Additionally, indoor parameters such as temperature, relative humidity (RH) and ventilation rates may affect microbial growth. Lower total and viable bacteria, moulds and air allergens were measured in classrooms with lower temperature, CO_2 levels and humidity [30]. More specifically, CO_2 levels in heavily occupied schools have been found to correlate with the levels of airborne bacterial markers, with an increase of 1 ppm in CO_2 levels corresponding to an increase of 1 CFU/m^3 in airborne fungi [31], [32]. Due to the complexity of the fungal exposure assessment, there is a lack of clearly defined threshold levels for fungi and substances derived from fungi [24].

Volatile Organic Compounds (VOCs) in schools originate from a combination of emissions from indoor building materials, human activities and outdoor sources. Suspected emission sources in school classrooms include cleaning products, paints, teaching materials, interior finishing and furniture introduced in the classroom. Specific VOCs have been related to carcinogenicity in humans (such as benzene) and WHO 2010 sets limits of exposure

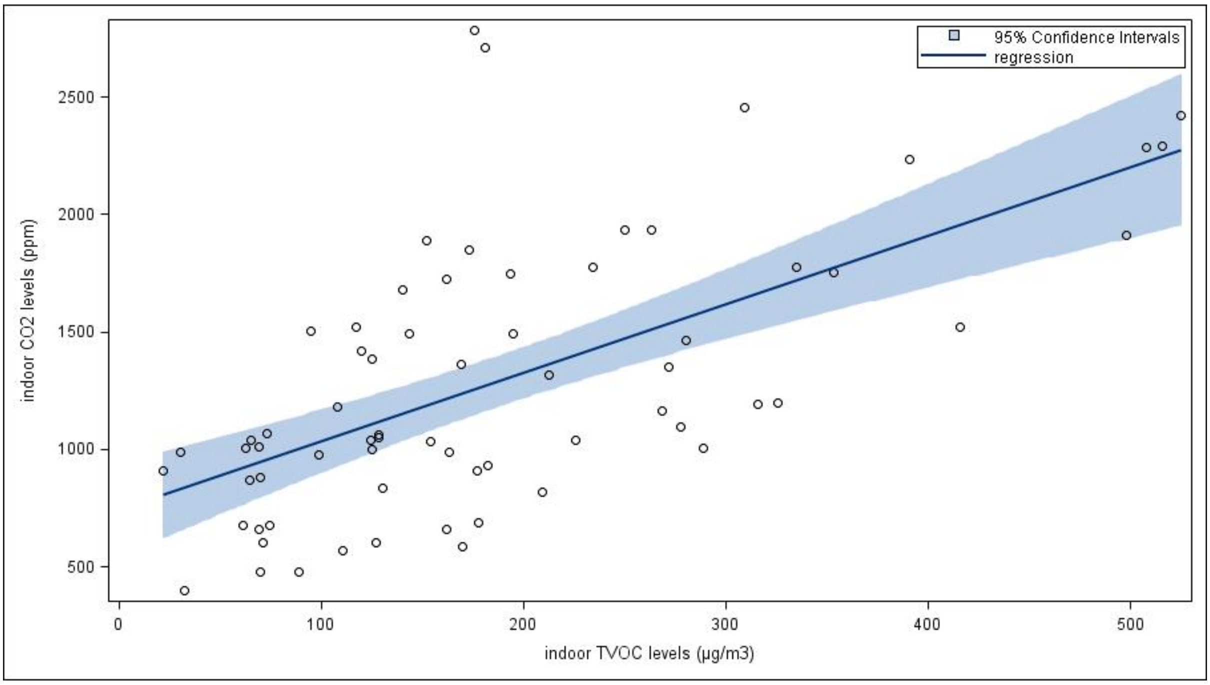

Figure 2: Moderate relationship between CO_2 concentrations and TVOCs in 132 classrooms in published literature [3]

in relation to health risk. However as it is possible to detect more than 50 different compounds indoors, each at a low concentration but higher than outdoors, the concept of Total VOCs (TVOCs) has been introduced in existing literature [33]. Although in the UK there are no guidelines for TVOCs, in some countries, thresholds for TVOCs in indoor non-industrial environments have been developed and most of them are in the magnitude of 200 to 600 μg/m3 [34]. A moderate relationship between mean indoor CO_2 levels and mean TVOCs concentrations was detected in a meta-analytic study [3] of school classrooms (Figure 2). Concentrations may vary significantly between different settings depending on the strength of emission sources. However, mean indoor TVOCs concentrations of 200 $\mu g/m^3$, which is the lowest threshold value of discomfort in some countries [34], occurred when indoor CO_2 levels were around 1300 ppm (95% CI: 1200-1400 ppm). The efficiency of ventilation in reducing VOC concentrations was stronger for VOCs with indoor sources, specifically limonene and pinene [29].

3 Methodology

3.1 Aims

This report deals solely with the effects of IAQ and thermal conditions in school settings, and explores the relationship with academic performance, comfort and attendance in children aged 6 to 16 years old attending schools.

3.2 Search strategy

Four conceptual themes were developed: environmental factors, environment, human outcomes, and publication, each using a variety of search terms (Table 2). Search-terms were developed using combinations of controlled vocabulary and free-text terms. Only papers with title, keywords or abstracts including records in each of the four search categories were selected.

The term Indoor Environmental Quality (IEQ) refers to Indoor Air Quality (IAQ) (including biological, chemical and particulate pollutants), thermal conditions (temperature, relative humidity, air movement), as well as noise and light. The environmental factors of primary interest considered in this review are two measured IEQ factors: IAQ and thermal conditions. IAQ was further analysed in two specific terms: ventilation and indoor pollutants (Table 2).

IEQ plays an important role for human health, comfort and performance. Health, comfort and performance can be influenced by physiological, behavioural and psychological factors, while performance can additionally be influenced by the individual (skills, gender, circadian cycle, emotional state) and social variables. The human outcomes of primary interest in this review are performance, absenteeism and health, and comfort. Performance is related to the ability of an individual to undertake different mentally and physically demanding tasks. Cognitive assessment in relation to school exposure is normally evaluated with standardised tests which can be pen-and-paper or computer based tests. Research focusing on the relationship between IEQ and performance considers two distinct aspects of human performance; accuracy and speed. This review does not consider current debates about the proper measurement of academic performance, but considers educational achievement tests and neurobehavioral performance tests to be relatively objective metrics of learning or performance that, whatever their limitations, are more accurate than subjective assessments of performance.

Absenteeism is the degree to which pupils are absent from school. Some studies separate illness related from non-illness related absenteeism. Because absence from schools may be related to respiratory infections, asthma, allergies, gastrointestinal infections, or other disease, it can serve as an indicator of health effects sufficiently severe to require staying home from school. Absenteeism can reasonably be considered to have an impact upon educational attainment. Reduced attendance may impair learning by decreasing class time for teaching and learning. Finally, the review collected evidence on factors that may affect school occupants' comfort in relation to thermal conditions and IAQ. Thermal comfort is depended on hydrothermal conditions of the environment, as well as personal factors such as activity levels and cloth insulation. Sensory irritations and perceived IAQ may provide a first indication of exposure, and affect health and comfort of the occupants.

This review used electronic databases of scientific publications available up to September 2013, including Medline/PubMed, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), ScienceDirect, Scopus and SpringerLink. In addition, a manual search was conducted for selected publications in the journal *Indoor Air* (over the past 10 years).

3.3 Inclusion and exclusion criteria

Based on the above, inclusion and exclusion criteria were applied in the titles, keywords and abstracts, before obtaining full reports of the studies that appeared to meet the criteria. Inclusion criteria were as follows:

- Includes children between 6 years old (the youngest age for national educational tests in England), and 16 years old (the statutory school-leaving age in England).
- Reports a measure of health outcome, including asthma and allergy; respiratory infections such as colds,

lower or upper respiratory symptoms; and neurological symptoms such as headache, fatigue, or difficulty concentrating. Health effects are generally assessed with medical tests or standardised questionnaires of self-reported symptoms with validity similar to medical interviews.

- Reports a measure of academic performance.
- Reports on perceived IAQ.
- Reports on thermal comfort in educational settings.
- Reports on ventilation in school classrooms, including ventilation strategies (eg natural ventilation, mixed mode etc).
- Reports that provide empirical evidence on levels of specific pollutants in school settings regardless of the method of quantification.
- Reports on traffic-related pollutants; Nitrogen Dioxide (NO_2), Particulate Matter (PM) with aerodynamic diameter less than 10 μm (PM_{10}), less than 2.5 μm ($PM_{2.5}$) and less than 1μm (PM_1).
- Reports on pollutants with indoor sources: Volatile Organic Compounds (VOCs).
- Published between 2000 and 2013, as evidence before 2000 has already been summarised in previous meta-analytic studies [4], [5]. In some cases older references were included as necessary background scientific knowledge.
- Reports the findings of a primary research study or secondary analysis.
- Published in English.

Moreover, findings of this report were compared with findings from other meta-analytic studies on IAQ, ventilation, health and student performance. As already stated, the review primarily focuses on children in school environments, as other environments accommodating adults may differ significantly in terms of the tasks, motivation, and aspects of the built environment. However, when evidence was inconclusive (assuming that children are at least as sensitive as adults to environmental exposures) findings of this review were compared with meta-analytic studies of adult office workers. Particularly strong design studies on adults in controlled laboratory environments were also included as there are no laboratory experiments with children. Exclusion criteria were as follows:

- Studies by same author that repeat results (the most recent were selected).
- Studies with weak design, such as case studies (small sample) and uncontrolled interventions.
- Papers that were included in previous meta-analytic studies included in the review.

3.4 Classification and quality assessment of studies

Figure 3 outlines the flow of the review process and number of articles involved in this review. Two of the authors independently reviewed titles and abstracts for relevance, and assessed which were not related to the scope of this study. Relevant papers were then included for full text review (total = 226 articles), and were tested against the eligibility criteria presented in section 3.3. Reviewers were not blind to the name of the authors, institutions, journal of publication, and results when applying the eligibility criteria.

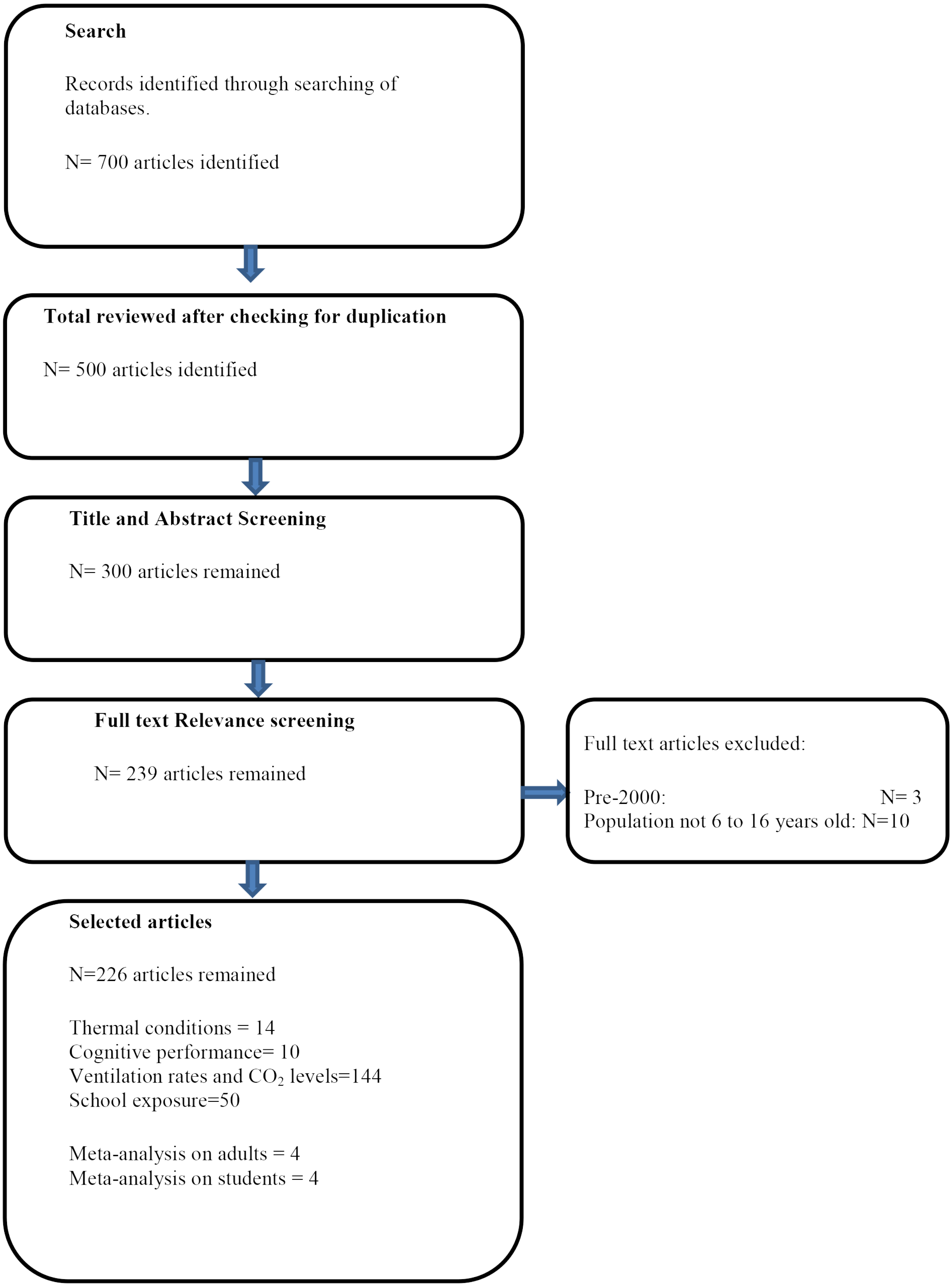

Figure 3: Flow diagram of study selection

Table 2: Keywords used

Conceptual themes	Specific themes	N of search terms	Search terms
Environmental factors	thermal conditions	8	temperature, Relative Humidity, air movement, draught, air temperature, mean radiant temperature, relative air velocity, water vapour pressure.
	ventilation	9	air change rate, air supply rate, carbon dioxide, natural ventilation, mechanical ventilation, cross ventilation, single-sided ventilation, mixed mode ventilation, ventilation rates
	Air quality	17	Particulate Matter, PM_1, $PM_{2.5}$, PM_{10}, respirable fraction, thoracic fraction, fine particles, ultra-fine particles, Volatile Organic Compounds, formaldehyde, pinene, limonene, nitrogen dioxide, ozone, dog allergen, cat allergen, moulds
Environment		3	Schools, classrooms, educational setting
Human outcomes	health	19	Symptoms, diseases, asthma Wheeze, allergy, sensitisation, nasal patency, nasal obstruction, headache, fatigue, tiredness, malaise, cold, flu, influenza, Sick Building Syndrome, mucosal, dermal, ocular
	Attainment	3	Absenteeism, school attendance, illness-related absenteeism
	Academic performance	6	Cognitive performance, learning, productivity, attention, speed, accuracy.
	Comfort	9	perceived air quality, subjective air quality, odour, olfactory irritations, olf, sensory irritations, bio-effluents, thermal comfort, clo-value
Publication		3	journal article, journal apper, ASHRAE Transactions

The methodological quality of the studies was assessed based on population size, study design, air pollutant exposure measurement, contact time determination methods, doctor diagnosed current asthma, confounding factors, controls used and statistical methods utilised. Quality of reporting was evaluated by using the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement checklist for cohort, case-control, and cross sectional studies, version 4 [35]. Quality appraisal of all the studies were performed by one reviewer independently and these appraisals were amended or confirmed in consultation with another reviewer.

3.5 Data extraction and synthesis of evidence

Full text relevant studies were coded accordingly to address the topic focus of the review: study type (e.g. primary research, meta-analysis), the focus of the study (e.g. health outcomes, cognitive performance), the country in which the research was conducted and the study population (e.g. age group). Two of the authors independently extracted data from each article on:

- population (age of participants and sample size),
- variables used in analysis,
- outcome measures,
- associations proposed by the study.

Numerical data available in scientific evidence were used to create a quantitative database. Linear regression models with Confidence Intervals (CI) and prediction limits were produced in SAS 9.3. All reported data points were included regardless of the level of statistical significance, which was more than $p<0.05$ in all studies.[2]

4 The effect of temperature on health, cognitive performance and comfort

Nine studies on thermal comfort in school settings were found (Table 3). Four studies were identified which provided evidence of the association between temperature and health (N=2), cognitive performance (N=2) or

[2] In statistical significance testing, the p-value is the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true. A researcher will often "reject the null hypothesis" when the p-value turns out to be less than a certain significance level, often 0.05, 0.01 or 0.001. Such a result indicates that the observed result would be highly unlikely under the null hypothesis.

perceptions of IAQ (N=2). Details of these studies can be found in Table 4.

Most field studies in school classrooms on thermal comfort of children were performed in warm climates [36], [37], [38], [39] in children older than 13 years old (Table 3). In the UK, only one study in secondary [40] and one in primary schools [41] investigated thermal conditions in classrooms and thermal preferences of school-aged children. Mumovic et al (2009) reported a tendency for winter overheating with temperatures as high as 28.9 °C. The most common reason for such high temperatures was that classroom ventilation rates were too low to mitigate overheating caused by high internal heat gains and solar radiation. Suggestive consistent evidence indicates that children 9 to 11 years attending schools in temperate climates [42], [41] may be more sensitive to higher temperatures than adults. When the actual thermal sensation votes of children were compared to comfort predictions and adaptive temperature limits, lower temperatures than predicted by these methods were preferred [42], [41]. More specifically, comfort temperatures were found 4 °C lower than the Predicted Mean Vote (PMV) and 2 °C than the EN 15251 adaptive comfort model predictions [41] in the current regulations (section 2.1).

Table 3: Thermal comfort studies in school settings

Study	Age Group	Country	Climate	Ventilation Type
Wong and Khoo, 2003 [36]	13 to 17	Singapore	Tropical	NV
Kwok and Chun, 2003 [37]	13 to 17	Japan	Sub-tropical	NV, MV
Hwang et al, 2006 [38]	11 to 17	Taiwan	Sub-tropical	NV
Liang et al, 2012 [39]	12 to 17	Taiwan	Sub-tropical	NV
Corgnati et al, 2007 [43]	12 to 23	Italy	Mediterranean	NV
Corgnati et al, 2009 [44]	12 to 23	Italy	Mediterranean	NV
Mors et al, 2011 [42]	9 to 11	Netherlands	Temperate	NV
Teli et al, 2012 [41]	9 to 11	UK	Temperate	NV
Mumovic et al, 2009 [40]	12 to 16	UK	Temperate	NV, MM, MV

NV: Natural Ventilation, MV: Mechanical Ventilation, MM: Mixed-mode Ventilation.

Generally, current evidence on the association between thermal conditions and cognitive performance of students is limited. In the previous section there was evidence that overheating in classrooms is very common even in the heating season in mild climates, therefore both studies [6] and [45] on thermal conditions and cognitive performance focused on slightly warm/ warm thermal sensations. The experimental design of both studies was cross-sectional where participants were blind to the interventions. The experiments were performed in two classrooms in a school for a week, and then switched conditions between classrooms. Therefore, children were used as their own controls, so any observed differences in performance between conditions cannot have been due to differences between groups of individuals. Temperature was controlled though mechanical cooling either operating or idling the cooling function. The air-circulation fans were operated regardless of the provision of cooling, so participating teachers and children were blind to interventions. During the experiments, the teachers and pupils were allowed to open the windows and doors as usual, and no changes to the lesson plan or school activities were made, so as to ensure that the teaching environment and daily routines remained as normal as possible. Both studies controlled for personal factors that may affect cognitive performance (such as mood, health, level of hunger, quality of sleep during the previous night), comfort, $PM_{2.5}$ levels and noise levels.

Table 4: Summary of the studies [6], [45], [46], [47] assessing the effect of temperature on academic performance indicators, health and comfort of children in school settings

Study	Population	Country	Design	Outcome measure	Authors' findings
Cognitive performance					
Wargocki and Wyon, 2013 [6]	Meta-analysis study from seven intervention studies Ns=5 primary schools Nc= 380, Age: 10-12	Denmark	Cross-sectional blind intervention study	Performance in school associated tasks including language and mathematical skills	For every 1 °C reduction academic performance in terms of speed was improved by 2 to 4 %. No improvement in terms of accuracy.
Bako Biro et al, 2012 [45]	Ns=8 primary schools Nc=332, Age: 9-10	England	Cross-sectional blind intervention study	Computer-based software - VISCoPe (Ventilation in Schools and Cognitive Performance)	Cognitive performance of pupils improved by 6% to 8% when lowering the temperature from 25.3 °C (σ:0.4) to 23.1 °C (σ: 0.8) in terms of speed.
Health outcomes					
Zhang et al, 2011 [46]	Ns=10 secondary schools Nc=1143, Age:11-15	China	Longitudinal study Simultaneously controlling for a large number of indoor pollutants	SBS	T, RH and CO_2 levels were negatively related with SBS symptom.
Mi et al, 2006 [47]	Ns=10 secondary schools Nc=1414, Age:13-14	China	Simultaneously controlling for a large number of indoor pollutants	Asthma, asthmatic and respiratory symptoms	Lower temperatures were associated with reduced breathlessness.

Ns= number of schools, Nc= number of children

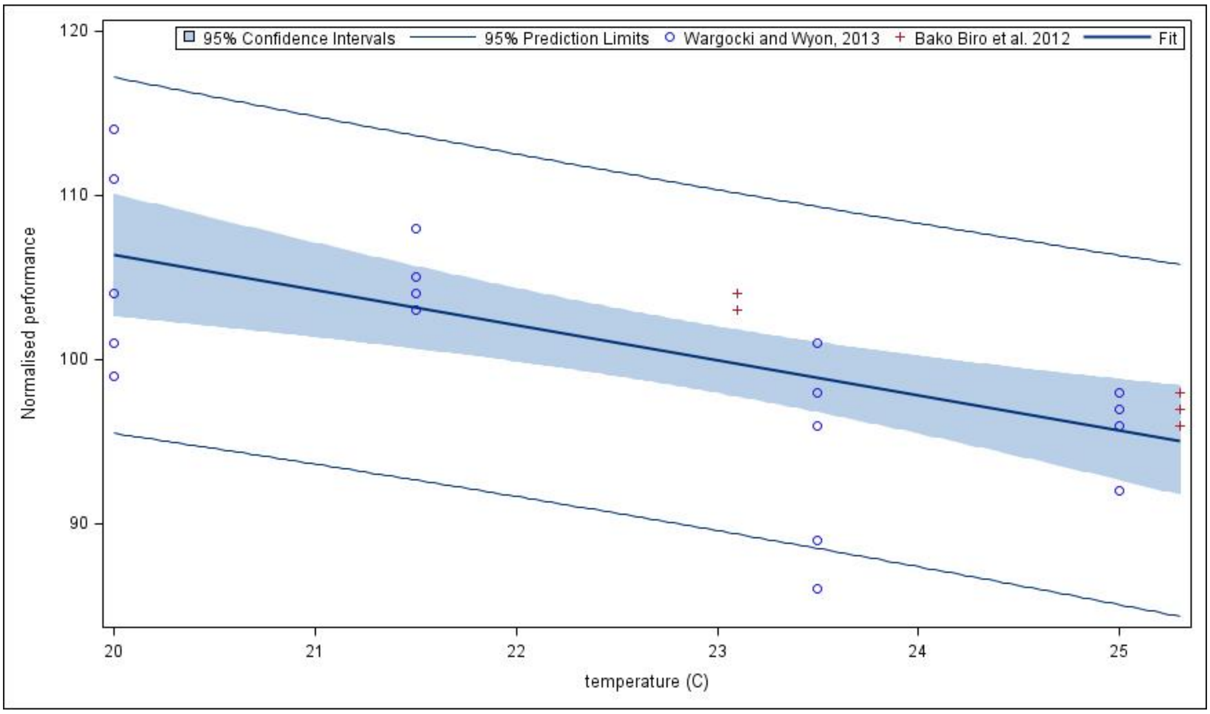

Figure 4: Normalised performance as a function of classroom temperature. Graph synthesised from two peer-reviewed publications [6], [45].

Studies [6] and [45] employed a relatively large sample, and had a robust experimental design as they were organised as cross-sectional blind interventions. The meta-analytic study [6] summarized evidence of a major series of independent field intervention experiments by the authors using a relatively large sample of N=380 students (age 10-12) attending five mechanically ventilated primary schools (Table 4). The temperatures achieved in the classrooms were dependent on the outdoor conditions, but were always lower during the intervention study. The study focused on temperatures in the range between 25 °C to 20 °C. Temperature difference between the warmer reference condition (control) and cooling condition (intervention) was no more than 3.6 °C. Bako Biro et al (2012) [45] investigated the effect of temperature on cognitive performance in the range from 25-23 °C. Performance tests represented different aspects of school work including language-based and numerical tests. Bako Biro et al (2012) [45] used computer-based tests, while study [6] used pen-and-paper tests. In both studies tests were performed on the same weekday during the intervention week and control week during the appropriate lesson. In total students were asked to compete eight different tasks, which were explained to them by performing examples with their teachers.

As already stated, cognitive performance evaluations focus mainly on two aspects of human performance: speed (how quickly each pupil worked per unit time) and accuracy (expressed as a percentage of possible errors). The five studies included in meta-analytic study [6] aimed to examine empirical dose-response relationship between the performance of schoolwork and classroom temperature, and suggested that for every 1 °C reduction academic performance in terms of speed was improved by 2 to 4%. A similar relationship was noticed in study [45] in English primary schools. The analysis of cognitive performance of pupils suggested an improvement by about 6% to 8% when lowering the temperature from 25.3 °C (σ: 0.4) to 23.1 °C (σ: 0.8).

A linear regression model was fitted to synthesise (Figure 4) evidence extracted from the intervention studies [6], [45]. Overall, synthesised relationship shows that an improvement of 11.0% (95% CI: 10.0% to 11.2%) in cognitive performance may be expected when temperature drops from 25 °C to 20 °C.

Little evidence is available regarding health symptoms of students in relation to classroom thermal conditions (Table 4). One study found a suggestive relationship that temperatures at the lower end of the comfortable range may improve health, cognitive performance and perception of school children [47]. Average indoor temperatures recorded were 17 °C (range: 13–21 °C) and concluded that lower temperatures had a protective effect on health by reducing breathlessness among students. Suggestive evidence indicates that lowering the temperature from 25 to 20 °C reduced SBS symptoms among students [46].

5 The effect of ventilation rates and CO_2 levels on health, cognitive performance and perceived IAQ

In line with current guidelines, the majority of studies have focused on CO_2 measurements as an indicator of IAQ (Figure 2) reflecting the relative difficulty and expense of obtaining measurements of specific pollutants and identifying any related effects on performance. In total there were six studies found that investigated the effects of CO_2 and corresponding ventilation rates on cognitive performance of children, and a summary is presented in Table 5. All studies were performed in primary schools in children from 9 to 12 years old, and three of them were conducted in UK schools. Two studies investigated the effect of ventilation rates and CO_2 levels on absenteeism of school children. Four studies associated the impact of reduced ventilation rates on specific health symptoms.

Three studies [6], [45], [48] employed experimental designs with a relatively large sample, as they were organised as cross-sectional blind interventions as described in section 4. Similarly to interventions controlling indoor temperatures in the classrooms, the blind interventions were performed by modifying ventilation rates. Findings of these studies were consistent reporting improvement in cognitive performance. More specifically, increasing the ventilation rate in classrooms improved the performance in pen-and paper school tasks that required mathematical skills [45]. The effect was evident for tasks that required more complex skills (such as spatial working memory and verbal ability to recognize words and non-words), and improved the results obtained in a range of computer-based psychological diagnostic tests [39]. Higher ventilation rates were found to improve performance by 8% in terms of speed, but not in percentage of errors [6]. One study in the UK [49] used a similar experimental design with cross-sectional intervention studies; however the sample was smaller and the interventions were not blind, as higher ventilation rates were provided with natural ventilation strategies. The results were consistent with study [6] as the study also reported in improvement in terms of speed by 5% but not accuracy.

Two studies that used a large sample of schools [50], [51] compared the performance of students in national tests attending classrooms with varying CO_2 levels and ventilation rates. The studies controlled for various socio-economic factors that may affect performance of children and compared national test scores. These studies showed that in classrooms with high ventilation rates, as indicated by a lower concentration of CO_2, a higher proportion of pupils passed the standard language and mathematical tests that were routinely applied by educational authorities. The relationship was significant for mathematical tasks [50], [51] which was consistent with previous findings [45].

Table 5: Summary of the studies [6], [45], [48], [51], [50], [49] assessing the effect of ventilation on performance indicators of children in school settings

Study	Setting	Country	Ventilation rates (L/s-p)	CO_2 concentrations (ppm)	Design	Outcome measures	authors' findings
Wargocki and Wyon, 2013 [6]	Ns =5 primary schools, Nc=380, age:10-12	Denmark	3.0 to 9.5		Cross-sectional blind intervention studies (2 weeks)	Numerical and language based tests	Improve Speed: 8% No effect on accuracy.
Bako Biro et al, 2012 [45]	Ns=8, primary school	UK	Control: 0.6-4.1 Intervention: 5.1-9.6	Control: 5000 Intervention: 1000	Cross-sectional blind interventions.	Computerised assessment tests software (VISCOPE –	Choice reaction:2.2%, Colour Word Vigilance: 2.7%,
	Nc=332, age 9-10				Controlled for comfort, personal factors, airborne particles ($PM_{2.5}$) and noise levels. (3 weeks)	Ventilation in Schools and Cognitive Performance) Traditional tests were carried out on paper for 40 minutes maths and reading	Picture Memory:8%, Word Recognition:15%
Bako Biro et al, 2007 [48]	Ns=8 primary school	UK	Control:0.3-0.5 Intervention :13-16	No data	Cross-sectional blind interventions.	Computerised assessment tests software (VISCOPE –	Increased pupils' speed 7% in maths (addition, subtraction). No significant effect on accuracy
	Age= 9-10				Controlled for comfort, personal factors, airborne particles ($PM_{2.5}$) and noise levels.	Ventilation in Schools and Cognitive Performance) Traditional tests were carried out on paper for 40 minutes maths and reading	
Shaughnessy et al, 2011 [51]	Ns=100 primary school	US	0.9–7.1	Mean: 1779 (σ:852) (range: 661 -6000)	Restricted windows and doors. Monitoring CO_2 over a typical teaching day. Control for socio-economic factors.	Standardised national tests in math and reading;	For every 1 L/s-p an improvement in maths by: 2.9% (95% CI: 0.9–4.8%) and
	Age: 9-10				Compared students' performance with performance standards established by the State Board of Education.	Obtained standardized test scores and background data related to students in the specific classrooms	reading: 2.7% (95% CI: 0.5–4.9%)
Shaughnessy et al, 2006 [50]	Ns= 54 (analysis Ns=50)	US	0.9 to 11.7		Restricted windows and doors. Monitoring CO_2 over a typical teaching day. Control for socio-economic factors.	Standardised national tests in math and reading	Improvement in numerical tasks by 8 to 14%. (modest association)
	primary schools, Age: 9-10				Compared students' performance with performance standards established by the State Board of Education.		
Coley and Greeves, 2004 [49]	Ns=1 primary school	UK	intervention:13 control: 1.5	Intervention: 690 (σ: 122) (range 501-983)	Cross-sectional intervention studies (not blind)	Cognitive Drug Research (CDR) computerised cognitive assessment system (10 minutes to complete)	Increased speed by 5% but not accuracy
	Nc=18, age: 10-12			control: 2909 (σ:474) (range: 2096-4140)	Natural ventilation with split unit for temperature control. Tests were performed 10 consecutive school days		

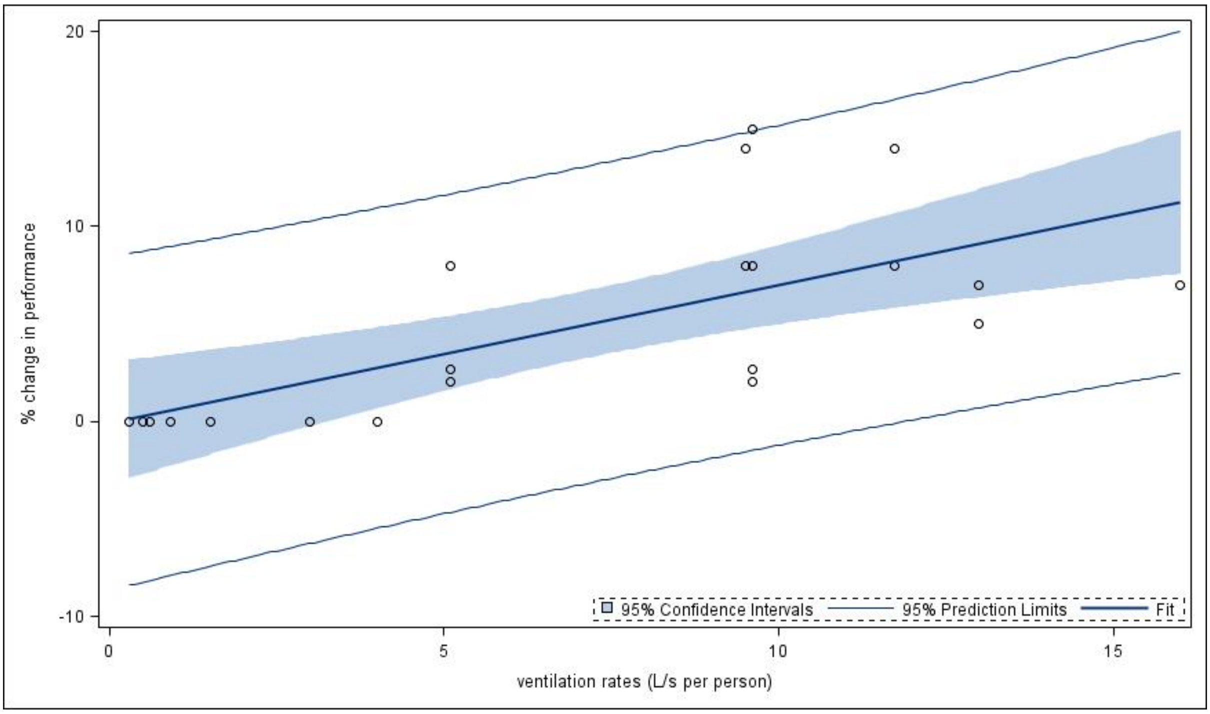

Figure 5: Percentage change in performance vs. average ventilation rate, fitted with a linear regression model derived from six studies [6], [45], [48], [51], [50], [49]

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The quantitative relationship between ventilation rates and improvement in performance was estimated from synthesising data reported in six studies [6], [45], [48], [51], [50] , [49] in the range from 0.3 L/s-p to 16 L/s-p (Figure 5). This synthesis suggests that an increase of ventilation rates from 5 L/s-p to 15 L/s-p will result in an improvement in performance by 7% (95%CI: 4 to 10%).

However, one recent study [52] failed to detect a correlation between thermal conditions and CO_2 levels with the learning rates of students. The study adopted an integrated approach, so as to concurrently investigate multiple factors that may affect learning rates of students. This suggested that school building design combined with non-environmental factors accounted for 50% of the variance in the learning rates of students in primary schools. Six influential school building design factors were identified as important, namely: (a) colour (especially wall and floor); (b) choice (ergonomic tables and chairs, purpose designed furniture fixture equipment); (c) connection (wide corridors, easy navigation); (d) complexity, (opportunities for alternative learning, display and decoration); (e) flexibility (easily changeable space configurations, varied learning activities); and (f) light (natural and electrical lighting, unobstructed space adjacent to windows). IAQ was assessed with spot measurements of CO_2, which was found uniformly to be poor in all classrooms. Similarly, temperatures in different classrooms were also assessed with spot measurements and also showed small variations.

In concentrations commonly found in school classrooms, CO_2 is generally not considered a harmful pollutant. However, the probability of airborne communicable infection is well-documented, and among other factors (time of exposure, personal susceptibility) is dependent on ventilation rates (Wells-Riley equation). A recent study in school settings [53] using the Wells-Riley equation estimated the risk of indoor airborne transmission of infectious diseases in relationship to indoor CO_2 levels because airborne communicable infection can only be acquired by inhaling air that has been previously exhaled.

A study that quantified this relationship found that an increase in CO_2 concentrations by 1000 ppm was associated ($p<0.05$) with a 0.5–0.9% decrease in annual average daily attendance [54], which averaged to 5% of total student absences. The study used a relatively large sample size of 436 classrooms located in 22 schools over the period of a year. The range of indoor CO_2 levels were 10 to 4200 ppm above outdoor levels (ΔCO_2). The limitations of the study include that it did not separate illness from non-illness related absenteeism, and used spot measurements of CO_2. A recent study [55] used a more robust methodology in a sample of 162 classrooms located in 28 primary schools in three climatic districts over a two-year period. Both studies [54] and [55] controlled for socio-economic and demographic characteristics of the population. Study [55] used long term CO_2 measurements to infer more detailed ventilation rates and obtained records of illness related absenteeism over a two-year period. Regardless of climate, season or ventilation strategy, findings consistently estimated that for every 1 L/s-p increase in classroom ventilation rates in the range between 4.0 L/s-p to 7.1 L/s-p illness related absences were reduced by 1.0 to 1.5% ($p<0.01$). Converting findings of [55] to a comparable metric, each decrease of indoor CO_2 levels by 1000 ppm was associated with a 1.0% to 2.5% relative decrease in illness absence, approximately 2 to 5 times lower than the findings reported in [54].

The suggestive evidence linking higher CO_2 levels in classrooms with increased absenteeism of children might be related to the increased probability of viral infections. Viral infections can trigger asthmatic attacks in a subpopulation of children. Therefore, indoor CO_2 levels in the classrooms were associated with current asthma (odds ratio: 1.18 per 100 ppm, 95%CI: 1.06-1.32, $p<0.01$) [47]. One study that used non-invasive medical tests associated low ventilation rates and corresponding high CO_2 levels with nasal patency [56] and other SBS symptoms [46].

6 The effect of school exposure on health and perceived IAQ

Information compared in this section highlights the critical health implications addressed in exposure studies in the school environment. Moreover, suggestive evidence links exposure to specific pollutants with IAQ dissatisfaction. Sensory irritations may affect health and comfort of the occupants directly and performance indirectly, and provide a first indication of exposure. Very little evidence is currently available on the association between cognitive performance and specific pollutants in the school environment. Two studies [6] and [45] that directly tested whether reducing particle concentrations in classrooms would improve the performance of schoolwork found that even though the electrostatic air cleaners reduced the PM levels, there was no general effect on the performance of schoolwork.

A recent meta-analytic study [57] employed a systematic approach to evaluate the potential relationship between asthma and asthmatic symptoms in children with exposure to traffic related pollutants. The systematic meta-analysis included 19 studies, which did not separate school-exposure from non-school exposure. Overall, the study concluded that children living or attending schools near high traffic density roads were exposed to higher levels of motor-vehicle pollutants, and had higher incidence and prevalence of childhood asthma and wheeze. The meta-analysis odds ratios (meta-OR) were estimated. More specifically, prevalence of childhood asthma was positively associated with exposure to NO_2 (meta-OR: 1.05, 95%CI: 1.00–1.11), NO (meta-OR: 1.02, 95%CI: 1.00–1.04), and CO (meta-OR: 1.06, 95% CI: 1.01–1.12). Exposure to NO_2 was positively associated with a higher incidence of childhood asthma (meta-OR: 1.14, 95%CI: 1.06–1.24), and exposures to particulate matter was positively associated with a higher incidence of wheeze in children (meta-OR: 1.05, 95%CI: 1.04–1.07).

Limited evidence related school exposure to NO_2 at 34.8 to 44 $\mu g/m^3$ with increased allergy exacerbations; current conjunctivitis; current wheeze; and current itchy skin rush [58], which is around WHO 2010 guideline values (Table 1). School absenteeism was significantly related to exposure to O_3 [59], [60], [61], PM [61], [62] and CO [59], [63].

Studies have reported positive associations for general and respiratory symptoms, including a higher occurrence of respiratory infections, with exposure to fungal particles [64], [64]. The total amount of viable and non-viable airborne fungi species (total moulds) may provide quantitative information on microbial concentration in indoor settings. Two studies [65], [66] found that total moulds were a significant predictor of satisfaction with IAQ, and quantified the relationship that for every 10-fold increase of moulds satisfaction decreased by OR: 1.9 (95% CI: 1.3-2.8, p<0.01). The study [65] controlled for other environmental exposures (such as dust, VOCs, and traffic related pollutants), and personal factors (age, gender, atopy, home exposure etc). High levels of TVOCs in classrooms were suspected to be the source of SBS symptoms such as throat dryness, eye symptoms and adverse health effects [67].

7 Discussion

7.1 Synthesis of findings

This report primarily investigated the potential associations between thermal conditions and ventilation rates in educational settings with health responses and cognitive performance of school children. In this section findings are synthesised by considering overall evidence available on specific relationships, and emphasising strong or consistent trends.

Currently, CO_2 is generally not considered harmful at concentrations normally found indoors, and so is often accorded little significance other than as an indicator of ventilation; however emerging evidence indicates that high CO_2 levels and low ventilation rates may impact on health and academic performance of school occupants.

1. Indoor CO_2 concentrations can be considered a measure of risk of transmission of airborne disease throughout the classroom. It can be hypothesised that decreased ventilation rates in classrooms may be associated with increased illness absences from respiratory infections, due to increased indoor airborne concentrations of respiratory virus. Two studies found a positive association between reduced absenteeism with increased ventilation rates inferred from CO_2 measurements. However, the magnitude of the association differed significantly between the studies: the reduction rate of absenteeism ranged from 1.0% up to 7.1% for every increase in ventilation rates by 1 L/s-p. Explanation for the discrepancies included the different methods of estimation of ventilation rates, as well as the distinction in the outcome between illness related and total absenteeism which could inflate results. A similar study in office workers found a 2.9% decrease in short-term illness absence in adults per 1 L/s-p increase in ventilation rates (range: 12 to 24 L/s-p) [68]. Suggestive evidence links higher CO_2 levels with increased asthmatic symptoms and nasal patency, which could be explained by the increased probability of conducing viral infections. However, as these studies are correlational, causality cannot be established.

2. Limited evidence is available on the association between lower ventilation rates and higher CO_2 levels with increased SBS symptoms of school occupants. A meta-analytic study in office workers [69] indicated that outdoor airflows up to 10 L/s-p may be effective in reducing SBS symptom prevalence and dissatisfaction with air quality, and a similar relationship might be likely for schools.

3. There is indicative evidence associating high CO_2 levels and corresponding low ventilation rates to reduced performance resulting from impaired attention span, concentration loss and tiredness. More specifically, a linear regression model synthesised from published evidence indicates that an increase of ventilation rates from 5 L/s-p to 15 L/s-p was associated with a 7% increase in academic performance of children. Findings of this report agree with previous systematic meta-analytic studies in school children [4] and adults [70]. The quantitative relationship between work performance in adults and a wider range of ventilation rates showed a statistically significant increase in performance per unit increase in ventilation rates up to 15 L/s-p by a 1-3% improvement in average performance of office workers per 10 L/s-person increase in outdoor air ventilation rate [70]. Because children are more sensitive than adults to environmental exposure, it is expected that the magnitude of effect would be greater.

   Studies included in the review examining the potential associations between CO_2 levels and inferred ventilation rates with academic performance employed cross-sectional experimental designs. The studies performed blind interventions altering only ventilation rates and using each student as their own control, and therefore eliminating socio-economic confounding factors and variations between individuals that may affect performance outcomes. However, one limitation of the studies was the lack of simultaneous monitoring of pollutants with indoor sources which are likely to build-up at lower ventilation rates and might affect performance. In light of these concerns, the recent experiment performed on adults in controlled laboratory conditions [71] provides strong suggestive evidence that cognitive performance may be affected at CO_2 levels as low as 1000 ppm. Findings of this study are not definitive, as a small population sample was used.

4. There is indicative evidence indicating that increased ventilation rates may also improve cognitive performance and health and comfort of the occupants indirectly through: (a) mitigating overheating; (b) reducing TVOCs; and (c) reducing microbial concentrations;

   (a) Two studies in temperate climates showed that the PMV and adaptive comfort model used in existing thermal comfort standards have limited suitability for predicting the thermal comfort conditions as both models did not accurately reflect the children's actual thermal sensation. The results suggested that children prefer an indoor thermal environment with lower temperatures compared with adults. Possible explanations are that children have higher metabolic rate per kg body weight, have limited available adaptive opportunities in classrooms or are more physically active than adults. Limited evidence associated higher temperatures in school classrooms with dissatisfaction with IAQ and increased SBS symptoms.

       Two cross-sectional experimental interventional studies indicated that lowering the temperature from 25 to 20 °C improved speed of performance by 2-4%. The observed effects of temperature on performance could be caused by physiological effects of thermal discomfort, and also by the distraction by thermal discomfort [6]. Although there are no experiments in school settings that investigate cognitive performance of students in temperatures above 25 °C or below 20 °C , previous work in office workers

[72] showed maximum relative performance between 20-25 °C that decreased rapidly outside this range (See Appendix Figure A1), possibly because thermal discomfort (feeling too warm or too cold) led to reduced performance (see Appendix Figure A2). Systematic meta-analytic evidence in office-workers suggested that optimum performance can be achieved slightly below neutral thermal sensations [72].

Studies examining thermal conditions and CO_2 levels separately in association with academic performance have suggested relationships between the two. By contrast one recent study that used an integrated approach to investigate multiple environmental factors [52] simultaneously, failed to detect an association. There were a number of reasons why this study may have failed to detect relationships: the small variation of these environmental conditions between classrooms or the use of spot measurements which does not provide a comprehensive picture of the indoor conditions. Nonetheless further studies should extent this result by considering the impact of multiple environmental factors.

(b) Concentrations of TVOCs exhibited a moderate positive relationship with CO_2 concentrations. Apart from controlling indoor TVOCs sources, overall evidence suggests that CO_2 levels below 1300 ppm may result in indoor TVOCs below 200μg/m3, which is the lowest threshold to prevent sensory irritations. Suggestive evidence links TVOCs concentrations to dissatisfaction with IAQ.

(c) Moulds were also associated to dissatisfaction with IAQ and increased respiratory symptoms.

Most studies focus on ventilation rates and CO_2 levels, and only a small number of epidemiology studies related school exposure with specific health symptoms, as it is difficult to separate school-based and non-school based exposures to an observed health outcome. A further challenge to assess personal exposure includes the evaluation of spatial and temporal variations of pollutants in school buildings. Although associating school exposure to specific health symptoms is challenging, exposure to NO_2, NO and CO was positively associated with a higher prevalence of childhood asthma. Moreover, exposure to NO_2 was positively associated with a higher incidence of asthma, which could in term affect school absences. There were no studies found which explained the direct links of exposure to pollutants with cognitive performance.

7.2 Future work and recommendations

Research conducted in school environments focused on the effect of environmental factors in isolation on cognitive performance, health and comfort of students. Limited research is available on possible interactions of multiple factors; therefore future research should adopt an integrated approach so as to concurrently investigate multiple factors that may affect learning rates and health outcomes of students. Where possible experimental designs which assess performance and learning over time should be used.

UK guidelines on thermal conditions in classrooms focus on conditions of overheating in the non-heating season, although there is evidence of occurrence of winter overheating in temperate climates. While statistical valid thermal comfort studies are sparse, suggestive evidence indicated that children prefer lower temperatures compared with adults. It was also suggested that keeping the air dry and cool may improve cognitive performance and reduce SBS symptoms among children. It is therefore necessary that schools do not allow temperatures to drift above the recommended range of 20-22 °C in the winter season and 22-24 °C in the summer.

Monitoring campaigns found that the school environment is a significant site of microbial exposure, and should be assessed by detailed on-site investigations. Strong evidence related microbial exposure to asthma exacerbations and suggestive evidence linked them to increased dissatisfaction with IAQ. Concentrations of indoor moulds were positively related to increased temperature, RH and CO_2 levels. Mitigation of overheating and control of indoor RH with increased ventilation rates would therefore contribute indirectly to improvement of IAQ perception and health of students. Indoor finishing acting as dust reservoirs, such as wall to wall carpeting and textiles, collect irritants and allergens that get re-suspended during occupancy period increasing indoor microbial concentrations. Moreover, cleaning products, teaching materials and furniture introduced in the classrooms may increase indoor VOCs emissions associated with increased SBS symptoms. It is essential to ensure that the broad range of construction materials and cleaning products introduced in classrooms do not seriously impact indoor air quality, even when ventilation rates fall below code requirements.

Finally, low indoor CO_2 levels cannot guarantee a healthy environment as traffic related pollutants can penetrate indoors. Traffic related pollutants were linked to increased absenteeism, asthma morbidity and asthma exacerbations. Stakeholders and policy makers should take these findings into consideration when selecting locations for new school buildings, and introduce traffic-free zones when restoring existing school buildings.

7.3 Strengths and limitations of review

Some limitations of this review reflect limitations of most review studies. As negative studies performed are less likely to be submitted or accepted for publication, they are less likely to be identified and included in this review leading to bias in similar reviews towards positive findings [73]. Therefore, the results presented here may be skewed by publication bias. Quantitative data extracted from the literature were used to fit linear regression models. Although the relationships may not be linear, the environmental conditions investigated in the literature were within a very limited range, and therefore a linear relationship was more evident. Moreover, linear models are more parsimonious compared with more complicated models. One limitation of the statistical analysis was the lack of weighing of the data, as different sample sizes were included in each study. However, the difference is expected to be small, as findings of these models agreed well with previous models. This review did not include possible important effects of noise, light, nor did it include the relations of IEQ to distractions. Specific pollutants such as radon were excluded from the review.

The review has been conducted in accordance with key systematic review principles to ensure that it is transparent, replicable and updateable. Included studies met all the quality criteria, which were critically appraised independently by two reviewers. Therefore findings of this review are based on sound evidence.

8 Conclusions

This systematic review focused primarily on IAQ factors and thermal conditions that may influence cognitive performance. Included studies focused on cognitive performance of children aged 9 to 12 years old attending primary schools. Emerging evidence indicates a strong association between temperature, ventilation rates and CO_2 with cognitive performance. While the relationships are not causal, more research in controlled laboratory conditions with a larger population including children is necessary, as the magnitude of the effects may differ between children of different age groups and adults. As well as improving thermal comfort of students, lowering the indoor temperatures in classrooms below 25 °C may also improve academic performance of students. Overall evidence suggested limiting indoor CO_2 levels in classrooms below 1000 ppm (approximately 8 L/s-p), as at concentrations above that limit cognitive performance of adults became marginally dysfunctional and absenteeism rate of students increased. Moreover, a strong positive association between CO_2 levels and risk of viral infections was proposed. It is also likely that low temperatures, low CO_2 levels and corresponding increased ventilation rates will improve satisfaction of students with IAQ and reduce SBS symptoms.

Future work is required to establish evidence based guidelines for average temperatures and CO_2 levels in classrooms. These findings suggest that high ventilation rates and low temperatures required to provide optimum health outcomes and learning conditions may limit the potential for energy savings in school buildings.

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Appendix

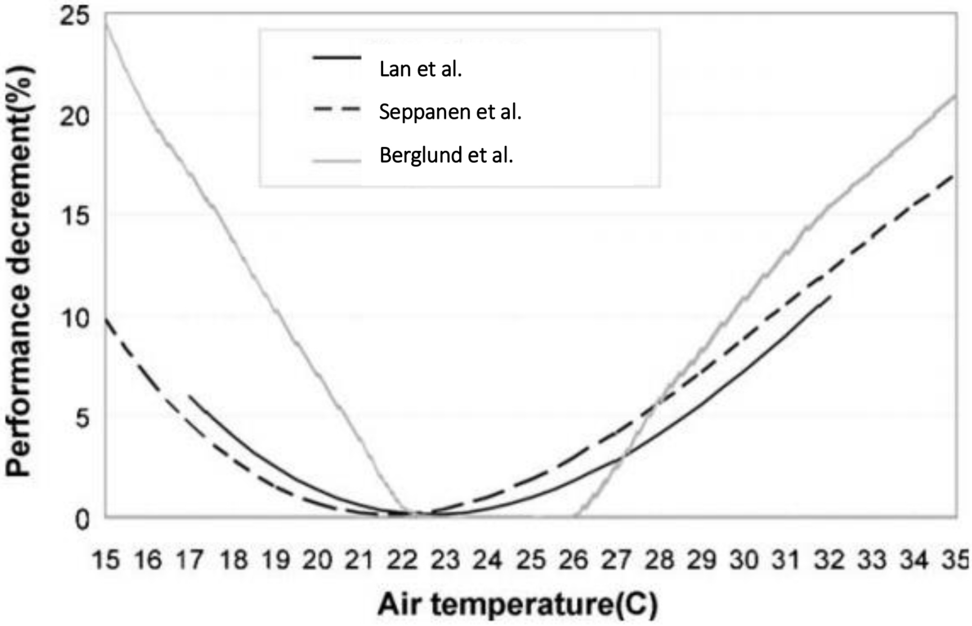

Figure A.1: Comparison of the relationship between air temperature and relative performance developed in three studies in office workers [72].

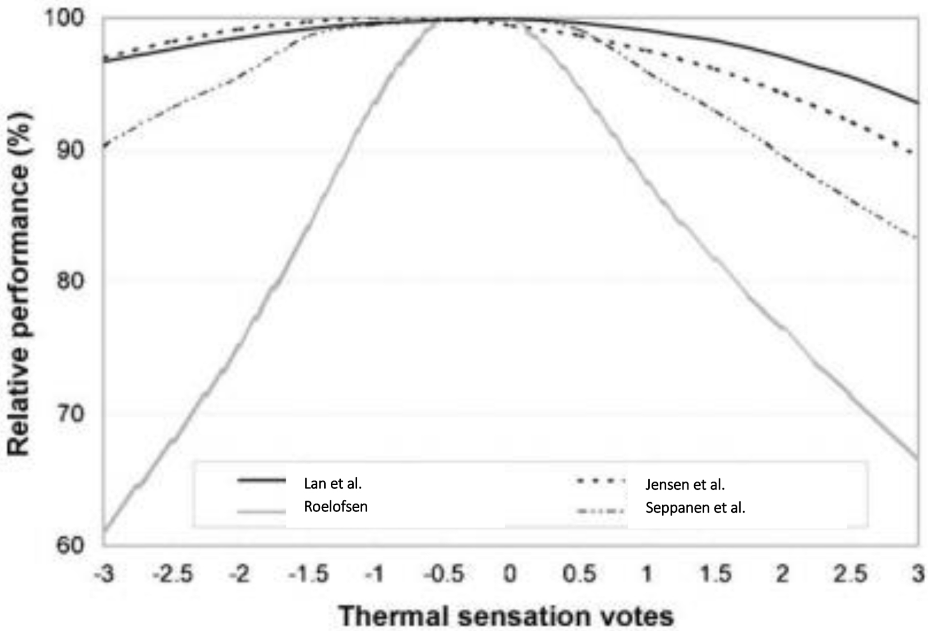

Figure A.2: Comparison of the relationship between thermal sensation and relative performance developed in four studies in offices [72].

Studies compared in the Figures A.1 and A.2 taken from the meta-analytic study [72]:

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