3 Ventilation, Indoor Air Quality, Health, and Productivity

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CONTENTS

3.1 INTRODUCTION

Buildings should provide shelter and appropriate conditions for working, learning, leisure, and comfortable living. A built environment should be safe, with no health hazards for its users due to poor design and construction, and/or inadequate operation and maintenance and performance. Negligence and failing to take any actions required to comply with appropriately set quality criteria for the indoor environment can lead to serious indoor environmental problems that result in substantial financial costs and other undesirable consequences for health and comfort. It is the purpose of this chapter to describe how ventilation and indoor air quality (IAQ) in different types of buildings, homes, schools, and offices affects these aspects of human life.

What is IAQ? IAQ depends on the composition of air and the content of airborne contaminants, which are gases, aerosols, particles, and microorganisms. When exposures to these contaminants do not pose risk for adverse health effects and do not result in (olfactory) discomfort, the air quality is rated as high. In contrary, when the risks for health and discomfort are elevated and/or apparent the air quality is judged as poor. There are different definitions of IAQ but the most obvious one relates it to the human responses and the effects that it may have on humans. In other words, air quality can be defined when human requirements are met and these requirements can be differently defined depending on the context and the need. These may refer to the requirements which are needed for relaxing, rest, and recovery (e.g., in homes), for working conditions that promote creativity and high work performance (e.g., in offices), and conditions that are not distracting from proper learning and the teaching process (e.g., in schools). The underlying requirement common for all these different environments is that the air quality should not be detrimental to human health. The earlier human-centric definition of indoor air is somewhat different from the definition taking its roots in the exposure to pollutants that stresses what type of pollutants can be present in indoor environments and at which concentrations. The difference is entailed in the overall message: The human-centric definition motivates and underlines the purpose of the built environment, which should support and safeguard human needs. The definition referring to exposures in this context belongs to the general framework for achieving high IAQ.

IAQ should meet the World Health Organization (WHO)'s mandate (2000) that everyone should have the right to enjoy IAQ that does not endanger his or her health. This mandate should be recognized and treated analogous to the quality of water that we drink. About 11,000 L of air flow through our lungs daily; however, we consume three to four orders of magnitude less food and liquids. For example, an average adult daily consumes no more than 2–5 L of liquids. This is why much effort must be placed on achieving that the air that we breathe does not create danger and hazard to our health and life, similarly as has been done to ensure the quality of drinking water, which has considerably reduced the prevalence of diseases related to contaminated water and the consequent death toll.

Another reason why the air breathed indoors is important is that people spend on average from 80% to 90% and even 95% of their time indoors during their entire lifetime (Klepeis et al. 2001). Employed people spend anywhere from 20 to 60 hours per week in offices or factories of various kinds, and it can be estimated that children spend about one-third of their day in primary or secondary school. Still, the major sites of exposure to indoor air are homes. During different periods of our life, exposures in homes can be from 60% to 95% of our total daily exposure. The latter figure specifically applies to infants, young children, and senior citizens, whereas the former is more or less typical for our total lifetime exposure. It is striking that about 30% of our lifetime-weighted exposures is spent when we sleep; with the current life expectancy in the more developed world being 75 years, sleep constitutes roughly 25 years of our life.

The air breathed indoors may contain dust, fumes, microbes, or aerosolized toxins, and according to different sources, the pollution indoors can often be 2–100 times higher than outdoors. The origin of the pollutants present indoors is both the ambient (outdoor) air and the sources present indoors. Thus, humans staying indoors also inhale outdoor pollutants transported indoors via cracks in construction, openings, or special systems for securing proper ventilation and conditioning of the air indoors. Exposures to outdoor pollutants indoors have significantly longer durations than exposures outdoors; humans staying outdoors on the other hand can be briefly exposed to sparks of pollutants at considerably elevated concentrations.

Outdoor pollutants mainly include particles generated outdoors through traffic and combustion processes, ozone, and organic compounds including polycyclic aromatic hydrocarbons, inorganic compounds, and metals, as well as pollens. Many of these pollutants do not have origins indoors and thus cannot be avoided by simple means of dealing with indoor exposures through, e.g., increased ventilation or control of indoor sources of pollution. Their levels need to be regulated outdoors.

Indoor pollutants originate from humans and their activities, such as cooking or bathing and laundering, as well as cleaning with products containing a variety of chemicals, from tobacco smoking or combustion of fossil fuels, all materials that are used for construction purposes, decoration, finishings and furniture, electronic equipment as well as the equipment and installations that support the environment in buildings, e.g., ventilation and air conditioning systems or systems used to purify and clean air indoors. Sometimes human activities create conditions that can further promote the release and the exacerbation of pollutants. The best example is moisture, which can lead to mold growth or exacerbation of house dust mites, when too high, and spread of infectious diseases, when too low.

Indoor pollutants comprise organic species, inorganic species, particles, fibers, allergens, radioactive gases, or species of microbiological origin such as mold and fungi; they can cause allergies, irritation of mucous membranes, sick building syndrome (SBS) symptoms, toxic reactions, infections, inflammation, cancer, and mutagenic effects. For example, organic pollutants are the major sensory pollutants in indoor air. A typical mixture of organic pollutants can contain up to 6000 compounds, of which at least 500 are emitted by humans and at least 500 are emitted by building materials and furnishing. Thus, it is very difficult to name all the pollutants of concern, and even though they have been identified, the challenge would be on how to measure them. Pollutants known to be particularly hazardous can be controlled via filtration and air cleaning, as well as control of sources emitting these pollutants, but the cocktail of pollutants present indoors is often unknown, and the identification of the air composition is difficult, time consuming, and very expensive. In the case of industrial environments, the hazardous effects are handled by defining the maximum acceptable concentrations or the threshold limit values (TLVs) for individual substances. However, in the case of nonindustrial environments, the situation is more complicated as the pollutants are at concentrations much lower than TLV levels.

No simple index was agreed upon for defining the level of IAQ. Therefore, IAQ is often closely associated with ventilation, which is assumed to reduce exposures to pollutants indoors. It is surmised that when ventilation is high, the air quality should also be high, and when it is low, then the IAQ is presumably poor, assuming at the same time that the air used for ventilation is of a high quality (clean), too. This, however, will not apply in cases when ambient air pollution is high and no efficient methods are used to remove them before this air is used for ventilation. Because ventilation is easier to measure, quantify, and interpret than the hundreds or thousands of pollutants present in indoor air, ventilation is often measured and used as a proxy (surrogate) for IAQ.

Sometimes IAQ is also approximated by defining the percentage of people who find it unacceptable (i.e., percentage dissatisfied). If there are few dissatisfied, then the air quality is high, and if there are many dissatisfied, then the air quality is low. Often the relation between percentage of dissatisfied and ventilation is used to express the underlying effects of improved IAQ, and this is reflected in some ventilation standards that have determined ventilation requirements by defining the percentage of dissatisfied (e.g., EN15251 [2007]; American Society of Heating, Refrigerating, and Air-Conditioning Engineers [ASHRAE] [2013]). It should be recognized that there are large individual differences between the occupants of buildings. Some are easy to satisfy and some are are especially difficult to satisfy or are more sensitive than the general population due to inherited properties and/or chronic diseases or psychological reasons.

Studies by Berglund and Cain (1989), Fang et al. (1998a,b), and Toftum et al. (1998) show that the perception of air quality is also influenced by the humidity and the temperature of the inhaled air, even when the chemical composition of the air is constant and the thermal sensation of the entire body is kept neutral. Keeping the air dry and cool reduces the percentage of dissatisfied persons with air quality and causes the air to be perceived as fresh and pleasant. The effect is probably due to the stimulation of the thermal sense as a result of convective and evaporative coolings of the respiratory tract, if only the temperature is different from the mucosal temperature, which is around 30–32°C. The impact of temperature and the relative humidity on sensory perceptions that cause the estimated percentage of dissatisfied with air quality is not only caused by exposures to pollutants, but also by the thermal properties of air. This metric thus cannot be purely associated with loads of pollutants indoors. This may be considered as a factor limiting to some extent a universal application of this metric for dimensioning ventilation requirements. Impartial observers are used to evaluating the IAQ and the percentage of dissatisfied, as this metric cannot be directly measured with an instrument yet, although there have been attempts to make it happen (Wenger et al. 1993; Müller et al. 2007). There is also no relationship between the percentage of dissatisfied and acute health symptoms, although studies suggest that when the percentage of dissatisfied is reduced, the intensity of symptoms is also reduced (e.g., Wargocki et al. 1999, 2000).

Indoor air pollutants can often cause unspecific effects. Multitudes of biological mechanisms are involved at the same time in response to multiple exposures indoors, and only a few objective measurements are available. The most frequent effects include acute physiological or sensory reactions, psychological reactions, and subacute changes in sensitivity to environmental exposures. The term *SBS* (WHO 1983) is used to describe cases in which building occupants experience acute symptoms and discomfort that are apparently linked to the time they spend in the building, but for which no specific illness or cause can be attributed. Many different symptoms have been associated with SBS, including respiratory complaints, irritation, and fatigue. Sensory perception of odors and mucous irritation lead to perceptions of poor air quality and possible risks thereof and consequently to stress and some behavioral responses (window opening or even leaving the building or changing the workplace). The relevant indoor air pollutants that can cause these effects are those which alone or in combination can stimulate the senses or cause tissue changes.

This chapter will not specifically look at different pollutants present indoors or their origins and the methods for amending the elevated exposures. Instead, it will discuss the consequences for health, comfort, and performance of the exposures indoors to a variety of pollutants. Health will be understood very broadly as mental and social well-being, not merely the absence of disease or infirmity, similarly to how it is defined by WHO (1948). Comfort will express the satisfaction with the environment. In the context of IAQ, it will relate to the sensory response due to the activation of the olfactory sense that is sensitive to around half a million odors and the cranial common chemical sense, which is stimulated by the hundreds of thousands of compounds that cause irritation or pungency response. Performance will be related to the ability of an individual to perform different mentally and physically demanding tasks. Often, in this context, the term *productivity* is used instead of performance, but in this chapter, the former term will be used because *productivity* describes a wider economic term that combines a volume measure of the output in relation to the input and is thus less relevant, as it will also depend on many external factors not directly related to IAQ.

Health, comfort, and performance can be influenced by different factors including physiological, behavioral, and psychological factors, while performance can additionally be influenced by personal and organizational, as well as administrative and managerial variables. These factors are not discussed in the context of the present chapter, which is solely addressing the impact of exposures indoors and IAQ.

IAQ issues received significant interest in the past, especially in the nineteenth century. A renaissance of the interest in IAQ was observed after energy crisis in the 1970s, when the lack of oil caused significant reductions in energy use in buildings and nearly epidemic growth in building-related health symptoms due to exposures to air pollutants indoors beginning with excessive concentrations of formaldehyde and later focusing on a wide variety of air pollutants indoors potentially hazardous to human health. Subsequently, other factors that could contribute to poor air quality were examined as well. It is interesting to notice that similar events are likely to occur in the twenty-first century, when weatherization programs and tightening of buildings, use of excessive insulation, and need to reduce energy, as well as many new chemicals present on the market different than those measured in the past (Weschler 2009), can again create an environmental problem indoors, elevating indoors, exposure to levels at which they may have negative consequences for health and well-being.

3.2 SHORT HISTORICAL PERSPECTIVE ON VENTILATION AND INDOOR AIR QUALITY

Because ventilation is often used as a proxy for IAQ, as indicated earlier, it is instructive to briefly review how the need for ventilation was perceived through history as well as to examine different theories that were put forward to justify the need for ventilation. It should be mentioned at the onset of this short historical review that ventilation has always been treated as a remedy for ill health, i.e., to remove and/or dilute polluted indoor air. Only in the last 100 years has the premise for ventilation been to ascertain comfort, mainly the reduction of foul and/or unpleasant odors (sometimes also avoiding thermal discomfort), assuming that this will also secure health.

Ventilation was recognized as an important factor for providing IAQ by the ancient Egyptians, who required the use of ventilation for stone carvers to avoid exposures to particles and dust generated during this process (Janssen 1999; Addington 2000). Hippocrates (460–377 BC) indicated the adverse effects of polluted air in crowded cities and mines. During Roman times (1 BC), Sergius Orata developed hypocausts, underfloor heating systems, to uniformly distribute heat in a house, which most importantly allowed avoiding combustion indoors and subsequently reduced the risk of harmful exposures. In the case of an open fire indoors, the minimum ratio of window-to-floor area was set and parchment above the window was required during these times to assure infiltration.

During Venetian times, roof windows were developed, while Leonardo da Vinci recognized that no animal could live in an atmosphere where a flame does not burn and that dust can cause damage to health, thus implying a need for ventilation. This was later confirmed by studies of Mayow and Lavoisier. In the seventeenth century, Wargentin expressed the common knowledge of this time that expired air was unfit for breathing until refreshed. In the same century, Gauger, quoting Cardinal Melchior de Polignac, remarked that it is not warmth but inequality of temperature and want for ventilation that cause maladies.

In 1756, Holwell described an accident in the Black Hole of Calcutta, a small dungeon where prisoners and soldiers were kept overnight in poor conditions, and 125 out of 146 died due to suffocation. It was observed during the Crimean War (1853–1855) that there was faster spread of diseases among wounded soldiers in poorly ventilated hospitals. Higher morbidity and mortality were observed in the overcrowded rooms, especially when they were poorly ventilated. The importance of ventilation in small room volumes to avoid the death of people was also informed by Baer in 1882. A few years later, Reid expressed the view that between mental anxiety and defective nutriment, defective ventilation should be considered as one of the evil enemies of the human race. (In this context, it should be noted that even now WHO recognizes poor air quality as one of the most important public health challenges.) A similar view was expressed by Griscom in 1850, who acknowledged that deficient ventilation is fatal, as it leads to the spread of tuberculosis and other diseases. An effective treatment of tuberculosis using country fresh air was then achieved by Trudeau, who opened the first Airdonack Cottage Sanatorium in 1873.

In the early twentieth century, Winslow and Palmer suggested that ill-ventilated rooms do not create large discomfort but result in the loss of appetite. Later Winslow and Herrington observed a similar result of loss of appetite for food when they heated the dust from the vacuum cleaner.

3.2.1 Theories of Ventilation

Different theories have been put up through the last two to three centuries to explain the effects associated with a lack of ventilation (i.e., poor IAQ) (Janssen 1999), starting with the Miasma theory that prevailed for a long time until the eighteenth to the nineteenth century, attributing cholera, chlamydia, and Black Death to a noxious form of "bad air." It was later displaced by the germ theory of disease after the discovery of germs in the nineteenth century. In the early seventeeth century, breathing was attributed to a cool heart. In the same century, Mayow attributed the effects observed from igneo-aerial particles that cause the demise of animals.

One century later, in 1775, Lavoisier discovered two gases in air and attributed the effects of igneo-aerial particles to carbon dioxide (CO_2) and air stuffiness. The theory that CO_2 is a dominant cause of physiological effects of bad air remained dominant for nearly 100 years, although it was acknowledged that other factors could also contribute to the effects observed. The theory prevailed until Pettenkofer, who, in the 1800s, indicated that it is neither the deficiency of oxygen (O_2) nor the excess of CO_2 but the presence or lack of biological pollutants (from humans) that are responsible for the vitiation of air. He said that "the corruption of the air is not caused solely by the carbon dioxide content, we simply use this as a benchmark from which we can then also estimate a higher or lower content of other (pollutant) substances." In 1872, Pettenkofer and Saeltzer suggested CO_2 to be the surrogate for vitiated air, a "stick" for deleterious substances of unknown origin.

Later, in 1887–1889, Brown-Sequard and d'Arsonval attributed anthropotoxin (the toxic effluvia—toxic substances in exhaled air) to be responsible for the negative effects reported through history, when ventilation was lacking. Organic matter from lungs and skins had also been proposed as poisonous by many others prior to the anthropotoxin theory. The theory was rejected by many experiments later performed by Haldane and Smith in 1892–1893, Billings in 1895, and Hill in 1913. They could not confirm that the condensate of expired air could kill the animals, which was claimed by Brown-Sequard. The anthropotoxin theory was then superseded by the idea put up by Billings in 1893 suggesting that the purpose of ventilation is to dilute contagions emitted by humans and thus to reduce the spread of infectious diseases.

The theory of reducing contagions prevailed until the large body of research in the early twentieth century on comfort. Among others, Billings, Flugge, Benedict, and Millner and Hill showed a the lack of ventilation causes discomfort exemplified by unpleasant body odors and temperature, while no negative physiological effects could be observed even at CO_2 levels as high as 1–1.5% (10,000 to 15,000 ppm). A lack of ventilation was consequently associated with thermal effects and discomfort. Since the studies of Lemberg and Yaglou in the 1930s, ventilation was required to merely keep body odors at an acceptable level, defined to be at moderate level.

In the 1980–1990s, it was also acknowledged among others by Fanger and his colleagues that in addition to the body odors emitted by humans, other sources of pollution indoors determine ventilation requirements, but the general principle of providing ventilation to reduce discomfort by achieving acceptable air quality as perceived by humans was not changed. Ventilation has become, as mentioned earlier, merely a question of comfort, not health.

3.2.2 Ventilation Guidelines and Requirements

The actual ventilation requirements have varied throughout history, and also as a result of changes in theories of ventilation.

In 1836, Tredgold suggested the minimum ventilation rate in mines, which should satisfy the needs of a miner. It was set at 1.7 L/s per person, of which 0.2 L/s was for purging the CO_2 from lungs, 1.4 L/s was for removing the moisture produced by the body, and 0.1 L/s was for keeping the candle burning; thus, 1.6 L/s was basically defined to control and remove the body effluents.

In one of the first textbooks on ventilation and heating published in 1893, Billings provided the minimum requirements for ventilation. He was very much concerned about the spread of infectious diseases, as mentioned earlier, particularly tuberculosis, and proposed the minimum rate at 30 cfm/person (~14 L/s per person), while the recommended ventilation rate was set as high as 60 cfm/person (~28.5 L/s per person). He also calculated that 50 cfm/person (~23.5 L/s per person) would keep CO_2 at 0.05% (550 ppm); thus, the exhaled CO_2 would be kept at 0.02% (200 ppm) above outdoor levels (at his time, the average CO_2 levels outdoors were about 300 ppm and less). The ventilation rates proposed by any subsequent ventilation standards or guidelines have never been as high as these recommended by Billings.

One of the very first ventilation guidelines was proposed by the Chicago Commission on Ventilation in 1914; these guidelines were later reconfirmed by the studies and the conclusions of the New York State Commission on Ventilation (1923). Both documents attributed ill health to overheating rather than ventilation by stating: "Had the temperature been controlled well, the ventilation requirements could be reduced." Temperatures of 15–19°C in window-ventilated rooms were observed to cause the lowest prevalence of respiratory illnesses. Consequently, the guidelines recommended 20°C with proper control of relative humidity for living rooms to reduce the spread of infectious diseases. CO_2 was not recognized as a harmful agent, when encountered in working practice; no harmful effects could be designated to the expired air. Relative humidity was recognized as the most important factor regarding ventilation requirements for health. Recirculation was not acceptable, if 100% of air was recirculated. Window-ventilated rooms with natural drafts were the most preferred method for ventilation. These recommendations were made before the widespread use of air conditioning in nonindustrial buildings.

In the time after the recommendation proposed by Billings, the ventilation requirements considerably varied. They were as low as 2.5 L/s per person in the 1981 version of ASHRAE Ventilation Standard, through 4 L/s per person in the Nordic guidelines published the very same year (Sundell 1982), 5 L/s per person in the 1946 American Standard Association Code, reaching finally to 7.5–10 L/s per person, which is approximately the standard of today (Janssen 1999). These rates, to a large extent, reflect studies which determined ventilation requirements for acceptable IAQ to avoid discomfort and odors in the presence of emission from humans (human bioeffluents) as well as in the presence of human bioeffluents and the emissions from building materials and furnishings; for some time, they also acknowledged the effective dilution of odors produced by tobacco smoking. These rates harmonize well with a widely accepted CO_2 concentration of 0.1% (1000 ppm) proposed by Pettenkofer to be an indicator of adequately ventilated rooms. It is worth mentioning that Pettenkofer suggested 0.07% (700 ppm) for bedrooms, which is lower than for other spaces, thus implying that bedrooms require lower exposure levels and higher ventilation with outdoor air.

3.3 AIR QUALITY GUIDELINES AND REQUIREMENTS

It is challenging, and at the same daring, to propose pollutants that need to be regulated for achieving IAQ that secures no negative effects on health, lack of sensory discomfort, and high cognitive performance. The air quality guidelines for avoiding ill health have been proposed by WHO (1987, 2000, and 2005, 2009 and 2010), and they can be considered as a prototypical example for setting the guidelines related to other outcomes. The primary aim of the WHO guidelines is to provide a uniform basis for the protection of public health from the adverse effects of exposure to air pollution, and to eliminate or reduce to a minimum exposure those pollutants that are known or are likely to be hazardous. The guidelines are based on the scientific knowledge available at the time of their development.

The WHO Guidelines for IAQ: Selected Pollutants (WHO 2010) recommends targets for nine air pollutants: carbon monoxide, nitrogen dioxide, benzene, trichloroethylene, tetrachloroethylene, formaldehyde, naphthalene, polycyclic aromatic hydrocarbons (PAHs), and radon. Moreover, the levels of exposures indoors should meet the requirements applicable for pollutants in ambient air, i.e., fine particles (PM2.5), coarse particles (PM10), sulfur dioxide, ozone, styrene, and toluene (WHO 2005). WHO defines the allowable levels of these pollutants, indicating that for radon, benzene, trichloroethylene and PAHs, no safe levels can be established. Table 3.1 shows the guideline values recommended by WHO. Readers are warned that these values might be different from the guidelines recommended by the cognizant authorities relevant to their region and therefore they are requested to consult them. The list presented in Table 3.1 does not include either CO_2 or relative humidity, as neither of them can be considered to be a contaminant. However, both can be and are good indicators of certain processes or circumstances that can potentially create risks for health.

In addition to the guidelines for gaseous pollutants, WHO published guidelines on dampness and mold (WHO 2009). These guidelines concluded that

> (…) persistent dampness and microbial growth on interior surfaces and in building structures should be avoided or minimized, as they may lead to adverse health effects. As the relationships between dampness, microbial exposure and health effects cannot be quantified precisely, no quantitative, health-based guideline values or thresholds can be recommended for acceptable levels of contamination by microorganisms. Instead, it is recommended that dampness and mold-related problems be prevented. When they occur, they should be remediated because they increase the risk of hazardous exposure to microbes and chemicals.

TABLE 3.1
List of Indoor Air Pollutants Defined by WHO to Have Toxic Effects on Humans and Their Recommended Maximum Exposure Levels

	IAQ Guidelines	Ambient Air Guidelines	
Pollutant	**IAQ WHO (2010)**	**AQ WHO (2000)**	**AQ WHO (2005)**
CO (mg/m^3)	100 (15 min)	100 (15 min)	
	60 (30 min)	60 (30 min)	
	30 (1 h)	30 (1 h)	
	10 (8 h)	10 (8 h)	
	7 (24 h)		
NO_2 ($\mu g/m^3$)	200 (1 h)	200 (1 h)	200 (1 h)
	40 (1 year)	40 (1 year)	40 (1 year)
SO_2 ($\mu g/m^3$)		500 (10 min)	500 (10 min)
		125 (24 h)	20 (24 h)
PM10 ($\mu g/m^3$)			50 (24 h)
			20 (1 year)
PM2.5 ($\mu g/m^3$)			25 (24 h)
			10 (1 year)
Ozone ($\mu g/m^3$)			100 (8 h)
Benzene ($\mu g/m^3$)	No safe level	UR 6×10^{-6}	
Trichloroethylene	No safe level	UR 4.3×10^{-7}	
Tetrachloroethylene ($\mu g/m^3$)	250 (1 year)	250 (1 year)	
		8000 (30 min)	
Toluene ($\mu g/m^3$)		260 (1 week)	
		1000 (30 min)	
Styrene ($\mu g/m^3$)		260 (1 week)	
		70 (30 min)	
Xylenes ($\mu g/m^3$)	Insufficient evidence	Insufficient evidence	Insufficient evidence
Napthalene ($\mu g/m^3$)	10 (1 year)		
Formaldehyde ($\mu g/m^3$)	100 (30 min)	100 (30 min)	
PAHs	No safe level	8.7×10^{-5} per ng/m^3 of B[a]P	

Source: WHO, *The Right to Healthy Indoor Air*, WHO Regional Office for Europe, Copenhagen, 2000; WHO, *WHO Air Quality Guidelines*: *Global Update 2005*, WHO Regional Office for Europe, Copenhagen, 2005; WHO, *Guidelines for Indoor Air Quality: Selected Pollutants*, WHO Regional Office for Europe, Copenhagen 2010. With permission.

Note: B[a]P, benzo(a)pyrene; UR, unit risk estimated for an air pollutant is defined as "the additional lifetime cancer risk occurring in a hypothetical population in which all individuals are exposed continously from birth throughout their lifetimes to a concentration of 1 $\mu g/m^3$ of the agent in the air they breathe."

3.4 VENTILATION, INDOOR AIR QUALITY, PERFORMANCE, AND HEALTH IN OFFICES

3.4.1 Health Effects

The fraction of the incidence/prevalence of reports of discomfort and symptoms that can be related to IAQ in offices is not exactly known. However, in buildings without specific complaints of poor IAQ, the prevalence among occupants is often close to zero and normally below 30%, while in affected buildings, the prevalence often ranges much higher. Several studies and reviews of these studies have been published to date (e.g., Mendell 1993; Seppänen et al. 1999; Seppänen and Fisk

2002; Wargocki et al. 2002b; Li et al. 2007; Sundell et al. 2011; Carrer et al. 2015) to show the relationship between ventilation and air quality and health, and to understand and elucidate which factors could be responsible for the high prevalence of health effects in offices. The interest was on the unspecified weak acute health symptoms (SBS symptoms), being the most common complaint among occupants of the offices, and also on the difference in the prevalence of these symptoms between air-conditioned, mechanically ventilated, and naturally ventilated office buildings, as well as offices with different layouts.

One of the first reports was by Finnegan et al. (1984), who studied nine office buildings in the United Kingdom, and found that the symptoms were more prevalent for those workers in air-conditioned offices. Around the same time, Hedge (1984) also found that eye, nose, and throat symptoms were more prevalent among workers in the air-conditioned offices than in naturally ventilated offices, and additionally that headaches varied by office layout. A comparative study of adjoining air-conditioned and naturally ventilated office buildings (Robertson et al. 1985) showed that SBS symptoms were more prevalent among workers in the air-conditioned building, but the source of this difference could not be pinpointed from the variety of indoor environmental measures that were taken. Hedge et al. (1989a) found higher levels of total volatile organic compounds (TVOCs) in the air-conditioned offices and an association between formaldehyde levels and health reports. A U.K. survey of 47 office buildings and 4473 workers found a significantly higher prevalence of SBS symptoms in the air-conditioned offices compared to those that were simply mechanically ventilated or naturally ventilated (Burge et al. 1987; Wilson and Hedge 1987; Hedge et al. 1989b). Similar findings have been reported by Harrison et al. (1987) for 2587 workers in 27 UK office buildings; Harrison et al. (1990) for 13 U.K. office buildings; for 4369 workers in 14 Danish town halls and 14 nearby office buildings (Skov et al. 1990), and 12 Northern Californian office buildings (Fisk et al. 1993; Mendell et al. 1996).

Fisk et al. (2009) attempted to create a quantitative relationship between SBS and the ventilation rate. They summarized the existing data from studies reporting the ventilation rate and the prevalence and/or intensity of SBS symptoms. It was achieved by integrating slopes depicting the degree of change in symptoms, as a consequence of change in the ventilation rate. The quantitative relationship was established and showed that when the ventilation rate is reduced from 10 to 5 L/s per person, the relative symptom prevalence increases by 12–22% (23% on average), and when it is increased from 10 to 25 L/s per person, the prevalence decreases from 15% to 42% (on average by 29%). At rates higher than 25 L/s per person, the reliability of the established relationship is low.

The relationship of Fisk et al. (2009) confirms to some extent the recommendations of other reviews showing that ventilation rates of up to 25 L/s per person will provide the benefit in reducing symptoms (Wargocki et al. 2002b; Sundell et al. 2011). Their results also matched the observations made in one of the first reviews of the archival literature on SBS by Mendell (1993), who indicated that among the factors contributing to health symptoms among office workers are insufficient ventilation, presence of air-conditioning, presence of carpets, more workers in a space, and video display terminal (VDT) use (VDT is a nonflat computer monitor).

A common reason for the high prevalence of symptoms are improperly designed, operated, and maintained ventilation systems. As already indicated by the first reports of SBS symptoms, which were mentioned earlier, many studies showed that symptom prevalence is low in office buildings where no mechanical ventilation systems are installed compared with mechanically ventilated buildings or with buildings where in addition there is equipment for complete conditioning of the supplied air (air cooling and humidity control) (see, e.g., the review of Seppänen and Fisk [2002]). Poor maintenance of systems supplying and conditioning air, and especially pollution from filters that are dirty and loaded with particulate matter allowing gaseous pollutants to adsorb on their surface and transform into more hazardous pollutants (Bekö et al. 2006, 2007), can be one of the reasons for the observed differences in the prevalence of symptoms in office buildings with and without mechanical ventilation systems as well. In the Base project, which investigated the air quality in 100 office buildings in the United States, the presence of loaded filters was significantly associated with elevated prevalence of SBS symptoms (Buchanan et al. 2008). Other reasons can be the presence of moisture and dirt on other parts of the system (Sieber et al. 1996; Mendel et al. 2003). Yet another explanation could be that office buildings without a mechanical ventilation system had on average higher ventilation rates, which promotes more efficient removal and dilution of pollutants. Many of the buildings in the studies showing the difference between office buildings with and without mechanical ventilation system were actually located in moderate and cold climates, which create a wonderful opportunity to use natural forces due to differences between ambient (outdoor) temperatures and indoor temperatures even during the summer. Very little information is available on whether office buildings without mechanical ventilation would perform better in tropical and subtropical climates. However, there is a good deal of information that air conditioning without sufficient provisions of outdoor air will cause an elevated prevalence of symptoms (Wong and Huang 2004; Sekhar and Goh 2011). In these buildings, reduced outdoor air supply rates are the consequence of an attempt to save energy, considering that cooling and moisture removal are energy-demanding processes and thus consume a lot of energy especially in climates where air conditioning is indispensable.

In the case of buildings with air-conditioning systems, the main reasons for the elevated prevalence of symptoms can be the presence of water in the system, besides the mentioned general poor condition of the system, dirtiness and dust accumulated on ducts and filters, and reduction of outdoor air supply rate to save the energy. The presence of water promotes microbial growth and other potentially unwanted, dangerous, and harmful processes (Sieber et al. 1996). The presence of water in the system does create a risk for SBS symptoms, but even in this case, we have very little information from studies in tropical and subtropical climates about how large this risk actually is. In these climates, air conditioning is practically indispensable to perform modern work indoors. In a study of Sekhar et al. (2003), five air-conditioned office buildings were surveyed in Singapore in the tropical climate. However, this study did not reveal higher dissatisfaction levels with air quality or higher prevalence of SBS symptoms than those observed in the similar study in Europe in air-conditioned and non-air-conditioned buildings (Bluyssen et al. 1996). For example, the building symptom index integrating all symptoms was about two (meaning two symptoms per building) in Singapore and on average two in Europe. Studies in Brazil showed that the age of the ventilation system was a risk factor for upper respiratory symptoms (Graudenz et al. 2002), and that cleaning the ducting system and replacing an air-conditioning system with a new one reduced building-related respiratory symptoms, nasal-ocular symptoms, and persistent coughs (Graudenz et al. 2004, 2005).

There are no relationships that have been agreed upon between the SBS symptoms among office workers and pollutants indoors. The total concentration of volatile organic compounds (TVOCs) was proposed as an index integrating the impact of many volatile organic compounds (VOCs) present indoors at very low concentrations. However, the consensus at present is that it is not a valid proxy for health problems, although in some cases it may provide some indication of the potential problem. The reason is that no clear, systematic, and consistent association between TVOC and its levels has been found in the published literature, as indicated by Andersson et al. (1997), who carefully reviewed and judged the quality of the literature describing TVOC–health relationships and concluded that, although the air including VOCs will affect health, the literature is inconclusive with regard to the relationship between TVOC and health. No specific guidelines regarding TVOC levels and health could be established, suggesting that TVOC may not be an appropriate risk index for health effects associated with exposures in buildings in general and specifically in offices. One of the reasons for the lack of TVOC–health relationships could be the various definitions of TVOC and the different instrumentation used to measure TVOC using different principles and different reference.

Recent ENVIE (Oliveira Fernandes et al. 2009) and IAIAQ (Jantunen et al. 2011) projects do however acknowledge that organic compounds indoors are important contributors to negative health effects of occupants of buildings expressed as disability-adjusted life years. They show that as many as about 2.2 million healthy life years can be lost each year in Europe due to exposure to pollutants in buildings in Europe, of which 0.517 million can be attributed to VOCs causing irritation and odor.

In addition to the fairly consistent evidence that poor air quality in offices results in the elevated prevalence and/or intensity of acute health symptoms (SBS symptoms), studies also show that poor air quality and particularly too low ventilation rates can promote the spread of infectious diseases. Li et al. (2007) reviewed the literature on the role of ventilation in the airborne transmission of infectious agents. They concluded that there is strong evidence that ventilation and air movement in buildings are associated with the spread and the transmission of infectious diseases such as measles, tuberculosis, chickenpox, influenza, smallpox, and severe acute respiratory syndrome. This postulation agrees well with the historical evidence summarized earlier in this chapter. Although the strong link between the ventilation and the risk of infectious diseases is highly likely, the information published in the literature is somewhat weak and inconsistent. Myatt et al. (2004) indirectly showed that such risk exists. They found the probability of detecting airborne rhinovirus in filters and the weekly average CO_2 concentration. When weekly averages of CO_2 concentration above background were higher than 0.01% (100 ppm), the risk significantly increased. This level of CO_2 corresponds to a very high ventilation rate, in the range of 40–50 L/s per person; the level is also similar to the CO_2 of 200 ppm above outdoor level as recommended by Billings and mentioned earlier in this chapter. Infectious diseases can also be associated with increased absence rates. However, in another study, Myatt et al. (2002) could not observe increased absence rates among office workers when the interventions in two office buildings changed the CO_2 levels above outdoor from about 100 ppm to 200 ppm, which was estimated by the authors to correspond to ventilation rates as high as 40–45 L/s per person. The reason for the negative finding could be the too small size of the intervention group considering that Milton et al. (2000) did see the reduced short-term sick leave in many office buildings when outdoor air supply rates were increased from 12 to 24 L/s per person. Laboratory studies with personal ventilation (delivering the air directly to the breathing zone) and with coughing mannequins do provide further evidence of the role of good ventilation in reducing the risks of transmission of infectious diseases (Pantelic et al. 2009). Seppänen and Fisk (2006) showed that short-term sick leave prevalence can be reduced by roughly 10% each by doubling the outdoor air supply rate in offices.

With the current epidemiological data, no clear cutoff point for ventilation rates can be provided, which will certainly reduce the risk for health, infectious diseases, and elevated absence rates in office buildings. It is clear, however, that increased ventilation rates will reduce the risk but this increase may not be uniform for the entire building stock. This is somewhat confirmed in several reviews on ventilation and health (e.g., Godish and Spengler 1996; Seppänen et al. 1999; Wargocki et al. 2002b; Sundell et al. 2011; Carrer et al. 2015), which showed that increased ventilation rates may be effective in mitigating discomfort due to odor and poor perceived air quality, acute health symptoms such as irritation of mucous membranes, and headaches or fatigue associated with exposures in buildings. Some of these reviews also show that ventilation rates below 10 L/s per person in offices can increase the risk for health, but even rates of 15–17 L/s per person would sometimes be needed to reduce the risk, or even ventilation rates higher than 25 L/s per person.

Despite the incapability to select the cutoff point for ventilation in reducing the risk for health, the framework for setting up health-based ventilation requirements was proposed by the HealthVent project (Wargocki et al. 2013), also considering the findings of the review by Carrer et al. (2015) and the ENVIE and IAIAQ projects (Oliveira Fernandes et al. 2009; Jantunen et al. 2011). In this framework, the base ventilation rate of 4 L/s per person is proposed as the basic requirement in any type of indoor non-industrial environment to ensure no health effects related to exposures to poor IAQ, and the ventilation rates cannot be lower than this base rate. This rate was selected based on the epidemiological evidence showing the relationship between ventilation and health, and assuming that the only pollution would be humans. It was selected to create the benchmark or reference point. This ventilation rate is assumed to be sufficient to reduce the risk for chronic health effects if exposures meet the requirements of WHO air quality guidelines (WHO 2005, 2010). If exposures do not meet the guideline requirements at this rate, then the framework stipulates a double sequential approach, in which first, all options of source control resulting in reduced exposures levels are exercised. Only then should the ventilation rates be increased if exposures still do not meet the requirements of the guidelines; the increase should be a multiple of the base rate. Ventilation rates defined by the described approach can be called *health-based*. It has been estimated that if the framework is strictly followed (i.e., indoor sources of pollution are reduced and entrainment of outdoor pollutants into the building is diminished, as well), then the burden of disease due to exposures to pollutants (in all types of buildings, not only offices) can be halved only if the base ventilation rate is used (Asikainen et al. 2012, 2013). The estimations made by Asikainen et al. (2016) showed that the reduced burden of disease can also be obtained by only increasing the ventilation rates; this effect will however be quite small and smaller than according to the framework presented earlier. Ventilation rates up to 14 L/s per person would be needed if only the ventilation is used to mitigate exposures indoors, and the higher rates would be counteractive; they will result in an increase in risk, as more ambient pollutants would be brought indoors.

3.4.2 SBS and Personal and Occupational Factors

Numerous studies of SBS in offices have shown that symptom prevalence is affected by various non-environmental factors including employee's gender, with symptoms being more prevalent among women than men, and this may indicate a greater sensitivity to poor IAQ among women; hours of computer use, which could indicate exposure to VOCs from computer emissions; and higher levels of job stress, which again could change individual susceptibilities to indoor air pollutants (Burge et al. 1987; Wilson and Hedge, 1987; Hedge 1988, 1998; Hedge et al. 1989a, 1995, 1996; Skov et al. 1989; Tamblyn and Menzies 1992; Zweers et al. 1992). An additional complication is that acute health symptoms (SBS symptoms) are very common in the general population and it is likely that no causal relationship can be shown between symptoms and indoor environmental quality, especially when the prevalence is low (Brauer et al. 2006).

3.4.3 Effects on Performance

Employed people spend anywhere from 20 to 60 hours per week in offices or other various kinds of work places. Series of experiments have been carried out in the laboratory and in field to investigate whether air quality and ventilation affect different aspects of office work, and if so, to which extent, i.e., the potential magnitude of the effects is observed.

Laboratory studies were performed under controlled conditions, when IAQ was the only variable/factor that was modified; all other factors defining the quality of an indoor environment such as noise and acoustics, light and temperature, and relative humidity remained unchanged. The observed effects could have thus been mainly attributed to the changes in IAQ. In laboratory experiments, subjects were recruited and exposed to different conditions in exposures lasting up to 5 hours (a bit more than half of a usual working day broken normally by the lunch break lasting from anywhere between 30 minutes to 2 hours, usually though less than an hour); sometimes experiments lasted even 8 hours. Subjects were usually students or young healthy individuals. During exposures, the office work was simulated by engaging the subjects in different tasks typical of office work, from arithmetical calculations to typing and proofreading. In some experiments, subjects performed diagnostic psychological tests, which were presented to them to examine a wide range of cognitive skills and how different motor, cognitive, and other skills were affected by changing the air quality conditions. These tests comprised measurements of reaction time, concentration endurance, and memory, as well as other skills, sometimes requiring higher cognitive demand such as decision-making or creativity. In some studies, the subjects were also asked to evaluate themselves by rating their performance or rating the effort exerted to complete the tasks.

The laboratory experiments generally showed that improving the air quality by either reducing the sources of pollution or increasing the ventilation rates improved the performance of tasks completed by recruited subjects, less so though in the case of some diagnostic psychological tests.

The improvement was usually in terms of increased speed at which the tasks were performed; only rarely was the error rate improved, as well, and it usually remained unchanged. These results suggest that the subjects performed the tasks at such a pace that the error rate could be minimized and they did not want to compromise the quality of the performed work by overexerting the speed at which the work was performed. The studies are described briefly in the following.

Exposures to toluene at 380 mg/m^3 (Bælum et al. 1985) and to a mixture of 22 common indoor air pollutants at concentrations of up to 25 mg/m^3 (Mølhave et al. 1986) have been shown to reduce the performance of diagnostic psychological tests in experiments in which subjects were exposed. However, these studies were performed on selected indoor air pollutants and at concentrations considerably higher than those typically encountered in office buildings (Brown et al. 1994; Wargocki 1998). In a study by Wargocki et al. (1999), the performance of text typing improved as typing speed improved by 6.5%, and the error rate was reduced by 18% when the proportion of dissatisfied with the air quality was reduced from 70% to 25% by removing a 20-year-old carpet. A repetition of this study with the same carpet showed that the performance of text typing improved by 1.5%, and the number of errors in addition reduced by 15%, when the proportion of dissatisfied with the air quality was reduced from 60% to 40% (Wargocki et al. 1999, 2002a; Lagercrantz et al. 2000). In a study by Bakó-Biró et al. (2004), the performance of text processing improved by 9% when the proportion of dissatisfied with the air quality was reduced from 40% to 10% by removing personal computers. In the study by Wargocki et al. (2000), the performance of text typing improved by about 1% for every two-fold increase in the outdoor air supply rate in the range between 3 and 30 L/s per person, causing the proportion of dissatisfied with the air quality to be reduced from 60% to 30%. In another study, in which the ventilation rate was changed, Park et al. (2011) showed improved performance of typing, addition, and memorization by on average of 2.5–5% when the ventilation rates were changed between 5, 10, and 20 L/s per person. In a study of Kaczmarczyk et al. (2004), providing a personalized ventilation providing clean air directly to the breathing rate that increased the amount of unpolluted air supplied to the breathing zone also improved the performance as well; this time, however, the performance was evaluated by the subjects themselves; the authors did not provide information on the size of effect.

There have also been a good deal of field studies examining the effects of improved air quality and ventilation on the performance of office work. In this case, however, it has been more difficult to control all exposures as it has been achieved in laboratory experiments. Many variables can change and eventually affect the performance of office work. The resulting effect on the performance can be simply an integrated effect of changes in many factors. Most of the experiments performed in field experiments were consequently intervention experiments with repetition rather than cross-sectional studies. Interventions with repetitions accounted for, at least to some extent, the many uncontrollable factors. In these intervention experiments, the air quality was modified by changing the ventilation rates, i.e., increasing and/or decreasing the rates at which outdoor air was delivered to office buildings. The field studies were performed in actual buildings with employees in their natural working environment so that they could perform their normal work during the experiments. This is a clear advantage when comparing it with the laboratory studies, especially as the results obtained can be easily transferred into performance/productivity metrics that are relevant for office work. This is much more difficult in the case of results obtained in laboratory studies, as several assumptions need to be made in order to translate the effects on, e.g., typing, to the actual working scenario/context. The reason is that there is a sizable gap between some measures of performance (for instance, the performance of brief diagnostic tests) and actual work performance and productivity that is of an economic significance over longer periods. To this end, the essential step would be to identify critical tasks for office work, which may not be easy due to the variety of tasks performed during office work, and then to make an estimate of the proportion of total work time, for which they are significant (for instance, even if office workers read 30% more slowly because of indoor air pollution, the overall effect on their productivity will be only 3% if the reading speed is only critical for 10% of their working day). An attempt to somewhat deal with that problem was made by Jensen et al. (2009), who used Bayesian models to estimate the contribution of performance on different tasks performed in the laboratory to the average performance relevant for the office working context and economical estimations. But still, the essence of the issue, how the performance measured in laboratory studies translates into actual work performance in buildings, remains unsolved.

In addition to the difficulty of controlling all parameters that may affect the performance in field experiments, it is difficult to identify the exact building and/or office type for experiments, where the work can be reliably quantified. The intention is to use the work performed by the building occupants to estimate the effect on performance, but sometimes it is not possible. Similar tasks can be presented as in the laboratory. This approach can potentially distort the natural aspect of the experiment, and sometimes the employees have to additionally perform the tasks that are neither familiar and customary to them nor often relevant for their work. Field studies performed so far used the former approach, in general. They were carried out in call centers with operators/consultants or nurses, so that their talk time with customers/patients and the wrap-up time to write a brief report after the call could be credibly and reliably measured. None of the studies measured the actual level of air quality, which was approximated by the rate at which ventilation with outdoor air was supplied to office buildings, where the field interventions were performed. The studies are briefly summarized in the following.

In the case of call centers, Wargocki et al. (2004) observed the reduced talk time of operators in the call center when the ventilation rates were increased from 2.5 to 25 L/s per person. Federspiel et al. (2004) observed significant improvement in the average handling time of call center operators only when the measured levels of CO_2 were lower than 100 ppm above outdoor levels; at higher CO_2 levels (up to 300–500 ppm), no effects were observed. The condition of a supply air filter could potentially be an important disturbing factor in the study of Federspiel et al. (2004), because, as shown by Wargocki et al. (2004), the performance of operators did not improve when a used filter was in place in the recirculated airflow after the ventilation rates were increased to 25 L/s per person. The presence of used filters was probably also the reason why the performance of the simulated office work, including addition and typing, could not be shown to be significantly affected by the reduced ventilation rates, resulting in CO_2 concentrations of 3000–4000 ppm in the experiments carried out by the New York State Commission on Ventilation in the 1910s (1923). Tham (2004) showed that the performance of call center operators improved by 9% when the ventilation rate was increased from 10 to 23 L/s per person in an office building with no bag filters (electrostatic filters were used instead).

The results of field experiments thus confirm the results obtained in laboratory experiments and, together with the laboratory experiments, form a very consistent and coherent body of evidence that the performance of office work is expected to be improved when IAQ is improved (outdoor air rates are increased). Based on the results of studies investigating the effects of ventilation on the performance of office work, Seppänen et al. (2006) suggested the quantitative relationship of office work and ventilation rate (Figure 3.1). It shows that work performance will on average increase by approximately 1.5% for each doubling of the outdoor air supply rate.

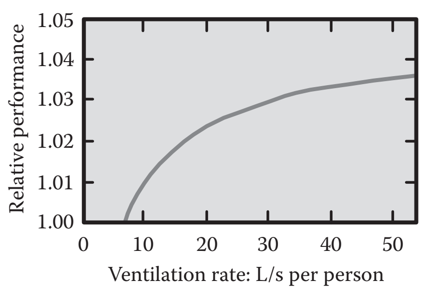

FIGURE 3.1 Ventilation and performance of office work. Quantitative relationship between outdoor air supply rate and performance. (From Seppänen, O. A. and W. Fisk, *HVAC&R Res J.*, 124, 957–73, 2006. With permission.)

The potential mechanisms by which the observed effects occurred are unknown, but it can be argued that those who do not feel very well and experience SBS symptoms such as headaches and difficulty to concentrate and cannot clearly think when the air quality is poor will not work very well. Other possible mechanisms for an effect of poor air quality on performance include distraction by odor, sensory irritation, allergic reactions, or direct toxicological effects. Studies of adult subjects performing simulated office work provide further information on the effects of IAQ on performance. They showed that increased air pollution caused by gaseous emissions from typical building materials, furnishings, and office equipment caused subjects to exhale less CO_2. Some studies suggest that the effect could be due to reduced metabolic rates as the consequence of reduced motivation to perform work in the polluted air, or a consequence of physiological changes leading to inefficient gas exchange in the lungs when polluted air is breathed (Bakó-Biró et al. 2005). The latter mechanism would lead to an increased CO_2 concentration in the blood (a mild acidosis), which is known to cause headaches. It can also be due to elevated CO_2 levels following the results of recent experiments by Satish et al. (2012), who showed that elevated levels of pure CO_2 can reduce the ability of subjects to make decisions at levels of CO_2 as low as 2500 ppm. But few new studies by Zhang et al. (2016a,b) did not observe the effects of CO_2 pn psychological test and office type tasks.

3.4.4 Implications and Costs

By affecting the health and the productivity, indoor air pollution influences the well-being, which, as a result, incurs different costs. By reducing indoor air pollution and improving IAQ, these costs can be reduced and/or avoided.

Reductions in productivity costs due to indoor air pollution were estimated in the 1980s, in the Unites States, to reach ca. \$60 billion. This figure is compatible with other estimations carried out in the mid-1990s, also using U.S. data, showing that improving indoor environments can create potential annual savings and productivity gains from \$29 to 168 billion by reducing the costs of respiratory illnesses, the costs of asthma and allergy, the costs related to SBS symptoms, and the productivity losses unrelated to health (Fisk and Rosenfeldt 1997).

The total cost of SBS was assumed in the mid-1990s, using U.S. data, to be \$50 billion per year and caused by reduced productivity; this corresponds to about \$400 per worker annually, which is about 2–3 lost working days of each worker per year. Some of these costs are due to factors not directly related with IAQ and are related to job satisfaction, psychosocial conditions, or personal issues. However, even if half of them are attributed to IAQ, they are still considerable at the level of \$7.5–20 billion annually, and 10% reduction in the prevalence of symptoms would result in a significant reduction of costs at \$0.75–2 billion annually. For comparison, in Finnish offices, a reduction in the prevalence of SBS symptoms was estimated, in late 1990s, to result in savings of ca. €330 per worker annually, which corresponds to about 1–2 lost working days of each worker per year (Seppännen 1999).

Changing the ventilation rates in U.S. offices would contribute significant benefits due to improved productivity; it could yield benefits of \$13 billion from increasing the minimum ventilation rates from 8 to 10 L/s per person and \$38 billion from increasing the minimum rates from 8 to 15 L/s per person, which is in significant contrast to savings obtained by reducing the minimum ventilation rates from 8 to 6.5 L/s per person yielding \$0.04 billion annually (Fisk et al. 2012). Fisk et al. (2011) postulated that up to 20% reduction in SBS can be obtained by improved ventilation, and it would result in savings of \$5 billion annually. The earlier figures are slightly lower than the estimates of Fisk and Rosenfeld (1997) mentioned earlier, but they are still very significant and much higher than the energy savings due to reduced ventilation. Filtration can also bring significant benefits, but they can be offset due to offending pollutants emitted from used filters, which can eventually reduce the performance as indicated earlier (Bekö et al. 2008).

For individuals, the costs of reduced air quality can be associated with reduced wages, time away from work, medical and insurance costs, and generally reduced life quality due to reduced health conditions and potential disability to optimally perform work.

Building owners can enjoy reduced life cycle costs. Wargocki and Djukanovic (2003) compared the life cycle costs of investments that would improve IAQ in an office building with the resulting revenues from increased office productivity that would be predicted from results of experiments investigating the effects of ventilation on performance. Analysis showed that the benefits from improved IAQ can be up to 60 times higher than the investment required to achieve it; the investments can generally be recovered in no more than 2 years (i.e., with payback times similar to the payback of 1.4 years suggested by Dorgan et al. [1998]), and the rate of return can be up to 7 times higher than the minimum acceptable interest rate. In fact, the estimations suggest that the full costs of installing and running the building can be offset by productivity gains of just 10% (Federation of European Heating, Ventilation and Air Conditioning Associations 2006). The benefits estimated by Wargocki and Djukanovic (2003) do not include benefits that result from reduced health costs and reduced absenteeism; lower absenteeism from an increased outdoor air supply rate can result in additional annual savings of $400 per employee, according to a study by Milton et al. (2000). Reduced life cycle costs result in increased property values (Virta et al. 2012). Moreover, improving the air quality can result in extended building and equipment life span, longer tenant occupancy and lease renewals, reduced churn costs, reduced insurance costs, reduced liability risks, and brand value.

Considerable benefits can also be achieved by employers when IAQ is improved. These are due to not only improved productivity and health status of employees, but also a generally satisfactory working environment, lower staff turnover, and more satisfied customers: A 1% increase in productivity corresponds to reduced sick leave of 2 days per year, less breaks from work, improved effective time at work of 5 minutes per day, or 1% increase in the effectiveness of physical and mental works.

In summary, all stakeholders will benefit from improving the air quality, and these benefits outweigh potential energy and investment costs, of course if only the effects of improved performance are taken into account in the calculations. It is, however, surprising to see that despite high economic premiums and rewards, potential health and productivity benefits are not yet integrated in the conventional economic calculations pertaining to building design and operation, which consequently affect indoor air pollution. The potential reason could be the still very low perception of the benefits of improving air quality and low willingness for paying for these improvements. This has been documented by the study of Hamilton et al. (2016) performed among the U.S. building industry. Less than half of the respondents expected that improving ventilation and filtration of buildings would improve productivity, and even less associated these interventions with lower absence rates and risk for health. Large costs were attributed by respondents to the interventions aimed at improving IAQ, larger than the estimated actual costs, and green building owners were less likely to pay for the upgrades.

3.5 VENTILATION, INDOOR AIR QUALITY, LEARNING, AND HEALTH IN SCHOOLS

3.5.1 Effects on Health

Studies show that the environmental conditions in schools are often inadequate, even in developed countries, and that they are frequently much worse than in office buildings. For example, measurements in 39 schools in Sweden showed that 77% of schools did not meet building code regulations (Smedje and Norbäck 2000). The most common defects in schools include insufficient outside air supplied to occupied spaces; water leaks; inadequate exhaust air flows, poor air distribution or balance; and poor maintenance of heating, ventilation and air-conditioning systems, as indicated by the analysis of the National Institute of Occupational Safety and Health Health Hazard Evaluation Reports for educational facilities in the United States where formal complaints had been registered (Angell and Daisey 1997; Daisey et al. 2003). Outdoor air supply rates in schools are considerably lower than in offices, and in many cases even lower than those observed in dwellings (Brelih 2012; Dimitroulopoulou 2012). They are also often much lower than they should be according to current recommendations for classrooms (Daisey et al. 2003; Dijken et al. 2005). For example, ASHRAE Standard 62.1 (2014) recommends for classrooms 5 L/s per person plus 0.6–0.9 L/s per m^2 of floor. Low ventilation rates often lead to carbon dioxide (CO_2) levels being well above the recommended level of 800–1000 ppm (sometimes 1400 ppm) during school hours (Sowa 2002; Dijken et al. 2005; Boxem et al. 2006; Santamouris et al. 2008; Wyon et al. 2010; Gao et al. 2014), implying that the concentration of other pollutants, not only the bioeffluents from children for which CO_2 is a good indicator, will be high, and that classroom air quality is consequently poor. In recent air quality measurements in 320 schools in Denmark, CO_2 concentrations exceeded 1000 ppm in more than 50% of classrooms (Clausen et al. 2014). The air quality in these classrooms did not meet the requirements of the Danish Building Code or the Danish Working Environment Authority, because the outdoor ventilation rates were too low. For comparison, similar measurements in Norway and Sweden showed that only in no more than 20% of classrooms were the CO_2 concentrations above 1000 ppm. Many studies have also reported high concentrations of particles in classrooms (e.g., EFA 2001; Dijken et al. 2005; Simoni et al. 2006).

Higher concentrations of pollutants in classrooms increase the risk of health problems. This has been confirmed by a recent comprehensive review of the measured and reported pollutants in classrooms and the associated health effects (Annessi-Maesano et al. 2013). Among the possible health effects are respiratory problems (both measured and self-estimated) including increased allergic reactions (e.g., Simoni et al. 2010; Zhang et al. 2011), especially for children with asthma, allergy, or any other hypersensitivity, as well as symptoms of fatigue, headache, and poor concentration (e.g., Norbäck et al. 2008a,b). Simoni et al. (2010) found that schoolchildren exposed to CO_2 levels below 1000 ppm had a significantly lower risk of dry cough and rhinitis. Measurements in European schools within the European Sinphonie project confirmed the earlier observations and showed that pupils exposed to an elevated level of indoor pollutants showed higher prevalence of nonspecific respiratory symptoms (Zivkovic et al. 2014). This is particularly worrisome considering that at least every third child suffers from some atopic disease. Studies point toward elevated levels of formaldehyde, ozone, nitrogen oxides, acrolein, and microbiological pollutants due to molds as well particulate matter, having both indoor and outdoor origins. Especially, particular matter is in the focus considering that airborne particles have been shown in many studies to have negative health effects on children. For example, Ward and Ayres (2004), in a meta-analysis of 22 panel studies of the effects of PM10 and PM2.5 values on children's health, found that PM2.5 had a greater effect than PM10 and that nonasthmatic children were more affected than asthmatic children, while Moshammer et al. (2006), in a panel study of 163 healthy children in Austrian schools, reported that their lung function was reduced when the ambient air contained elevated concentrations of particles. In addition, the recent study by Dorizas et al. (2014) confirms the elevated levels of PM10 in school classrooms, especially when chalk to write on blackboards is used.

Pupils, teachers, and other adults working in schools are at an elevated risk when pollutants in schools are higher; however, there are very few data for school personnel. Among them, for example, Wålinder et al. (1998) investigated the influence of the ventilation rates and ventilation system type on the nasal symptoms of school personnel in randomly selected primary schools in Sweden and found that nasal symptoms were worse in mechanically ventilated classrooms (with balanced supply and exhaust) than in naturally ventilated classrooms, even though the former had higher air exchange rates; the only exceptions were mechanically ventilated classrooms with displacement ventilation, in which nasal symptoms were less frequent.

3.5.2 Effects on Performance of Schoolwork and Learning

Poor classroom environmental conditions have been shown to occur frequently. These conditions, in addition to increasing risks for negative health effects, have been shown to reduce the performance of schoolwork. Different methods for measuring the effects on learning performance of students have been used in the reported studies, which all have been completed in schools and not under laboratory conditions. In some cases, psychological and neurobehavioral tests were used; some studies used standard tests for measuring academic achievement and some used absence rates, as the proxy for negative effects on learning. These studies are briefly summarized in the following.

The majority of studies examining the effects of IAQ and ventilation on the performance of schoolwork and learning used psychological and neurobehavioral tests. These tests examine different skills needed for proper learning, such as the ability to concentrate and memorize (Myhrvold et al. 1997; Ribic 2008; Bakó-Biró et al. 2012; Sarbu and Pacurar 2015). They also used shorter tests examining the ability to read, comprehend, and calculate (Wargocki and Wyon 2013). For example, a classroom study by Myhrvold et al. (1996) found a weak association between CO_2 levels and simple reaction time, suggesting a positive effect of increased ventilation on performance. In studies reported by Wargocki and Wyon (2013), pupils performed arithmetic calculations and language-based tasks under different conditions of air quality achieved by changing the ventilation rate between 3 and about 10 L/s per person (Figure 3.2). The speed at which the tasks were solved was improved with increased ventilation, but there were no effects on errors. Similar results were observed by a recent study, which copied the experimental approach used by Wargocki and Wyon (Petersen et al. 2015). In a study by Bakó-Biró et al. (2012), the performance of range of cognitive tasks was improved. Moreover, the time needed to solve simple math tests was reduced when the ventilation rate was increased from about 0.3–0.5 to 13–16 L/s per person. Haverinen-Shaughnessy and Shaughnessy (2015) also confirmed that the results of the tests in math and reading of fifth grade pupils improved with increasing the ventilation rate up to about 7 L/s per person. Ribic (2008) observed improved performance on the d2 test, a standard test for measuring concentration, when the CO_2 concentration was reduced from around 3800 to 870 ppm (absolute). Sarbu and Pacurar (2015) found that the performance of students on two psychological tests requiring concentration and cue utilization (Kraepelin tests and Prague test) linearly improved with reduced CO_2 levels. In contrast to these observations, Mattsson and Hygge (2005) did not observe any positive effect of operation of particle air cleaners on psychological tests despite the measureable effect on reducing the classroom levels of particles.

Although long-term learning outcomes are expected to be affected by the absence of abilities to perform simple psychological tests and ability to read, calculate, and comprehend, the connection between the progress in learning and these abilities is not very well documented. Therefore, some studies measured long-term learning using standardized tests, which are often developed by national education departments. These tests monitor the progress in learning and benchmark both individual pupils and schools, as well as evaluate the effectiveness of teaching methods and curricula over time.

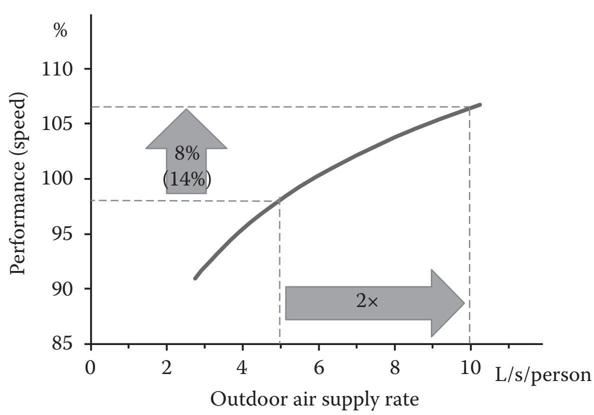

FIGURE 3.2 Ventilation and performance of schoolwork. The effect of increased outdoor air supply rate on the performance on language-based and mathematical tasks. (Reprinted from *Build Environ*., 59, Wargocki, P. and D. P. Wyon, Providing better thermal and air quality conditions in school classrooms would be cost-effective, 581–9, Copyright (2013), with permission from Elsevier.)

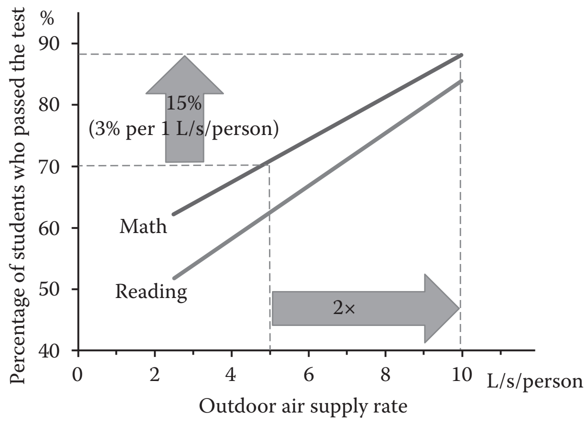

FIGURE 3.3 Ventilation and performance of schoolwork. The effect of increased outdoor air supply rate on the number of students passing the language and math exams. (From Haverinen-Shaughnessy, U., D. J. Moschandreas, and R. J. Shaughnessy, *Indoor Air.*, 21(2), 121–31, 2011. With permission.)

Haverinen-Shaughnessy et al. (2011) showed that poor ventilation in classrooms reduced the number of pupils just passing language and math tests (Figure 3.3). Mendell et al. (2015) showed an increase in mathematics and English scores when ventilation rates were increased, but only in the former case did the effects reach statistical significance. In another study by Toftum et al. (2015), academic achievement was evaluated with the scores from a standardized Danish test scheme, adjusted for a socioeconomic reference score. The lowest national test scores were generally found for pupils in classes with CO_2 concentrations above 2000 ppm, although the association was not significant. Pupils in schools with some means of mechanical ventilation scored on average higher in the national tests than pupils in schools with natural ventilation, probably because the efficacy of ventilation was higher.

Some studies measured illness absence and associated it with poor air quality or poor classroom ventilation to examine indirectly the effects on learning outcomes. Pilotto et al. (1997) showed in a cohort study that air pollutants from gas heaters had a negative effect on attendance at school, which was presumed to be due to a negative effect on children's health. Berner (1993) showed an association between the poor maintenance of schools and the poor academic achievement of the children attending them. Ervasti et al. (2012) found increased short-term sick leave among teachers in schools with poorly perceived air quality. Shendell et al. (2004) found student absence to decrease by 10–20% when the CO_2 concentration was decreased by 1000 ppm in 434 American classrooms. However, a recent study by Gaihre et al. (2014) in Scottish schools showed that an increase of 100 ppm of CO_2 corresponds to only 0.2% increase in absence rates (roughly one order of magnitude lower than the data of Shendell et al. [2004]), corresponding to approximately 0.5 day a year in a 190-day long school year. The study by Gaihre et al. (2014) is in contrast to the studies mentioned earlier, as it did not find any relation between air quality approximated by the levels of CO_2 and educational attainment measured as the percentage of class attaining the average level expected for this group. Simons et al. (2010) found high student absenteeism to be associated with poor ventilation in 2751 New York schools. In a recent work, though performed in day care centers equipped with the balanced mechanical ventilation system, Kolarik et al. (2016) found that increasing the air change rate by 1 h^{-1} would reduce the number of sick days by 12% even though the ventilation rates were quite high in these day care centers, as high as the CO_2 levels were below 1000 ppm, and on average around 640 ppm (absolute). Another recent and very comprehensive study in 162 Californian classrooms observed that illness absence decreased by as much as 1.6% for each additional 1 L/s per person of ventilation rate (Mendell et al. 2013); this is again lower than the data of Shendell et al. (2004) but higher than the data of Gaihre et al. (2014). The earlier findings are quite systematic and suggest that increasing classroom ventilation may substantially decrease illness absence. This may affect the learning experience though there is no clear evidence between the short-term absence of pupils and academic performance (Mendell and Heath 2005). It is also worth mentioning that absence rates can be influenced by many other factors not necessarily related to school environments.

The results from the previous experiments on the effects of classroom air quality on the performance of schoolwork do confirm that these effects are systematic and suggest that improving classroom air quality will have a significant positive effect on some aspects of learning, both on cognitive skills and academic attainment, as well as academic achievements and absence rates. The level of this effect is not the same across different studies as might be expected, but with reasonable confidence, it can be assumed that doubling the ventilation rate would improve the performance of schoolwork by up to 14% and each additional 1 L/s per person would increase the number of students passing the tests by 3% and would reduce the absence rates by at least 1.6% (Figures 3.2 and 3.3).

3.5.3 Implications and Costs

It would be interesting to estimate some economic indicators of the expected effects on learning and school performance, as a result of improved classroom air quality. However, this may not be that simple, as the measurable economic effects of quality of educational process cannot be immediately registered, as is the case for offices. The economic effects are first expected to be demonstrated, when pupils begin to work.

Wargocki et al. (2014) tried to estimate future socioeconomic consequences of improved IAQ in Danish primary schools. Assuming that the increased school performance will improve productivity and reduce the duration of primary education (in the Danish system, the pupil can take either 9 or 10 grades in elementary education, depending on the educational attainment) and absenteeism of teachers, the macroeconomic effects were estimated from increasing the ventilation rates from 6 L/s per person required by the Danish Building Code to 8.4 L/s per person required by the Swedish Code. The modeling of benefits showed that increasing the ventilation would yield an average annual increase in the gross domestic product (GDP) of €173 million due to increased productivity of the workforce and more pupils leaving school earlier and an average annual increase in the public budget of €37 million, again through improved productivity and shorter stays in primary school, as well as lower teacher sick leave. These effects correspond to no more than 0.07% of the Danish GDP in 2011. All effects are expected to increase (being higher and higher from year to year over the 20 years from the moment for which the analyses were performed); more students leave schools where the air quality and ventilation are improved.

A different estimation of the effects of reduced absence rates was performed by Mendell et al. (2013). They assumed that the ventilation rates in Californian K–12 schools will be increased from the current levels of 4–7.1 and 9.4 L/s per person, and estimated the benefits from decreased illness absence to school districts (i.e., increased revenue from the state for student attendance, which is the model adopted by the schooling system there) and the benefits to families through decreased costs from lost caregiver wages/time. Such estimated benefits yielded figures from US$33 to US$66 million annually from increased revenue from the state, and from US$80 to US$160 million annually from reduced losses to caregivers.

Both estimations show that the benefits and the potential losses due to reduced learning ability as a consequence of poor air quality are considerable and cannot simply be considered as negligible.

3.6 VENTILATION, INDOOR AIR QUALITY, HEALTH, AND SLEEP QUALITY IN HOMES

3.6.1 Effects on Health

The data that exist on actual ventilation rates in residential buildings are limited and not representative of the entire residential building stock considering the different typologies of buildings, different building codes, climatic region, and merely cultural and historical merits. Moreover, the data that exist at present were collected during different times, including relatively old and relatively new buildings, and buildings complying with different code and standard requirements. Still, they can provide some information on the levels of ventilation rates that can be expected in residential environments and consequently the levels of exposures to potentially hazardous pollutants in residential building stock. These data indicate that the ventilation rates in dwellings are lower than in office buildings and higher than in schools. This observation is primarily based on the data collected by Brelih and Seppänen (2011) and Brelih (2012), who reviewed studies in dwellings in Europe and showed that the measured mean ventilation rates range from ca. 0.3 to 1 h^{-1}, which is about 5–15 L/s per person, with lower rates being prevalent in naturally ventilated dwellings or dwellings with exhaust ventilation only, and the upper and the middle range being more typically measured in the mechanically ventilated dwellings; the measurements in U.S. homes by Pandian (1988) show very similar levels of air change rates, about 0.5–0.7 h^{-1}. For comparison, the reports of Brelih and Seppänen (2011) and Brelih (2012) showed that the measured ventilation rates in schools in Europe range from ca. 1.5 to 9 L/s per person, and in offices from ca. 9 to 20 L/s per person. Asikainen et al. (2012, 2013) estimated the fraction of dwellings in Europe that do not meet the ventilation rates prescribed by the national standards. Using Bayesian regression, in which the location of the country, the annual mean temperature, and the gross domestic product were treated as explanatory variables, and the existing measurements of ventilation rates and the required ventilation standards by the national standards were the input variables, they showed that about 33% of dwellings in Europe can be expected to have ventilation rates below the national standards. This means that about 20% of European citizens (ca. 110 million) live in housing where there are elevated concentrations of hazardous pollutants.

Ventilation rates in homes that do not meet the standard requirements may not necessarily be reason for concern that the exposures will consequently lead to elevated risk for health problems, since it will all depend on the level of exposures to hazardous pollutants, which will additionally depend on the strength of the pollution sources. Without knowing the actual levels of exposures, many studies performed to date in dwellings suggest that it is beneficial to increase ventilation rates. These studies mainly examined the effects of ventilation on acute health outcomes such as asthma and allergy, building-related symptoms and complaints called SBS symptoms, and respiratory problems. Some were remotely observed by either mortality, cardiovascular and respiratory hospitalizations, obesity, and lead poisoning and can be associated with ventilation levels in homes. The results of these studies show that increasing the ventilation rates will generally reduce health problems (Figure 3.4), though the relationship presented in the figure was developed using data collected in offices; it may be assumed that it would apply also in domestic environments, as well.

Additionally, these studies also show that it is beneficial to retrofit homes with a ventilation system (either mechanical, hybrid, or natural) that secures that the ventilation rates are sufficiently high to deal with the pollutants generated indoors. The installed ventilation systems, however, need proper maintenance, because otherwise they may become the source of pollution and their presence can actually elevate the risk for health or does not bring the expected benefits. This could be one of the possible explanations why, in some studies, increased ventilation rates did not bring the intended positive effect in the form of reduced health risk.

No single ventilation rate can be recommended as protective based on the evidence collected through studies performed in homes, similarly to what has been observed for offices. The effects on health outcomes were significant over a wide range of ventilation rates. At the same time, the results from these studies show that ventilation rates below 0.4 h^{-1} would always increase the risk. This may suggest that ventilation rates in dwellings should not be reduced below 0.4 h^{-1} in case the emissions from sources indoors are similar to the studies, which form the basis for this recommendation. This rate is actually only slightly lower than the rates recommended by many building codes and standards. For example, the Danish Building Regulations Danish Housing and Building Agency (2010) set the requirements at 0.5 h^{-1}, as recommended by some reviews of the effects of ventilation on health (e.g., Wargocki et al. 2002; Sundell et al. 2011).

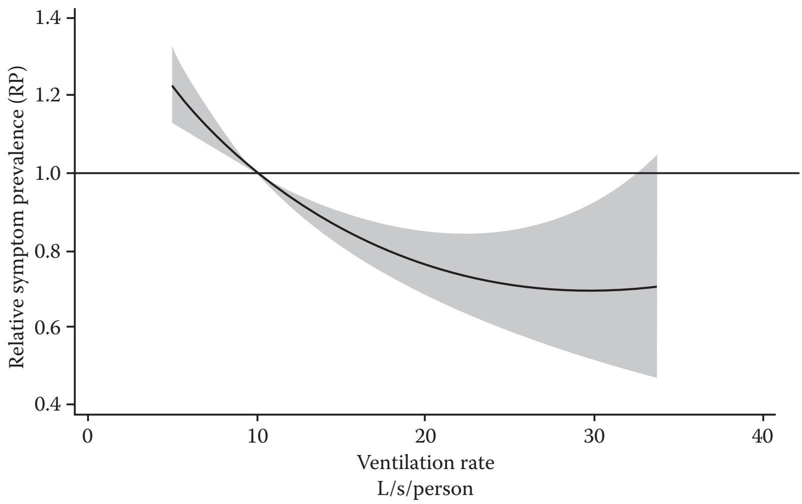

FIGURE 3.4 Ventilation and acute health symptoms in dwellings: The effect of increased outdoor air supply rate on prevalence of acute symptoms. (Fisk, W. J., A. G. Mirer, and M. J. Mendell: Quantitative relationship of sick building syndrome symptoms with ventilation rates. *Indoor Air.* 2009. 19. 159–65. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.)

The strongest evidence of the effects of ventilation can be seen with asthma, allergy, and respiratory symptoms. Any problem with ventilation defined as improper ventilation was associated with the elevated risk of asthma (Ezratty et al. 2003). In studies with children, it was shown that proper ventilation can reduce the risk for wheezing and rhinitis, both approved as reliable indicators of symptoms of asthma and allergy (Bornehag et al. 2005; Hägerhed-Engman et al. 2009; Kovesi et al. 2009). In the case of adults, it has been shown that nocturnal chest tightness, a symptom of problems with the respiratory system as a consequence of asthma, is higher with higher CO_2 levels being an indicator of too low ventilation rates (Norbäck et al. 1995). Retrofitting houses with mechanical ventilation systems was also shown to reduce the risk for asthma symptoms for infants (Kovesi et al. 2009), children (Lajoie et al. 2015), and adolescents (Howieson et al. 2003). The installation of new mechanical ventilation systems with heat recovery in homes without such a system was additionally associated with improved lung functions (Wright et al. 2009; Xu et al. 2010). Emenius et al. (2004) and Clausen et al. (2012) could not, however, confirm the relationship between ventilation rates and asthma and allergy symptoms, and neither could Warner et al. (2000) show that the installation of the mechanical ventilation system would especially improve lung functions. Many studies confirmed that the presence of ventilation in residential buildings does not guarantee a low risk of respiratory and allergic symptoms (e.g., Gustafsson et al. 1996; Jones et al. 1999; Willers et al. 2006). In addition to this Kovesi et al. (2009) showed that, although the levels of relative humidity are reduced when the new ventilation systems are retrofitted, this may not always translate into less health center encounters and hospitalizations due to respiratory problems.

Emenius et al. (2004) showed that humidity and window pane condensation (a marker of elevated humidity) were associated with elevated risks of symptoms. Large amounts of water are produced in homes by their occupants, and their study suggests that all efforts should be made to ensure that the moisture is removed. A typical family of four may produce between 5 and 10 kg water a day or even up to 15 kg can be produced by larger families (BS5250 1989; Ucci et al. 2004). This estimation includes the moisture produced through respiration and during different activities occurring indoors including cooking, washing, and drying clothes. Water is not harmful to health per se but excessive moisture indoors can result in the presence of unwanted contaminants and allergens and can modify the perception of air quality.

High levels of relative humidity (>50–60%) are frequent in residential environments. Relative humidity of >50% will increase survival of the population level of house dust mites (HDMs) and levels >60% will exacerbate their reproduction. HDM's feces cause house dust mite allergy, which is demonstrated in form of allergic reactions, asthma, and rhinitis. Several studies have shown that increased ventilation rates can reduce the concentration of HDMs (Harving et al. 1993, 1994; Sundell et al. 1994); the same conclusions are reached when the houses are retrofitted with the new mechanical ventilation system (Warner et al. 2000), most likely because the ventilation rates are consequently increased. These data constitute additional evidence of benefits of increased ventilation for reducing the risk of asthma and allergy symptoms in homes, but only when the ventilation will reduce the levels of relative humidity to levels that are at least below 50%. The reduction of humidity and moisture to deal with HDMs will additionally bring other benefits by reducing the risk of other health problems related to too high moisture levels that can, e.g., cause mold and related health problems (Bornehag et al. 2001, 2004; WHO 2009).

Relative humidity of >80% in the boundary levels of external walls and partitions increases the risk of condensation and mold growth. The germination of molds will depend on the surface type (which needs to provide sufficient substrate), availability of nutrients, temperature, and moisture. When it does occur, the mold spores can enter the air, and the exposure to spores can cause allergic reactions in the form of bronchial asthma or runny nose. Mold spores and particles containing molds, even when dead, can still emit toxic chemical compounds, so-called mycotoxins. Molds can also emit metabolic VOCs (mVOCs), which are secondary metabolites producing a musty odor typical for houses where molds are suspected. Exposure to mVOCs can cause immune system activation. In homes with verified dampness problems and plasticizer-containing surfaces, low ventilation rates were associated with the risk of bronchial obstruction (Øie et al. 1999).

High levels of moisture can also increase emissions from building materials and furnishings (Fang et al. 2004). Moisture on surfaces and in construction can cause hydrolysis reactions causing decomposition. An example of such a process includes di-2-ethylhexyl phthalate from polyvinyl chloride flooring hydrolyzing on a moist concrete, which produces 2-ethylhexanol, which has a mild odor and may potentially cause strong irritation. This process could be one of the underlying mechanisms explaining the results obtained by Øie et al. (1999) mentioned earlier. Hydrolysis can produce alcohols and monoesters (carboxylic acids), which can contribute to odor problems and irritation. Only limited data are available so far on these processes.

The presence of mechanical ventilation systems in homes and most likely the resulting higher ventilation rates and lower exposure levels were associated with reduced self-estimated health symptoms typical of SBS symptoms among adults compared with homes without mechanical ventilation systems (Ruotsalainen et al. 1991; Engvall et al. 2003; Leech et al. 2004). Ruotsalainen et al. (1991) additionally showed that the important requirement for this to occur is the higher air change rates and not merely the presence of a mechanical ventilation system. Some studies did not, however, find a relation between the building-related (SBS) symptoms and the existence and the operation of mechanical ventilation systems (Kishi et al. 2009). One of the reasons could be the lack of proper maintenance of these systems by the occupants of the dwellings or by simply blocking the outlets and the terminals due to experienced drafts and noise that they were generating (e.g., Coelho et al. 2005; Palonen et al. 2008).

Often the use of air conditioning in homes can result in reducing ventilation rates to minimize the expense for energy. This will also consequently result in an increase in the risk for elevated SBS symptoms (Wong and Huang 2004). The use of central air conditioning in homes may also have benefits by protecting people against ambient sources of pollution and reducing indoor temperatures that can be mortal, especially for the elderly during hot weather (Marmor 1978; Rogot et al. 1992). Bell et al. (2009) showed that the use of air conditioning in homes reduced the exposures to particulate matter mainly having origin in outdoor traffic, and was associated with reduced cardiovascular and respiratory hospitalizations, as well as mortality among the elderly. Deger et al. (2010) showed that children living along streets with highly dense traffic (especially those living on the ground floor) had an increased risk of asthma, so homes need to be sealed against ambient pollution that can be, e.g., transported by ventilation. However, the elimination of ambient pollution by sealing houses should not compromise IAQ and should not elevate indoor exposures. The data from two national longitudinal studies in the United States on house characteristics indirectly suggest this. They show that the increased use of air conditioning resulting in most cases in lowering ventilation rates to achieve energy savings, together with other factors such as lifestyle and nutrition, were associated with obesity and lead poisoning (Jacobs et al. 2009).

The use of air conditioning and/or high ventilation during very cold periods when the absolute humidity is close to zero may reduce the relative humidity in homes below 20–30%. This is occurring very seldom and only for the relatively short periods particularly when houses have very low occupation density. Low relative humidity in clean air has not been shown to cause any negative health effects or sensory discomfort (Wyon et al. 2006), even during half-a-week exposures (Andersen et al. 1974). However, the presence of VOCs with low relative humidity exacerbates the symptoms of dryness and/or irritation (Andersen et al. 1974; Wyon et al. 2006). Low relative humidity lowers the resistance to infections. At low moisture levels, the transmission of infectious particles and diseases is promoted, and short periods with increased humidity have been proposed as an interim solution for handling and inhibiting epidemic outbreaks (ASHRAE 2013).

3.6.2 Effects on Sleep and Next-Day Performance

IAQ in homes can disturb sleep quality and next-day performance, as shown in the studies that observed the correlation between sleep quality and next day concentration (Tynjälä et al. 1999; Meijer et al. 2000). Disturbed sleep is a widespread problem, but essentially, there are marginal data that document whether IAQ in bedrooms plays the important role for these outcomes. Three relatively small experiments provide some support that these can be the case.

In one study, students in dorms slept with windows open and closed so that the resulting ventilation rates were 0.4–1 h^{-1} and 0.2–0.3 h^{-1}. The objective sleep measures showed no differences, while students reported more awakenings during night and that they better remembered dreams with the windows open (Laverge and Janssens 2011). In another experiment, also performed in dorms, students slept with high and low rates of ventilation with outdoor air achieved by a simple fan mounted in the aperture, so that the air change rates were at about 0.3 h^{-1} and 1.4 h^{-1}. This time students reported that the air in their room was perceived to be fresher, that they felt more refreshed, and that their mental state was better when the fan was on. The objectively measured sleep efficiency (time spent asleep) was higher, and their performance on the concentration test taken in the morning was better when the fan was on (Strøm-Tejsen et al. 2014). Yet another study showed that the elderly sleeping with personal ventilation with an air outlet device directly on the head of the sleeping person (thus securing that exposures are reduced had a shorter sleep onset latency (measured objectively) and their heart rate variability was reduced (Zhou et al. 2014). If the results of these studies are confirmed, the changes in the air quality in homes can result in substantial economic benefits.

3.6.3 Implications and Costs

Logue et al. (2012) estimated the burden of disease related to elevated exposures to pollutants in homes based on the American population. They identified major pollutants emitted in houses and their exposure levels and then attributed the health risk related to the inhalation of these pollutants in homes. They showed that 1.3–3.5 million of healthy life years can be expected to be lost due to premature death or disability to perform work each year in the United States due to poor air quality in homes. The pollutants that had the highest attributable risk were PM2.5, second-hand tobacco smoke, formaldehyde, acrolein, radon, and ozone. Similar estimations in Europe (EU-27), as mentioned earlier, though for the entire building stock, i.e., including public buildings (offices, schools, etc.) and residential buildings but excluding second-hand tobacco smoke, resulted in a very similar figure of ca. 2 million healthy life years lost (Jantunen et al. 2011). In addition, in this case, the exposure to PM2.5 had the highest contribution to the burden of disease. These two estimations clearly illustrate that indoor exposures in homes significantly contribute to the burden of disease in the population and create a significant challenge for public health. This burden of disease has also considerable economic consequences. If one healthy life year is valued at €115,000 (Quinet 2013), then even assuming that only 1 million healthy life year is annually lost creates a gigantic loss for the national economy.

Socioeconomical costs due to exposure to indoor air pollution are actually rare, but those that exist confirm that the cost of poor air quality is very high. For example, a recent estimate in France for selected indoor air pollutants (benzene, trichloroethylene, radon, carbon monoxide PM2.5, and environmental tobacco smoke) showed that the loss due to exposures to these pollutants is €20 billion annually, a substantial part of it, around €14 billion, being attributable to exposure to PM2.5 (Kopp et al. 2014).

In addition to costs for health related to exposures to pollutants indoors, there are other costs that can be incurred due to pollution in homes, for example, due to insurance claims or litigation as a result of mold remediation. However, there are no published studies that tried to estimate other economic consequences of poor air quality in homes, e.g., in the form of loss in productivity or impact on academic achievement. These costs can also reach significant figures considering that a large part of education and learning occurs in homes, and more and more work tasks are actually completed at homes as well and not only when not at work (e.g., e-mailing, conference calls, e-meetings, reporting, etc.). As indicated in the previous sections, there are direct links between poor air quality and reduced performance at work and learning. In addition to these effects, IAQ in homes can disturb sleep quality, which is essential for the proper resting and next-day performance, as presented earlier.

3.7 CONCLUDING REMARKS

Despite the ample ventilation rates in office buildings, building occupants suffer from poor air quality, acute health symptoms, and reduced work performance. There is a very consistent body of evidence that indicates that improving air quality will mitigate these problems. Increasing ventilation rates will bring benefits, but what actually should be mitigated are the exposures because ventilation is only the mean to reduce the exposures. The pollution source control and the reduction of sources of pollution both indoors and outdoors should always have the highest priority. There seems to be, however, a low perception about the link between health symptoms and performance and poor air quality, and low perception of the potential significant benefits therein.

A good education system constitutes one of the fundaments of a modern society, because poor learning can have lifelong consequences for a student and for society. A recent Organization for Economic Co-Operation and Development report (Hanushek and Woessmann 2010) shows that countries that perform better in the Program of International Student Assessment (PISA) have higher growth rates. It also shows that

> Foundation skills in mathematics have a major impact on individuals' life chances. The survey shows that poor mathematics skills severely limit people's access to better-paying and more rewarding jobs; at the aggregate level, inequality in the distribution of mathematics skills across populations is closely related to how wealth is shared within nations. Beyond that, the survey shows that people with strong skills in mathematics are also more likely to volunteer, see themselves as actors rather than objects of political processes, and are even more likely to trust others.

The present chapter provided evidence from the archival literature that good classroom air quality is an important prerequisite for learning and educational attainment and, not least, the condition that will secure no health risks for the younger generation and their educators.

Homes should create shelter and conditions fostering restoration and rest. The present chapter showed that the exposures in homes can significantly increase the burden of disease, which may have considerable economic consequences. There are also some data showing that poor air quality conditions in homes may result in reduced next-day performance due to effects on sleep quality, but these data are only preliminary. Increased ventilation could not be shown unequivocally to reduce the exposure so that the risk for health of asthma and allergy symptoms, acute building-related symptoms, and respiratory symptoms could be reduced, but the epidemiological data showed that rates above 0.4 h^{-1} would at least be needed to achieve this goal. Elevated humidity and moisture were seen to consistently increase the risk, but ventilation may not always be effective to reduce their levels. Retrofitting housing with the new mechanical ventilation systems was seen to lower the risk, but malfunctioning and improper maintenance would again increase the risk. Air conditioning in houses may serve a protective role, when the ambient air is polluted, but will otherwise elevate the risk for health due to reduced ventilation rates as a measure taken to conserve energy.

This chapter showed also that the economic benefits of improving IAQ will outweigh the costs needed to implement them and will significantly contribute to improving the quality of life. This provides a strong economic argument and incentive for securing people's lives, work, and rest in air of outstanding quality, the quality that will not be detrimental for health and that will foster our quality of life.

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