What do we know about indoor air quality in school classrooms? A critical review of the literature

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The increasing interest in indoor environmental quality of educational buildings has been underpinned by the rising incidence of asthma and respiratory disease among children, who spend a substantial amount of their lives on the school premises. The susceptibility of children to respiratory disease compared with adults has led to the formulation of regulatory frameworks for the school environment, which specifies maximum CO₂ concentrations and minimum airflow rates. This article reviews the evidence that school buildings provide a healthy and satisfactory indoor environment for the occupants. It summarized air pollution levels reported from indoor air quality (IAQ) monitoring surveys and evidence linking school exposure with health responses from the occupants. In addition, environmental and behavioural factors affecting pollution levels in school buildings were examined. The analysis has highlighted the degraded IAQ in some schools that often exceed WHO guidelines, while health impacts of school exposure were reported for concentrations below current guidelines.

Keywords: allergens; bacteria; carbon dioxide (CO₂); fungi; health impacts; nitrogen dioxide (NO₂); ozone (O₃); particulate matter (PM); schools; ventilation rates; volatile organic compounds (VOCs)

Introduction

The primary purpose of school buildings and facilities is to provide children with ideal places for their learning and development. Outside of the home, children spend most of their time indoors while at school (Eurostat 2011). At this developmental stage in their lives, children are vulnerable to a range of environmental exposures that can have long-term adverse consequences, such as respiratory illness and poor cognitive performance. So 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.

Children are more vulnerable to airborne pollutants than adults because their developing lungs breathe more air compared with their bodies, and their underdeveloped ability to communicate concerns in response to pollutant levels. Rising respiratory disease has led to an increasing research focus on IAQ in schools. World Health Organization (WHO) reports conclude that asthma is the most common chronic disease and the leading cause of hospitalization among children. 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 (WHO 2010). In many northern hemisphere countries, a significant increase in asthma hospital admissions among asthmatic children peak in September and coincide closely with their return to the school environment (Julious et al. 2007). The data indicate that a sub-population of school-aged children with asthma receive challenges when returning to school that trigger their asthma.

School buildings are complex spaces to design as they need to perform well in all aspects of environmental conditions, 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) average primary class size in European countries and US was on average 20.8 ± 2.0 pupils corresponding to a density ranging from 2 to 3.1 m²/person with a standard of 0.3. The high occupancy densities in school classrooms result to high internal gains, emissions of body odour together with various indoor pollutants.

Intelligent buildings of the future shall be designed considering an integrated approach on the interactions between physical characteristics, occupants’ behavioural patterns and microbiological and chemical exposure. Having this in mind, this article aims to collect empirical evidence and highlight the interrelationships between key factors affecting pollution levels in school classroom, and to contribute to better informed decisions on creating healthy and comfortable school environments.

In the first of three sections, we assess empirical data on the concentration of physical, microbial and chemical parameters and compare them with current guidelines. In addition, associations between potential health risks and the satisfaction of occupants with school environmental exposures are examined. In the second, factors affecting indoor pollution levels including meteorological parameters, traffic intensity, operational schedules, occupancy density and building characteristics – such as envelope airtightness and ventilation systems – are evaluated. In the last section, we discuss the implications of these factors on building design.

**Monitored parameters of IAQ in classrooms and health responses**

While some studies have investigated levels of specific pollutants in school environments, the vast majority have focused on CO₂ levels and ventilation rates. In addition, building regulatory frameworks for the provision of adequate IAQ has also been framed around CO₂ levels and ventilation rates rather than specific pollutants. Although WHO provides the basis for global standards in environmental quality, the reliance on proxies for IAQ assessment reflects the relative difficulty and expense of obtaining measurements of specific pollutants and identifying any related health effects.

Associating school environmental exposures to specific health symptoms is challenging, as it is difficult to separate the contribution of school-based and non-school-based exposures, such as from those due to the home environment, to an observed health outcome. A further challenge includes the evaluation of spatial and temporal variations of pollutants in school buildings. Studies assessing the effects of school exposure have typically obtained either broad-scale measurements from central stations, or school-based scales by monitoring pollutants in school buildings and their immediate surroundings, or calculated exposures at the personal scale using monitors attached to a number of children.

Information compared in this section highlight the degraded air quality noticed in monitoring studies, and their critical relationship to health implications addressed in exposure studies in the school environment.

**Physical parameters on health and cognitive performance**

Ventilation is the process of exchanging indoor polluted air with outdoor (presumably) fresh and clean air and provides simultaneous catering for adequate IAQ and thermal comfort.
Comparison among studies monitoring particulate matter (PM) in the classrooms was complicated by large differences in studies’ design, including duration, number of schools monitored and instrumentation used. Only a few studies address the epidemiological associations with exposure to PM$_{10}$ in school children and the health impacts of PM$_{2.5}$ and PM$_{1}$.

**Thermal comfort**

Thermal comfort in schools is currently evaluated in accordance to Fanger’s model (ASHRAE Standard 55/2004, EN15251/2007, ISO Standard 7730, CIBSE Guide A) using predicted mean vote and predicted percentage dissatisfied indications in relation to hygrothermal conditions and personal factors. The recommended temperature range lies between 20 ± 1 and 24.5 ± 2.5°C depending on the season.

Latest versions of standards include also an adaptive thermal comfort diagram allowing for a wider band of temperatures and corresponding energy savings. Adaptive models have been developed through field work 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 (Brager and de Dear 1998).

Studies on thermal comfort in schools are scarce and most focus on tropical settings (Kwok and Chun 2003, Wong and Khoo 2003, Hwang et al. 2006, Liang et al. 2012) with only a few studies conducted in mild (Corgnati et al. 2007, Mumovic et al. 2009) or cold climates (Mors et al. 2011). Overall the findings indicate that satisfaction of the occupants with thermal conditions depended on local climate, season (Corgnati et al. 2009) and ventilation system, as occupants in naturally ventilated classrooms accepted a wider range of temperatures compared with mechanical settings (Kwok and Chun 2003, Wong and Khoo 2003).

Temperatures at the lower end of the comfortable range may improve health, cognitive performance and perception of school children. Mi et al. (2006) recorded average indoor temperatures of 17°C (range: 13–21°C) and concluded that lower temperatures had a protective effect on health by reducing breathlessness among students. Reducing the temperature by 1°C in the range between 25 and 20°C improved academic performance in standardized tests by 2–4% (Seppänen et al. 2006, Bakó-Biró et al. 2007; Wargocki and Wyon 2007b).

**Ventilation rates and CO$_2$**

Recent versions of the standard ASHRAE 62–2010 determining IAQ in North America and some other countries recommend that the indoor–outdoor differential concentration should not exceed 700 ppm. In the UK, Building Bulletin 101 (BB101; DiES 2006) provides the regulatory framework for the adequate provision of ventilation in UK schools based on Part L and F of Building Regulations. In order to investigate ventilation rates and corresponding CO$_2$ concentrations, data from 312 classrooms in 80 schools investigated in 14 published papers.

A log-normal distribution described median concentrations of CO$_2$ in 53 classrooms in 14 published studies (Figure 1). In total, 30% of the investigated classroom exceeded 1500 ppm.

Previous meta-analysis studies have reported that low ventilation rates are common in schools and are linked to adverse health effects in children and adults (Wargocki et al. 2002, Daisey et al. 2003, Mendell and Heath 2005). The probability of airborne communicable infection is described by the Wells–Ridley equation, and among other factors is dependent on outdoor fresh air supply and CO$_2$ concentrations (Rudnick and Milton 2003) because airborne communicable infection can only be acquired by inhaling air that has been previously exhaled. Studies that have quantified this relationship (Table 1) have found that an increase in CO$_2$ concentrations by 1000 ppm is associated with an increase by 10–20% of absenteeism (Shendell et al. 2004a). Low ventilation
rates were associated with inflammatory biomarker response of the nasal mucosa (Wålinder et al. 1998) and asthmatic symptoms in children (Mi et al. 2006). Increased outdoor air flow rate from 1.3 to 12.8 l/s-p, with a corresponding decrease of mean indoor CO₂ from 1050 to 780 ppm, resulted in a significant reduction of asthmatic symptoms in pupils from 11.1 to 3.4% over a two-year period (Smedje and Norbäck 2000).

Meta-analysis studies have indicated that reduced ventilation rates might be linked to reduced academic performance in the school (Wargocki et al. 2002, Seppänen et al. 2006). More specifically, Seppänen et al. (2006) based on evidence from published literature estimated that an average improvement of 1–3% in learning performance was expected for an increase from 6.5 to 15 l/s-p. Wargocki et al. (2002) have found that the magnitude of similar effects on children doing schoolwork is greater than for the performance of adults with office work, which is probably due to children being more susceptible to environmental conditions than adults.

Four recent studies (Shaughnessy et al. 2006, Bakó-Biró et al. 2007, Wargocki and Wyon, 2007a, Bakó-Biró et al. 2012) have also reported an improvement of at least 7% in learning performance when providing fresh air supply above 10 l/s-p. Two studies reported significantly faster and more accurate standardized test responses (by up to 15%) at airflow around 10 l/s-p (Wargocki and Wyon 2007a, Bakó-Biró et al. 2012). In addition, Bakó-Biró et al. (2012) noticed that the magnitude of the negative effects with inadequate ventilation was even higher for tasks that require more complex skills such as spatial working memory and verbal ability to recognize words and non-words.

Studies which used CO₂ as surrogate for fresh air supply (Myhrvold et al. 1996, Coley and Greeves 2004) noticed significant decrease in the attention processes of school children at concentrations of CO₂ above 1500 ppm of approximately 5%. Bakó-Biró et al. (2012) suggested CO₂ daily average concentrations should not exceed 1000 ppm. The typical average concentrations of CO₂ in classrooms are between 500 and 1500 ppm. CO₂ in those concentrations is
Table 1. Ventilation rates on health and cognitive performance.

<table>
<thead>
<tr>
<th>Study</th>
<th>Setting school</th>
<th>Subjects</th>
<th>Ventilation rates l/s-p</th>
<th>CO₂ concentrations ppm</th>
<th>Methodology</th>
<th>Analysis</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wålinder et al. (1998)</td>
<td>Ns = 12 Adults</td>
<td>1.1 to 9 l/s-p</td>
<td>No data</td>
<td>Acoustic rhinometry; nasal lavage</td>
<td>Multiple regression</td>
<td>Low ventilation rate associated with reduced nasal patency and an inflammatory biomarker response of the nasal mucosa</td>
<td></td>
</tr>
<tr>
<td>Smedje and Norbäck (2000)</td>
<td>Ns = 39 Pupils</td>
<td>N = 234 Av: 4.4 l/s-p</td>
<td>840 vs. 780 ppm</td>
<td>Self-administered questionnaire posted to parent</td>
<td>Multiple logistic regression</td>
<td>At least one asthmatic symptom was less common with increased ventilation</td>
<td></td>
</tr>
<tr>
<td>Myhrvold et al. (1996)</td>
<td>Ns = 5 Pupils</td>
<td>Nc = 22</td>
<td>No data</td>
<td>Self-administered questionnaire</td>
<td>one-way ANOVA</td>
<td>general health symptoms;</td>
<td></td>
</tr>
<tr>
<td>Shendell et al. (2004a, 2004b)</td>
<td>Ns = 22 Pupils</td>
<td>No data</td>
<td>&gt;1000 ppm ΑΔCO₂</td>
<td>Multivariate linear regression models between absenteeism and indoor CO₂ levels</td>
<td>10–20% relative increases in student absence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coley and Greeves (2004)</td>
<td>Ncl = 436 Ns = 1</td>
<td>13 l/s-p compared</td>
<td>690 ppm (501–983) vs. 2909 ppm (2096–4140)</td>
<td>Standardized tests</td>
<td>LSmeans</td>
<td>Reduced attention performance by 5%</td>
<td></td>
</tr>
<tr>
<td>Shaughnessy et al. (2006)</td>
<td>Ns = 54 (analysis N = 50)</td>
<td>(0.90–11.74) l/s-p</td>
<td>Statistical analysis</td>
<td>Improvement in numerical tasks by 8 to 14%.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bakó-Biró et al. (2007)</td>
<td>Ns = 8 Pupils n = 32</td>
<td>0.3–0.5 vs 13–16 l/s-p</td>
<td>No data</td>
<td>Computerised assessment tests</td>
<td>Increased pupils’ work rate by ~7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Study</td>
<td>Participants</td>
<td>CO₂ Concentration</td>
<td>Test / Measurements</td>
<td>Statistical Test</td>
<td>Performance Impact</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Bakó-Biró <em>et al.</em> (2012)</td>
<td>Pupils</td>
<td>0.6–4 l/s-p</td>
<td>5000 ppm vs. 1000 ppm</td>
<td>Standardized tests/ ANOVA</td>
<td>Choice reaction: 2.2%, colour word vigilance: 2.7%, picture memory: 8%, word recognition: 15%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wargocki and Wyon (2007a)</td>
<td>Pupils 10–12</td>
<td>5.1–9.6 l/s-p</td>
<td>Language and numerical tasks</td>
<td>8–14%.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Myhrvold <em>et al.</em> (1996)</td>
<td>Ns = 5</td>
<td>No data</td>
<td>&gt;1500 ppm</td>
<td>One-way ANOVA</td>
<td>Reduced performance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ANOVA, analysis of variance; Ns, number of schools; Nc, number of classrooms.
not generally thought to be harmful (Seppänen and Fisk 2004) and so is often accorded little significance, other than as an indicator of ventilation, but if it contributes directly to increased tiredness and a loss of concentration even at concentrations encountered in school buildings (Bakó-Biró et al. 2012), then it might be regarded as a significant air pollutant.

**PM**

In addition to its gaseous components, indoor air may contain a variety of contaminants that occur as airborne particles. Conventionally, particles are classified by their aerodynamic diameter (usually referred to as particle size) because these properties govern the transport and time of suspension in the air, their deposition in the lungs, and they are generally related to their chemical composition (Morawska and Salthamer 2003). The main indoor sources of particles in school environments include human activities, plants and building materials, especially mineral fibres. Particles also penetrate in the classrooms through ventilation and infiltration from the outdoor environment, particularly in urban areas where exhausts from vehicles are the main source.

Numerous studies have found that daily mean concentrations of PM$_{10}$ in European classrooms exceed mean daily recommended WHO guidelines of 20 $\mu$g/m$^3$, with results ranging from 43 to 169 $\mu$g/m$^3$ (Branis et al. 2005, HESE 2006, ODPM 2006, Fromme et al. 2007, Heudorf et al. 2007). Mean concentrations of PM$_{10}$ Median daily concentration of PM$_{2.5}$ among studies in European classrooms was 20.2 $\mu$g/m$^3$ (Figure 2), which exceeded the WHO daily average guideline of 10 $\mu$g/m$^3$ when measured both with gravimetric and laser methods.

Epidemiology studies have related elevated outdoor PM$_{10}$ levels with absenteeism from schools (Table 2) (Ransom and Pope 1992, Park et al. 2002). Ransom and Pope (1992) estimated that an increase of outdoor PM$_{10}$ from 50 to 100 $\mu$g/m$^3$ resulted in an increase of 40% in school absences in children, an effect which lagged up to several weeks, and with younger children aged 5–8 years old primarily affected. Park et al. (2002) estimated that the relative risk for ill-related absenteeism was 1.06 (95% confidence interval, CI, 1.04–1.09) per 42.1 $\mu$g/m$^3$ increase of PM$_{10}$. The negative correlation reported in a strongly designed study (Chen et al. 2000) between PM$_{10}$ concentrations (mean: 32.4 $\mu$g/m$^3$) with absenteeism can be attributed to the failure of the study to separate illness- from non-illness-related absenteeism.

Very limited empirical evidence is available on the concentration of ultrafine particles in classrooms. The measurement process requires the use of particle counters due to the limitations of laser metres in detecting ultrafine particles. Concentrations recorded in various countries to date range from 188 to 14,300 n/cm$^3$ (Guo et al. 2008, Weichenthal et al. 2008). Branis et al. (2005) recorded average mass concentrations with gravimetric methods in a naturally ventilated school gym of 10.9 $\mu$g/m$^3$ (range: 3.5–34.4). No guidelines are yet developed for the ultrafine fraction.

Fine and ultrafine PM fraction may entail greater health risks as they are products of combustion processes (Fromme et al. 2008b). It is known that inhalation of PM entails greater risk for children than healthy adults (Bennet and Zeman 1998) due to different fractional deposition efficiency, and higher minute ventilation relative to their lung size. Only a few studies, however, have conducted on the health implications of school exposure to PM, and especially for the smaller fraction. One study (Timonen et al. 2002) has reported toxicological effects from exposure to PM$_{1}$ at school mainly related to impairment of baseline lung function in children with chronic respiratory illness. Exposure to mean PM$_{2.5}$ concentrations in the range reported in monitoring surveys of schools (20.5 ± 2.2 $\mu$g/m$^3$) were associated to current conjunctivitis, hay fever, current itchy rash and sensitization to outdoor allergens (Janssen et al. 2003).
Microbial concentrations in classrooms and health impacts

The large surface area-to-mass ratio of particles provides opportunities for them to act both indoors and outdoors as sinks for a variety of organic species. Bioaerosols contain allergens, viruses, bacterial, fungal cells and cellular fragments as well as by-products of microbial metabolism.

Allergens

In general, studies over the past decade have more often assessed allergens in settled dust than through air sampling and the correlation between methods has been poor (Karlsson et al. 2002). Evidence from a number of studies, however, has indicated that the school environment
may be important site of allergen exposure for children with no pets at home (Dybendal and Elsayed 1994, Perzanowski et al. 1999, Salo et al. 2009). The magnitude of exposure differs significantly between classrooms and is dependent on socioeconomic and cultural factors regarding pet ownership. Studies on European schools (Fromme et al. 2008a, Kim et al. 2005) have found higher concentrations than concentrations reported from a study in Asia (Zhao et al. 2006) and in South America (Rullo et al. 2002).

Most commonly detected in school classrooms were cat (Fel d 1) and dog (Can f 1) allergens. Sampling from 194 classrooms in six studies (Arbes et al. 2005, Kim et al. 2005, Ramachandran et al. 2005, Abramson et al. 2006, Zhao et al. 2006) detected cat allergen ranging from non-detectable to 2.3 μg/g (mean: 0.8 ± 1 μg/g). Mean dog allergen concentrations sampled in the dust from 62 classrooms (Kim et al. 2005, Zhao et al. 2006) ranged up to 3 μg/g (mean: 1.3 ± 0.9 μg/g). Studies have also detected cockroach (Foarde and Berry 2004, Chew et al. 2005), horse allergens (Kim et al. 2005, Zhao et al. 2006) and dust mites in low concentrations (Foarde and Berry 2004).

Findings from cross-sectional and cohort studies suggest that indirect exposure to pet allergens in school environments might influence asthma morbidity (Smedje et al. 1997b, Lonnkvist et al. 1999, Almqvist et al. 2001, Smedje and Norbäck, 2001, Langley et al. 2003, Kim et al. 2005, Zhao et al. 2006). Kim et al. (2005) associated wheeze, daytime breathlessness, asthma and atopic sensitization with dog allergen above 8 μg/g in settled dust. School exposure to cat allergens at low concentrations of 0.17 μg/g was related to higher risk for asthma diagnosis compared with 0.14 μg/g (Smedje and Norbäck 2001). It is common that allergen levels in

### Table 2. Pollutants on health.

<table>
<thead>
<tr>
<th>Study</th>
<th>PM$_{10}$</th>
<th>PM$_{2.5}$</th>
<th>CO</th>
<th>O$_3$</th>
<th>NO$_2$</th>
<th>NOx</th>
<th>Health effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ransom and Pope (1992)</td>
<td>↑</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>Absenteeism from school</td>
</tr>
<tr>
<td>Romieu et al. (1992)</td>
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<td>↑</td>
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<tr>
<td>Gilliland et al. (2000)</td>
<td>0</td>
<td></td>
<td></td>
<td>↑</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Chen et al. (2000)</td>
<td>↓</td>
<td></td>
<td>↑</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Currie et al. (2009)</td>
<td></td>
<td>↑</td>
<td></td>
<td>↑</td>
<td></td>
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<td></td>
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<tr>
<td>Park et al. (2002)</td>
<td>↑</td>
<td></td>
<td></td>
<td>↑</td>
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<tr>
<td>Janssen et al. (2003)</td>
<td></td>
<td>↑</td>
<td></td>
<td>↑</td>
<td></td>
<td></td>
<td>Current conjunctivitis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↑</td>
<td></td>
<td></td>
<td>Hay fever</td>
</tr>
<tr>
<td>Janssen et al. (2003)</td>
<td></td>
<td>↑</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Current wheeze/current phlegm</td>
</tr>
<tr>
<td>Kim et al. (2004)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Current itchy rash</td>
</tr>
<tr>
<td>Gilliland et al. (2001)</td>
<td></td>
<td></td>
<td></td>
<td>↑</td>
<td></td>
<td></td>
<td>Asthma</td>
</tr>
<tr>
<td>↑</td>
<td>Positive correlation</td>
<td>↓</td>
<td>Negative correlation</td>
<td>O</td>
<td>No correlation</td>
<td>Not investigated</td>
<td></td>
</tr>
</tbody>
</table>
classrooms exceed thresholds that have been associated with allergic sensitization (1.0 µg/g for Fel d 1 and 2.0 µg/g for Can f 1) or asthma symptoms in sensitized individuals (8.0 µg/g for Fel d 1 and 10.0 µg/g for Can f 1) (Salo et al. 2009).

Fungi species and by-products
Fungi colonies may release individual spores, clusters of spores or small fungal fragments. Fungal spores constitute a significant fraction of bioaerosol microbial particles and are often 100 to 1000 times more numerous than other bio-particles (Görny et al. 2002). In addition, various species may produce several mycotoxins (microbial volatile organic compound, MVOCs) depending on the substrate.

Several studies have found that mean indoor concentrations of total fungi in school classrooms fluctuated from 92 to 505 CFU/m³ with an average of 305 CFU/m³ (Scheff et al. 2000b, Jo and Seo, 2005, Godwin and Batterman 2007, Viegas et al. 2010), and indoor-to-outdoor ratios were greater than unity in most studies. The predominant fungi species detected in indoor school environments were Penicillium followed by Cladosporium, Aspergillus and Alternaria, and they vary with climate and location, in rural or urban areas.

Numerous studies have reported positive associations for general and respiratory symptoms, including a higher occurrence of respiratory infections, with exposure to fungal particles at mean concentrations of 260 to 1297 CFU/m³ (Taskinen et al. 1999, Savilahti et al. 2001, Meklin et al. 2002, Santilli 2002, Mi et al. 2006). A wide spectrum of health effects were reported among occupants of water-damaged buildings including the occurrence of new allergic diseases shortly after the start of the school year (Savilahti et al. 2001), increased incidence of wheezing (16% vs. 6%; \( P < 0.001 \)) (Taskinen et al. 1999) and asthmatic attacks (Mi et al. 2006). Severe general symptoms such as headaches (88%), sore throat (75%), fatigue (67%) and coughing (54%) were also noticed (Santilli 2002).

Only three epidemiological studies on MVOCs were found and all reported positive associations between the presence of MVOCs indoors and asthma or allergy (Smedje et al. 1996, Elke et al. 1999, Kim et al. 2007). Average concentrations of MVOCs indoors were 423 ng/m³, and were three to four times higher than outdoors (\( P > 0.05 \)), and were associated with nocturnal breathlessness and doctor diagnosed asthma (Kim et al. 2007).

Bacterial concentrations
The airborne bacteria that people are exposed to seldom cause illness; however, high exposure level is potentially harmful to health. Environments with high occupancy density, such as classrooms, should be investigated for bacterial concentrations.

Most studies of airborne bacteria in schools have referred to total bacteria counts, rather than identifications, (Jo and Seo 2005, HESE 2006) or they have separated bacteria according to whether they are Gram-positive and Gram-negative (Scheff et al. 2000b). Bacteria counts ranged from 577 to 1000 CFU/m³ with an average of 785 CFU/m³ (Scheff et al. 2000b, Godwin and Batterman 2007, Viegas et al. 2010). In a study of classrooms in Turkey, the most commonly observed bacteria were Staphylococcus (42.7%), Corynebacterium (20.4%) and Bacillus (6.9%) (Aydogdu et al. 2005). Kim et al. (2007) identified bacteria in 57 classrooms in Swedish schools, with Pseudomonas sp being the most commonly reported (57%), followed by Steptomyces sp (17%) and Bacillus sp (4%).

A few studies have measured endotoxin levels in schools (Rullo et al. 2002, Instanes et al. 2005, Oldfield et al. 2007, Fromme et al. 2008a, Morcos et al. 2011). Endotoxin is a component produced by Gram-negative bacteria. Mean concentrations ranged from 0.1 to 32.2 EU/mg, and were significantly higher in rural school classrooms compared with urban settings.
Although it is well documented that exposure in damp buildings can increase the relative risk of experiencing health problems, there is a lack of a clearly defined threshold for microbial concentrations and microbial by-products. According to the ‘hygiene hypothesis’ exposure to low microbial concentrations (Kim et al. 2007) and endotoxins (Morcos et al. 2011) in school may have protective effects from respiratory symptoms and asthma.

Chemical concentrations in classrooms and health impacts

While VOCs in schools have mainly indoor sources, gaseous pollutants such as NO₂ and CO are generally considered a measure of traffic intensity. Limited research is available on CO in the school environment while six studies on NO₂ and three studies measuring O₃ in the classroom were found.

NO₂

Mean indoor concentrations of NO₂ in schools fluctuated from 8.3 to 77 μg/m³ (Figure 3) (Blondeau et al. 2005, Poupon et al. 2005, Mi et al. 2006, HESE 2006, ODPM 2006, Van Roosbroeck et al. 2007, Zhang et al. 2011). Children attending urban schools were exposed to mean concentrations of NO₂ of 10 μg/m³ while children attending schools in close proximity to highways had four times higher personal exposure to NO₂, ranging between 34.8 and 44 μg/m³ (Van Roosbroeck et al. 2007). These exposures were related to increased respiratory symptoms, allergy exacerbations (especially to indoor allergens), current conjunctivitis, current wheeze and current itchy skin rash compared with children exposed to urban background concentrations (Janssen et al. 2003, Van Roosbroeck et al. 2007). However, these exposures are still around the WHO recommended guidelines for maximum exposure of 40 μg/m³ (WHO 2010). Exposure to higher indoor concentrations of NO₂ in school (34–77 μg/m³) commonly encountered in schools (Figure 3) was significantly related to asthma occurrence and respiratory morbidity (Janssen et al. 2003, Kim et al. 2004, Mi et al. 2006).

There is some limited evidence that suggested that indoor peak concentrations might be more important than average exposure. Pilotto et al. (1997) found a significant association between absenteeism and hourly school exposure of 150 μg/m³, which is below WHO (2010) guidelines of 200 μg/m³ for peak concentrations.

O₃

Studies on ozone levels in European classrooms have reported concentrations. Blondeau et al. (2005) in eight French schools reported mean concentrations of 11.6 μg/m³ in the summer (median range: 0–17.92) and 12.8 μg/m³ in winter (range: 4.18–33.3). Similar median results of 10.35 μg/m³ (median range: 3–15.1) were reported in HESE (2006) study in six European cities in 46 classrooms in 21 schools. Lowest mean indoor O₃ concentrations were reported in 10 schools in Shanghai (Mi et al. 2006) and ranged from 1.1 to 8.75 (average: 5.46 μg/m³ ± 3.1)

School illness-related absenteeism increased at higher outdoor concentrations of ozone (Romieu et al. 1992, Park et al. 2002), and could be significantly predicted if lagged effects of exposure were taken into consideration (Chen et al. 2000, Gilliland et al. 2001). Park et al. (2002) estimated that relative risks of illness-related absenteeism for O₃ were 1.08 (95% CI, 1.06–1.11) per 32 μg/m³, while Gilliland et al. (2001) for a similar increase in exposure quantified an increase of 63% risk of illness-related absenteeism with the effects lagged for a period of 5 days. Chen et al. (2000) reported that an increase of 100 μg/m³ in O₃ can increase the risk for illness-related absenteeism by 13% with lagged effects taken into consideration. While WHO (2010) recommended ozone concentrations lower than 100 μg/m³ over an 8-hour period,
overall evidence suggested that minimum increase of 6% in relative risks of illness-related absenteeism among children should be expected for an increase in the range of 30–50 μg/m³.

Specific health effects accounting for absenteeism at high ozone concentrations were mostly related to respiratory illness (Romieu et al. 1992, Gilliland et al. 2001). Gilliland et al. (2001) quantified that the relative risk per 40 μg/m³ corresponded to an increase by 83% for respiratory illnesses, 45.1% for upper respiratory illnesses, and 174% for lower respiratory illnesses with wet cough. No relationship between respiratory symptoms and lower indoor ozone ranging from 1 to 9 μg/m³ and 17 to 28 μg/m³ outdoors (Mi et al. 2006) could be established.

**CO**

Little research on CO levels in school classrooms is available. Measured average indoor concentrations fluctuated from 1.17 ppm during the summer to 3.96 ppm during the winter period (Chaloulakou et al. 2003). Although these levels are below WHO (2010) guidelines of
6.1 ppm for 24-hour exposure, epidemiological studies have associated mean CO levels of 2.73 ppm (range: 0.65–6.23 ppm) with an increase by 3.8% in absenteeism with no lagged effects (Chen et al. 2000, Currie et al. 2009).

VOCs

VOCs in schools originate from a combination of emissions from indoor building materials, human activities and outdoor sources. As it is possible to detect 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 (Mølhave 2009).

The concentration of TVOCs measured in 104 classrooms in four studies formed a log-norm distribution (Figure 4), with 60% of the monitored values between 80 and 200 μg/m³. Daisey et al. (2003) in an extensive review of published evidence reported higher average TVOC concentrations ranging from 100 to 1600 μg/m³.

Identifications of the most commonly reported specific compounds found indoors, in order of magnitude, were toluene, limonene, benzene, m,p-xylene, o-xylene and styrene, T3CE and T4CE (Norbäck 1995, Adgate et al. 2004, ODPM 2006, Godwin and Batterman 2007, Pekey and Arslanbas 2008). High concentrations of benzene in classrooms ranged from 0.6 (Adgate et al. 2004) to 19.77 μg/m³ (Pekey and Arslanbas 2008). In a study of Swedish classrooms ‘formaldehyde’ concentrations ranged from below detectable limits, while in Turkish schools it was

Figure 4. Distribution of TVOCs in 104 classrooms (Norbäck et al. 1995, ODPM 2006, Godwin and Batterman 2007, Sofuoglu et al. 2011).

As a result of the relative complexity of associating TVOCs to health outcomes due to individual susceptibility, and the unknown interaction of the compounds, TVOCs can only be used as an indicator of sensory effects. However, high levels of TVOCs in classrooms were suspected to be the source of irritations (Willers 1996), throat dryness (Norbäck 1995) and adverse health effects (Wargocki et al. 2002, Bakó-Biró et al. 2004, Wolkoff et al. 2008). Individual VOCs have been related directly to health outcomes, such as benzene and formaldehyde, which are known to be carcinogenic (WHO 2010) (Tables 3 and 4).

Subjective perception of IAQ

Little information is available to model how individual environmental conditions relate to thermal, acoustic and visual comfort and satisfaction with IAQ, and how these influence overall satisfaction with indoor environmental quality (IEQ). A review of current evidence suggested that in non-industrial environments, including schools building, users considered thermal comfort (Frontczak and Wargocki 2011) and satisfaction with IAQ (Astolfi and Pellerey 2008) to be the most important parameter influencing overall satisfaction with IEQ.

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). At present, it is not clear if SBS consists of symptoms correlated to an exposure or reflects an accumulation of effects of several unrelated indoor exposures.

Additionally to thermal sensation, keeping the air dry and cool significantly affects IAQ perception directly. Apart from the improvement in cognitive performance, lowering the temperature from 25 to 20°C reduced SBS symptoms among students (Mysen et al. 2005, Wargocki 2008, Zhang et al. 2011). Thermal conditions may also affect IAQ indirectly by influencing emission sources and indoor concentrations of pollutants.

Increased ventilation is known to mitigate overheating, and therefore indirectly improving IAQ perception. Direct relationships between outdoor airflows higher than 10 l/s·p and the reduction of the prevalence of SBS and occupant dissatisfaction with air quality were identified from a meta-analysis study (Godish and Spengler 1996). Although increased ventilation results in lower CO₂ concentrations, studies have failed to establish a direct relation between perceived IAQ and CO₂ levels (Myhrvold et al. 1996, Smedje et al. 1997a).

Most studies on subjective IAQ typically deal with office workers and few of them employ actual measurements of pollution levels (Wargocki et al. 2002). A study in 38 schools employed a questionnaire survey and exposure measurements and related dissatisfaction with TVOCs and mould concentrations (Smedje et al. 1997a). The study quantified that for every 100 µg/m³ of TVOCs dissatisfaction increased by 1.8 (CI: 1.1–3, CI 95%) The most commonly detected VOCs in the study were α-pinene, limonene, toluene and xylene.

Apart from TVOCs, total moulds were a significant factor affecting satisfaction with IAQ (Cooley et al. 1998). For every 10-fold increase of moulds, dissatisfaction with IAQ increased by 1.9 (1.3–2.8, CI: 95%) (Smedje et al. 1997a). Fungi species suspected to be related with dissatisfaction were Cladosporium, Mycelia sterilia and Penicillium. Moulds were also related to SBS complains from occupants in 48 schools in the US, particularly for Penicillium and Stachybotrys (Cooley et al. 1998).

Exposure to higher NO₂ concentrations might be related to SBS, especially mucosal symptoms (odds ratio = 1.13 per 10 µg/m³) (Zhang et al. 2011); however, Smedje et al. (1997a) found no relationship between perceived IAQ and NO₂ or CO.
Table 3. Summarizing table of guidelines, concentrations in indoor educational settings and suggestive evidence of exposure causing health irritations.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>WHO (2010) guidelines</th>
<th>Range of average indoor concentrations in schools</th>
<th>Indoor concentrations in schools associated with reported health responses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>O₃</strong></td>
<td>100 µg/m³ 8-hour mean</td>
<td>Mi et al. (2006) 5.46 (1.1–8.7)</td>
<td>Illness-related absenteeism were 1.08 (95% CI, 1.06–1.11) per 32 µg/m³ (Park et al. 2002)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blondeau et al. (2005)-summer 7.28 (3.6–28)</td>
<td>An increase of 63% of ill related absenteeism per 30 µg/m³ (Gilliland et al. 2001)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blondeau et al. (2005)-winter 12.8 (4.18–33.3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>HESE (2006) 14.3 (3.0–48.5)</td>
<td></td>
</tr>
<tr>
<td><strong>NO₂</strong></td>
<td>200 µg/m³ 1-hour</td>
<td>Blondeau et al. (2005) 5.9 (3.3–8.46)</td>
<td>34.8 ± 5.2 µg/m³ respiratory symptoms, allergy exacerbations (Janssen et al. 2003)</td>
</tr>
<tr>
<td></td>
<td>40 µg/m³ Annual</td>
<td>Blondeau et al. (2005)-winter 18.6 (3.5–50.6)</td>
<td>34–77 µg/m³: Current asthma (Mi et al. 2006) &gt;150.4 µg/m³: school absenteeism (Pilotto et al. 1997)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HESE (2006) 14.1 (3.4–14.5)</td>
<td>For 10 µg/m³ (odds ratio = 1.13) SBS symptoms (Zhang et al. 2011)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Van Roosbroeck et al. (2007) 69.8 (64.4–77)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zhang et al. (2011) 39.4 (15.5–61.6)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mi et al. (2006) 42.0 (25.4–57)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ODPM (2006) 58.0 (44–77)</td>
<td></td>
</tr>
<tr>
<td><strong>CO</strong></td>
<td>100 (= 87.3 ppm) 15 min</td>
<td>Chaloulakou et al. (2003) 1.17–3.96 ppm</td>
<td>2.73 ppm (0.65 to 6.23 ppm) an increase by 3.8% in absenteeism with no lagged effects (Chen et al. 2000).</td>
</tr>
<tr>
<td></td>
<td>35 (= 30.5 ppm) 1 hour</td>
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<tr>
<td></td>
<td>10 (= 8.73 ppm) 8 hours</td>
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<tr>
<td></td>
<td>7 (= 6.1 ppm) 24 hours</td>
<td></td>
<td></td>
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<tr>
<td><strong>PM₁₀</strong></td>
<td>20 µg/m³ 24-hour mean</td>
<td>Mean 43 to 1181.1 µg/m³</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 µg/m³ Annual mean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
<td>Unit</td>
<td>Description</td>
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<tr>
<td>-----------</td>
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<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>PM$_{2.5}$</td>
<td>10 µg/m$^3$</td>
<td>24 hour mean</td>
<td>Median 20.2 µg/m$^3$ (mean concentrations in studies 12 to 360)</td>
</tr>
<tr>
<td>PM$_1$</td>
<td>25 µg/m$^3$</td>
<td>Annual mean</td>
<td>188 n/cm$^3$ to 14,300 n/cm$^3$</td>
</tr>
<tr>
<td>TVOCs</td>
<td>No standards have been set for VOCs in non industrial settings</td>
<td>10 to 704 µg/m$^3$</td>
<td>Mean 35 µg/m$^3$ (2–302) dissatisfaction with IAQ (Smedje et al. 1997a, 1997b)</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>100 µg/m$^3$</td>
<td>30-min</td>
<td>From non-detectable 0.06 to 19.77 µg/m$^3$</td>
</tr>
<tr>
<td>Benzene</td>
<td>No safe limit</td>
<td></td>
<td>Carcinogen (?)</td>
</tr>
<tr>
<td>Cat allergen</td>
<td>1 µg/g</td>
<td>Sensitization</td>
<td>Non detectable -2.28 µg/g</td>
</tr>
<tr>
<td>8 µg/g</td>
<td>Acute asthma symptoms</td>
<td>0.173 µg/g was related to asthma diagnosis</td>
<td></td>
</tr>
<tr>
<td>Total fungi</td>
<td>No clearly defined guidelines</td>
<td>92 to 505 CFU/m$^3$</td>
<td>260 to 1297 CFU/m$^3$ (in one case 53 333 CFU/m$^3$ in complain school)</td>
</tr>
<tr>
<td></td>
<td>&gt;1000 CFU/m$^3$</td>
<td></td>
<td>Huge range of general symptoms (headache, eye symptoms, upper and lower respiratory symptoms)</td>
</tr>
</tbody>
</table>
Table 4. Factors affecting VOCs in classrooms.

<table>
<thead>
<tr>
<th></th>
<th>VOCs</th>
<th>Comments</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Benzene</td>
<td>Formaldehyde</td>
<td>T3CE</td>
</tr>
<tr>
<td>Occupancy</td>
<td>○</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td></td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Ventilation rates</td>
<td>○</td>
<td>.</td>
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<tr>
<td></td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>CO₂</td>
<td>○</td>
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</tbody>
</table>
Factors affecting IAQ and TC
In this section the effect of key environmental and behavioural factors on pollution levels in the classrooms are investigated.

Envelope permeability and indoor/outdoor ratios
The relationship between indoor to outdoor concentrations is often considered in terms of indoor to outdoor concentration ratios (I/O). In the absence of indoor sources, this ratio is also referred to as infiltration factor or penetration efficiency.

Indoor to outdoor concentrations of all PM fractions were always greater than unity during school hours and ranged between 1.08–3.59 for PM\(_{10}\) and 1.6–2.79 for PM\(_{2.5}\) and 1.52–2.18 for PM\(_1\) (Scheff \textit{et al.} 2000b, Branis \textit{et al.} 2005, Heudorf \textit{et al.} 2007, Goyal and Khare 2009).

In general, most studies found weak relationships between indoor concentrations of PM\(_{10}\) and ambient concentrations during unoccupied periods (Poupard \textit{et al.} 2005, Fromme \textit{et al.} 2007, Goyal and Khare 2009). Indoor concentrations of PM\(_{2.5}\) and PM\(_1\) in classrooms were significantly correlated to outdoors; the average rate of diesel traffic was the only significant predictor of average fine and ultrafine indoor concentrations (Blondeau \textit{et al.} 2005, Poupard \textit{et al.} 2005, Weichenthal \textit{et al.} 2008, Goyal and Khare 2009, Patel \textit{et al.} 2009). The strong influence of outdoor sources suggested that there was an absence of indoor sources and the envelope provided little protection.

Because bioaerosols are governed by the same principles as PMs, their I/O ratio was greater than unity and lay in the range 1.6 < I/O < 2.7 (Scheff \textit{et al.} 2000b, Jo and Seo 2005, Kim \textit{et al.} 2007).

Studies have found weak relationships between indoor concentrations of PM\(_{10}\) and ambient concentrations during unoccupied periods (Poupard \textit{et al.} 2005, Fromme \textit{et al.} 2007, Goyal and Khare 2009). Indoor concentrations of PM\(_{2.5}\) and PM\(_1\) in classrooms were significantly correlated to outdoors; the average rate of diesel traffic was the only significant predictor of average fine and ultrafine indoor concentrations (Blondeau \textit{et al.} 2005, Poupard \textit{et al.} 2005, Weichenthal \textit{et al.} 2008, Goyal and Khare 2009, Patel \textit{et al.} 2009). The strong influence of outdoor sources suggested that there was an absence of indoor sources and the envelope provided little protection.

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The role of the airtightness of the building envelope to indoor concentrations of ozone is unclear because it is a highly reactive gas. The I/O ratio of ozone has been reported as being between 0 < I/O < 0.5 (Poupard \textit{et al.} 2005, HESE 2006, Mi \textit{et al.} 2006), and for airtight buildings the ratio was close to zero and unrelated to outdoor concentrations. For more permeable buildings, the ratio increased with decreasing airtightness (Poupard \textit{et al.} 2005).

The contribution of strong indoor sources on VOCs concentrations was reflected on high I/O ratios; in 83% of monitored classrooms exceeded outdoor concentrations from 10 to 20 times (Norbäck 1995, Adgate \textit{et al.} 2004, ODPM 2006, Godwin and Batterman 2007, Pekey and Arslanbas 2008). The independency of indoor VOC concentrations from outdoor levels was reflected in their variability within schools (Roorda-Knape \textit{et al.} 1998, Heudorf \textit{et al.} 2007).

Overall evidence suggested that traffic-related pollutants with outdoor sources, such as NO\(_2\), CO and PM, had I/O ratios close to unity, as they were able to penetrate the building envelope regardless of airtightness. Lower I/O ratios were recorded for O\(_3\); however, the underlying relationship is not clear as ozone is a highly reactive gas. The relative strength of pollutants with indoor sources such as VOCs was reflected on high I/O ratios, and high variability of I/O ratios among adjacent classrooms.
Ventilation rates on indoor concentrations

The relation between CO₂ concentration and the corresponding air flow may be described by a power curve. Out of the 216 classrooms described in the literature, 44 mechanically ventilated classrooms achieved average ventilation rates of 8 l/s-p corresponding to an average CO₂ of 960 ppm. Naturally ventilated classrooms in the database achieved average ventilation rates of 4.5 l/s-p corresponding to average concentrations of CO₂ of 1470 ppm (Figure 5).

Average concentrations of indoor TVOCs had a moderate relationship with average CO₂ concentrations. CO₂ concentrations exceeding 1500 ppm were related to TVOCs above 100 μg/m³, and were also associated with increased dissatisfaction with IAQ (Smedje et al. 1997a). The efficiency of ventilation in reducing VOC concentrations was stronger for VOCs with indoor sources, specifically limonene and pinene (Godwin and Batterman 2007) (Figure 6).

Studies in schools generally found a negative correlation between air exchange rates and indoor particle concentrations, and this relationship appeared stronger for the smaller particle sizes (HESE 2006, Guo et al. 2008, Goyal and Khare 2009). Only one study noticed elevated PM levels during ventilation periods, most likely due to resuspension from air currents (Heudorf et al. 2007).

A weak positive relationship between air exchange rate and Aspergillus was detected and correlation was higher when total bioaerosols were considered (Godwin and Batterman 2007). Lower total and viable bacteria, moulds and air allergens were measured in mechanically ventilated classrooms with lower CO₂ levels and humidity (HESE 2006). CO₂ levels in heavily occupied schools have been found to correlate with the levels of airborne bacterial markers, with an increase of 1 ppm in CO₂ levels corresponding to an increase of 1 CFU/m³ in airborne fungi (Fox et al. 2003, Ramachandran et al. 2005).

Limited evidence is available on the relationship between NO₂ and O₃ levels and ventilation rates. While no relationship was found for NO₂ (Poupard et al. 2005), suggestive evidence related increased ventilation rates resulted to increased O₃ levels (Gold et al. 1996, Poupard et al. 2005).

Figure 5. NV and MV log chart of air flow rates and the resulting decrease in CO₂ levels in nine peer reviewed papers in 216 classrooms (Smedje et al. 1997a, 1997b, Coley and Beisteiner 2002, Kim et al. 2005, Mi et al. 2006, Zhao et al. 2006, Bakó-Biró et al. 2007, Santamouris et al. 2008, Mors 2009, Mumovic et al. 2009).
Gold et al. (1996) found I/O of ozone concentrations depended on permeability; in occupied classrooms it was up to $0.71 \pm 0.03$ when cross-ventilation took place, and dropped to $0.15 \pm 0.02$ when natural ventilation was eliminated.

Overall the evidence suggests that increased ventilation rates are effective in removing airborne particles, air allergens and TVOCs concentrations. No relationship between increased ventilation and NO$_2$ could be established. Timing of window opening in classrooms might be an important factor resulting to higher indoor concentrations of O$_3$.

**Seasonality**

Variations in pollutant concentrations can be observed in an hourly, daily, weekly, monthly and seasonal basis. Seasonal variations may directly influence the concentrations of pollutants both indoors and outdoors and indirectly through adaptive actions from the occupants. Varying climatic parameters may also indirectly influence the contribution of outdoor pollutants to indoor levels.

Limited research is available on the microbial seasonality in school classrooms. Studies repeating measurements among seasons found indoor summer to winter ratio of up to 15 and 10 for fungi and bacteria, respectively (Jo and Seo 2005, Ramachandran et al. 2005). The concentration order of individual fungi remained unchanged regardless season (Jo and Seo 2005). Higher temperatures favoured fungal and bacterial growth (Jo and Seo 2005, Ramachandran et al. 2005). Different humidity levels in similar temperatures had no significant influence on bacteria concentrations, but caused some fungal species to significantly increase. Only one study on diurnal variations of microbial concentrations was found, and reported higher levels for all investigated fungi and bacteria during the morning hours (Scheff et al. 2000b). Allergens and endotoxin were not found to be dependent on seasonality (Fromme et al. 2008a, 2008b). Some studies, however, reported seasonal variations of allergens, mostly on mice and cockroaches (Chew et al. 2005, Abramson et al. 2006).

Studies found higher indoor TVOCs concentrations during heating season than non-heating season (Adgate et al. 2004, Shendell et al. 2004a, 2004b, Pekey and Arslanbas 2008, Sofuoglu...
While most studies attributed the variations in different ventilation patterns (Shendell et al. 2004b, Pekey and Arslanbas 2008), a study speculated that elevated indoor TVOCs concentrations during the heating season resulted from emissions of a freshly painted wall when the radiator was on (Sofuoglu et al. 2011). Increased ventilation patterns during summer months altered the VOCs profile in the classrooms allowing greater contribution of outdoor VOCs (Pekey and Arslanbas 2008), which may be more harmful to human health.

While annual studies on PM concentrations in school classrooms are scarce, studies found two to three times higher concentrations in winter compared with summer, and the difference was higher when optical methods were compared with gravimetric (Fromme et al. 2007, Goyal and Khare 2009). Studies performed over shorter periods found no relationship or a weak negative relationship with temperatures and a moderate positive relationship with relative humidity (RH) (Branis et al. 2005, Goyal and Khare 2009). While temperature might influence PM concentrations directly (Table 5), the temperature difference between exterior and interior might affect penetration ability of the pollutants. In non-winter periods higher I/O ratios were noticed in the non-winter period (Branis et al. 2005, Goyal and Khare 2009).

When temperature is generally lower than outdoors, a temperature gradient is created leading PMs into the building; therefore seasonability also affected size variations of particles (Goyal and Khare 2009): PM$_{10}$ dominated indoor PM concentrations in non-winters, representing 70 ± 5% of total respirable particulate matter, followed by 17 ± 3% PM$_{2.5}$ and 13 ± 2% PM$_{1}$, while during winters, it was 49 ± 4% followed by 27 ± 2% and 24 ± 3% for PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ respectively. Rain had a wash out effects on outdoor particle concentrations (Guo et al. 2008).

Apart from seasonal variations, weekly and daily variations were also reported and were mainly related to traffic intensity. Increased outdoor particle matter during the start of the school day coincided with the traffic peak hours, and decreased later in the day with the increase of temperature (Goyal and Khare 2009). Weekdays had higher PM concentrations than weekends.

Wind speed was found to be significant predictors of indoor fine and ultrafine particles' concentrations (Branis et al. 2005, Weichenthal et al. 2008, Goyal and Khare 2009, Patel et al. 2009). While lowest wind speed from highway traffic elevated indoor PM$_{2.5}$ concentrations, higher wind speeds dispersed outdoor concentrations.

Similarly, wind direction and proximity to main traffic arteries were mainly affecting NO$_2$ indoor concentrations in flat terrain, low-rise area (Kim et al. 2004, Van Roosbroeck et al. 2007). A good agreement between fixed stations and indoor concentrations was reported only for schools located more than 300 m away from major high traffic areas or upwind. Measurements in school downwind and in proximity to pollution sources were up to 50% higher compared with background schools.

One study (Blondeau et al. 2005) examined seasonality of O$_3$ and NO$_2$ (Figure 3) in schools and found higher mean concentrations both indoors and outdoors in winter period. I/O ratios remained similar for both seasons. Mean indoor concentrations for O$_3$ in summer were 3.68 µg/m$^3$ (mean range: 3.6–20.72) compared with 8.66 µg/m$^3$ (mean range: 4.18–20.46) during winter. Similarly, CO concentrations observed during winter were higher than in summer (Chaloulakou et al. 2003). The contribution of outdoor CO concentration indoors was higher in winter, as the mean daily I/O concentration ratio ranged between 0.49 and 0.79 in the summer and between 0.53 and 0.89 in the winter period (Chaloulakou et al. 2003).

Overall, seasonality was found to affect microbial growth strongly. Temperature was found to affect concentrations of pollutants both directly and indirectly: as the temperature gradient increased, the outdoor contribution to the interior concentration of PMs and CO also rose. Varying wind speeds and directions throughout the year were also found to affect penetration ability of traffic generated pollutants, such as PMs (especially the smaller fraction) and NO$_2$. Increased ventilation rates during the non-winter period reduced TVOCs, but elevated levels of
### Table 5. Factors affecting indoor PM concentration.

<table>
<thead>
<tr>
<th></th>
<th>PM$_{10}$</th>
<th>PM$_{2.5}$</th>
<th>PM$_{1}$</th>
<th>Comments</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ventilation</strong></td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>PM$_{10}$ were not affected by ventilation rates during intense occupants’ activities</td>
<td>Goyal and Khare (2009)</td>
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<td><strong>Outdoor</strong></td>
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<tr>
<td><strong>concentrations</strong></td>
<td></td>
<td>↑</td>
<td></td>
<td>Indoor concentrations were strongly correlated to outdoor concentrations, similar indoor concentrations among schools in proximity</td>
<td>Patel <em>et al.</em> (2009)</td>
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<tr>
<td>Outdoor PM$_{2.5}$</td>
<td>↑</td>
<td>↑</td>
<td></td>
<td>Similar concentrations of smaller fractions within schools</td>
<td>Fromme <em>et al.</em> (2007)</td>
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<td><strong>I/O</strong></td>
<td>&gt;1</td>
<td>&gt;1</td>
<td>&gt;1</td>
<td>Occupied periods and ventilation periods</td>
<td>Goyal and Khare (2009)</td>
</tr>
<tr>
<td><strong>Occupancy</strong></td>
<td>↑</td>
<td>o</td>
<td>o</td>
<td>Occupancy affected indoor PM$_{10}$ concentrations more than other parameters</td>
<td>Goyal and Khare (2009)</td>
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<tr>
<td></td>
<td>↑</td>
<td>o</td>
<td>o</td>
<td>During unoccupied periods PM$<em>{2.5}$ and PM$</em>{1}$ was bigger</td>
<td>Branis <em>et al.</em> (2005)</td>
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<td></td>
<td>↑</td>
<td></td>
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<td>Higher concentrations of PM$_{10}$ in classrooms with younger children</td>
<td>Heudorf <em>et al.</em> (2007)</td>
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<th>Seasonality</th>
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<th>Non - winter</th>
<th>PM$_{10}$</th>
<th>PM$_{2.5}$</th>
<th>PM$_{1}$</th>
<th>Comments</th>
<th>Study</th>
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<td>Indoor and outdoor</td>
<td>Indoor and outdoor</td>
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<td>2–3 times higher during winter period</td>
<td>Goyal and Khare (2009)</td>
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<td>Outdoor</td>
<td>Indoor and outdoor</td>
<td>▼</td>
<td>Percentage of PM$_{10}$/total RSPM were higher during non-winter</td>
<td>Goyal and Khare (2009)</td>
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<td>RH</td>
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<td>Wind speed</td>
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<td>Physical characteristics</td>
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<td>Volume of the classroom cleanliness</td>
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<td>Mechanical ventilation</td>
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Goyal and Khare (2009)

Weichenthal et al. (2008)

Branis et al. (2005)

Goyal and Khare (2009)

Weichenthal et al. (2008)

Branis et al. (2005)

Fromme et al. (2007)

Goyal and Khare (2009)

Weichenthal et al. (2008)

Branis et al. (2005)

Patel et al. (2009)

Weichenthal et al. (2008)

Heudorf et al. (2007)

Fromme et al. (2007)

Fromme et al. (2007)

HESE (2006)
specific VOCs with outdoor sources. Heating sources might also affect emission rates of TVOCs from internal finishing.

**Occupancy**

There is strong evidence to indicate that the intense activities of students resulted in elevated concentrations of PM and affected the larger size fraction to a greater extend (Branis et al. 2005, Poupard et al. 2005, Fromme et al. 2007, Goyal and Khare 2009). The effect of occupancy systematically affected indoor PM$_{10}$ concentrations more than any other physical parameter (Sheff et al. 2000b, Branis et al. 2005, Poupard et al. 2005, Heudorf et al. 2007) including meteorological parameters (Fromme et al. 2008a, 2008b, Goyal and Khare 2009). Fromme et al. (2008a, 2008b) noticed that classrooms with children younger than 8 years old, who are physically more active than older children, had higher PM10 levels. Although it is likely that occupants may introduce new particles through clothing and shoes indoors, in the absence of data on the size distribution of particles generated indoors by humans or other sources, re-suspension is suggested as being the dominant phenomenon behind the increase.

Occupants’ activities increased bioaerosol concentrations both directly through the presence of children (Fox et al. 2003, Aydogdu et al. 2005), and indirectly through re-suspension of previously deposited particles (Scheff et al. 2000a, 2000b, Fox et al. 2003, Jo and Seo 2005, Godwin and Batterman 2007). Meaningful exposure to cat and dog allergens in classrooms transported from home through clothing has been documented; therefore, occupants’ pet ownership was found the most significant predictor of allergen levels (Patchett et al. 1997, Almqvist et al. 1999, Zuraimi et al. 2008).

Higher VOCs concentrations were monitored during occupied periods (Scheff et al. 2000b, Shendell et al. 2004b). Different activities in school microenvironment were reflected in large variability among secondary, primary and kindergarten classrooms (Godwin and Batterman 2007, Sofuoglu et al. 2011).

In summary, occupancy was found to affect PM and particularly the larger fraction due to re-suspension of previously deposited matter. Pollutants with indoor sources like VOCs and microbial concentrations were elevated during the occupied period. Traffic related pollutants, such as NO$_2$, O$_3$ and CO were not affected by occupancy.

**Building’s characteristics/maintenance**

Apart from absolute values of physical parameters such as ventilation rate and temperature, the ventilation system itself can affect the perceived environmental quality and health of the occupants. Frequency of symptoms in students learning in air-conditioned classrooms were higher than in naturally ventilated classrooms (Koo et al. 1997, Mendell and Smith 1990), and included watery and runny eyes although air changes were higher (Kinshella et al. 2001), and occurrence of new allergies (Mysen et al. 2005). The incidence of asthmatic symptoms was lower for children who attended schools with new ventilation systems installed (Smedje and Norback 2000). Potential causes of adverse health effects and dissatisfaction due to HVAC systems comprised improper maintenance of the HVAC systems (Wargocki et al. 2002), which was a significant predictor of high bacterial markers and total bioaerosol counts (Lee et al. 2002, Fox et al. 2003, Mysen et al. 2005, Wong et al. 2008).

Air dispersion in the occupied zone may affect satisfaction with IAQ. At the same level of exposure to airborne pollutants, more complaints were reported in mechanically ventilated schools with mixing flow (56%) and mechanical exhaust (61%) compared with naturally ventilated classrooms or classrooms with displacement ventilation (48%) (Smedje et al. 1997a).
combined with demand control CO₂ and temperature sensor (DCDV-CO₂) was found to significantly improve energy savings (Wachenfeldt et al. 2007). Although displacement of pollutants from breathing zone might improve air quality in the occupied zone, temperature difference between the supply and room air temperatures greater than 10°C may create local discomfort at ankle level (Mumovic et al. 2009).

Interior finishing in the classroom such as furnishings and textiles in the classroom may act as significant reservoirs of irritants and allergens, and have an impact on the school IAQ (Smedje and Norbäck, 2001, Foarde and Berry 2004, Arbes et al. 2005). Dirty carpets can pollute the indoor environment of the classroom (Bakó-Biró et al. 2012). Carpeting was the only significant factor affecting Alternaria (Arbes et al. 2005) and Aspergillus concentrations (Godwin and Batterman 2007). Carpeting also acted as cat and dog allergen reservoir, elevating concentrations 10-fold in day care centres compared with hard floor (Arbes et al. 2005). The highest levels of allergens have been found in upholstery seats (Zhao et al. 2006).

Various abatement measurements focused on reducing dust reservoirs, like introducing special clothing (Karlsson et al. 2004). Intensified cleaning removed deposited resuspendable dust and reduced indoor PM₁₀ concentrations (Heudorf et al. 2007) and pet allergens (Munir et al. 1996). Higher levels of settled dust in the classroom act as allergens reservoirs, and were related to nasal obstruction, inflammatory biomarkers in nasal lavage (Wålinder et al. 1998) and asthma occurrence (Smedje et al. 1997b). However, cleaning products used in classroom should be carefully selected, as they may contain terpenes, which raise indoor VOC concentrations and interact with ozone leading to the formation of secondary organic compounds (Morawska et al. 2009).

Different materials used in buildings of varying age may affect the growth of microbial concentrations and emissions. Increasing age of building has been positively correlated with bioaerosol concentrations (Aydogdu et al. 2005, Ozkutuk et al. 2008), and negatively with MVOCs (Kim et al. 2007). In similar conditions of temperature and RH, higher bioaerosol concentrations were monitored in portable compared with conventional classrooms (Godwin and Batterman, 2007) (e.g. median levels of Aspergillus and Penicillium of 1610 vs. 443 counts/m³, respectively) and in below ground classrooms (Jo and Seo 2005) and might be related to UV sun radiation levels.

Conclusions

This report primarily investigated the interrelationships between environmental quality currently predominating in educational settings, the health responses from the occupants and the adequacy of the regulatory framework. Overall evidence showed high concentration of pollutants in school classrooms were common, affecting health and academic performance of the occupants.

Scientific evidence suggests that ventilation rates above 8 l/s-p and CO₂ concentrations below 1000 ppm can improve health and comfort of the occupants and foster the learning process. Lower ventilation rates were linked to an increased risk for viral infections and also to asthmatic symptoms and nasal patency. Moreover, a decrease in ventilation rates and a corresponding increase in CO₂ concentrations resulted to impaired attention span, concentration loss and tiredness.

Increased ventilation rates were also related to increased satisfaction with IAQ both directly and indirectly through (1) mitigating overheating (2) reducing TVOCs and (3) reducing microbial concentrations:

1. Statistically valid studies on thermal comfort in classrooms are sparse but there is evidence that overheating is common. Apart from corresponding energy savings, lowering the temperature from 25 to 20°C also improved health and productivity of the occupants.
Keeping the air dry and cool might improve the perception and reduce SBS and health symptoms.

2. Concentrations of TVOCs exhibited a moderate positive relationship with CO₂ concentrations and were related strongly to dissatisfaction with IAQ. Therefore, increased ventilation rates resulting in lower CO₂ concentration also removed indoor generated pollutants and increased satisfaction with IAQ.

3. Moulds were also strongly related to dissatisfaction with IAQ. Moreover, concentrations of indoor moulds were positively related to increased temperature and RH. Mitigation of overheating would therefore contribute indirectly to IAQ perception.

Therefore, an integrated approach for the simultaneous provision of acceptable IAQ and thermal comfort should be adopted. In many cases, passive measures applied in buildings may be sufficient to limit internal temperatures to those specified earlier and improve IAQ: thermal mass, orientation of the façade, solar protection and design of windows to enhance ventilation effectiveness, and finally by controlling internal gains.

In other cases, dedicated ventilation systems that are appropriately maintained may be necessary to achieve the above targets. Mechanical ventilation can offer improved indoor environmental condition with better control of the indoor environment and filtering of the supply air. Moreover, the air dispersion and ventilation system itself can affect satisfaction with the environmental quality. Poor maintenance of the ventilation systems in examined schools increased indoor contamination and raised complaints among the occupants. Demand control displacement systems improved perceived IAQ and allowed for energy savings, although there might be a risk for local thermal discomfort.

Advantages of free running buildings operating in local climates rely on low operational energy use and maintenance costs, and greater satisfaction of occupants with the IEQ including acceptance of wider temperature range compared with mechanically ventilated buildings.

Although sensory effects may provide a first indication of IAQ problems, health risks should be considered separately from perception, as some harmful pollutants, such as CO or radon, are not sensed by humans.

A striking feature of this work is the high indoor concentrations of traffic-related pollutants above current guidelines reported in many European classrooms. Penetration to the interior of NO₂, CO and fine and ultrafine PM was mostly related to proximity to pollution sources and wind direction, while the building envelope provided little protection. Concentrations monitored in field surveys often exceeded guidelines for NO₂ and fine fractions. No guidelines have yet been developed for ultrafine particles. Therefore, location and orientation of new school buildings should take into account environmental parameters that affect personal exposure. Building envelope may act as a barrier for ozone; therefore, timing of window opening might be important. Ozone was associated to illness-related absenteeism, especially when lagged effects were taken into account.

While concentrations in schools exceeded recommended guidelines, persuasive evidence linked respiratory disease and illness-related absenteeism to exposure at concentrations of NO₂, O₃ and CO even below these guidelines. Limited research is available on health effects of exposure to fine and ultrafine particles. A limitation of epidemiological studies associating exposure to these pollutants lies in the use of measurements from central fixed stations whereas indoor concentrations may differ significantly.

High density in school classrooms was the most significant factor affecting microbial concentrations. Similarly to non-viable particle matter occupants’ intense activities re-suspend bioaerosols. Other factors affecting total bioaerosols concentrations positively may be related to building age, wall-to-wall carpeting and limited daylight. Increased fungal concentrations and allergens are
related to general symptoms, respiratory symptoms and higher occurrence of respiratory infections. More research is needed on the effect on asthmatic symptoms of by-products (particularly MVOCs) of microbial concentrations and plasticisers of newer materials.

It is essential to ensure the broad range of construction materials and cleaning products introduced in classrooms do not seriously impact IAQ, even when ventilation rates fall below code requirements.

This comprehensive review of recent literature has highlighted the degraded IAQ in school environments and the consequent health implications for children’s educational and physical development. Researchers and policymakers need to consider that high outdoor pollution levels, unsuitable interior finishing, high occupancy density, and inadequate legislation contribute to the high indoor pollution levels currently occurring in schools.

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