CCIAQ | Canadian Committee on Indoor Air Quality

Guide for Indoor Air Quality

Module 14

Indoor Environment Quality (IEQ) and Productivity in Workplaces/ Achievement in Schools

2020

Canadian Committee on Indoor Air Quality (CCIAQ)

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Indoor air quality is a very complex issue and there is currently a significant gap between knowledge of the effects of indoor air quality on the health of occupants and the effectiveness of various air quality technologies and solutions. User discretion is advised.

Preamble

The objective of the CCIAQ is, ultimately, to improve indoor air quality (IAQ) for all Canadians in every type of building. The CCIAQ has decided that its initial focus should be on buildings where many Canadians spend time outside their home, working, learning, shopping, being entertained, etc. For the most part, these buildings have relatively complex heating, ventilating and air conditioning systems that are operated and managed by knowledgeable persons. The table below gives examples of buildings that are covered using the classification found in the *National Building Code of Canada* (NBC). Documents produced by the CCIAQ are primarily intended for the use of building operators and facility managers, but the information contained in the guides can be helpful to anyone seeking a general understanding of indoor air quality issues.

The CCIAQ recognizes the importance of understanding how the indoor environment can affect health and productivity in buildings as well as achievement in schools, and what can be done to create healthier indoor environments. Module 14 – Indoor Environment Quality (IEQ) and Productivity/Achievement in Workplaces and Schools, is a response to this important need.

The Committee welcomes feedback on the documents as well as ideas for the development of new materials. Contact the CCIAQ at https://iaqresource.ca/contact-us/ or register on the website at www.IAQResource.ca

NBC Classification	Examples
Group A, Division 1	Theatres, movie theatres and other facilities for the performing arts
Group A, Division 2	Art galleries, museums, libraries, educational facilities (schools, colleges and universities), gymnasia, air and rail terminals)
Group A, Division 3	Arenas and swimming pools
Group C	Apartments, hotels, college residences
Group D	Offices, including medical and dental offices
Group E	Department stores, supermarkets, shops, retail space

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1. Purpose of this Module

The purpose of this guide is to inform building designers, managers, operators, educational authorities, employers, occupants and visitors about indoor environmental quality (IEQ), in relation to well-being, students' achievement in educational settings, and workers' productivity.

IEQ is a broad concept, including and complementing indoor air quality. "Green building" initiatives (tabulated in Section 7) aim to reduce energy use with a goal of Net Zero, while optimizing air quality, thermal comfort, light, acoustics and other functional and aesthetic factors. Previous Canadian Committee on Indoor Air Quality (CCIAQ) Modules address numerous indoor air quality topics, and may be accessed at: https://iaqresource.ca/en/home-iaq-resource/

This guide is written in the context of: 1) mounting challenges resulting from extremes in weather, as designers, operations managers and others aim to improve both energy efficiency and resilience of buildings; 2) rapid advances in technology and practices to monitor and control building operations and IEQ; and 3) adaptations in response to the 2020 COVID-19 pandemic, and to reduce contagion in the built environment.

Endeavours to combat climate change must not repeat the unfortunate consequences of ventilation reductions in response to the Gulf Oil crisis of the 1980s, leading to "sick building" symptoms (Module 13, *Addressing Chemical Sensitivities* [1]).

This module examines a broad range of studies on factors affecting resilience and efficiencies as they intersect with IEQ, and in turn the effects of IEQ on well-being, achievement and productivity in educational institution settings and workplaces.

2. Introduction

Buildings, including schools and offices, present opportunities to reduce greenhouse gases (GHGs) and energy use during every stage of planning, design, construction and commissioning, for renovations and new construction. In existing buildings, the majority of GHGs result from ongoing operations for occupants' expectations and needs, as well as occupants' activities. Details of design, HVAC equipment and operations, fixtures and maintenance may also affect the likelihood of contagion. Indoor environmental quality, the direct result of the continuum from concept and overall design through operations and details of indoor spaces, may either support or detract from students' and workers' successes.

2.1. What is Indoor Environmental Quality (IEQ)?

IEQ is multi-faceted, going beyond air quality to include thermal comfort, acoustics, ergonomics, electromagnetic factors (lighting, infrared as it affects thermal comfort, and wireless communications), technologies, services and controls, water supply and disposal, and subjective elements such as design and aesthetics.

It is not feasible within the bounds of this module to cover all details of IEQ. This module provides an overview, and more details are available in the numerous references, resources and links to leading organizations that are appended (Sections 6 and 7).

2.2. Benefits of optimizing IEQ

Students and workers are more successful in high quality environments,[2] so this guide examines specifically the means to and benefits of optimizing IEQ elements in "green buildings" for the performance and health (including mental health) of occupants of educational facilities [3,4,5,6,7] and offices.[5,6,8,9] Students and employees studying and working in facilities with superior IEQ have shorter reaction times and greater accuracy, and also experience less illness, absenteeism and employee turnover. There are also higher quality social interactions and collaboration.[10]

2.2.1. Affordability of IEQ versus student and employee productivity

School boards, governments and businesses typically operate with many demands and limited resources, and it may not be recognized that the value of wages, attendance and productivity substantially outweigh the financial costs of ventilation, heating and cooling.[3] The well-being and productivity of students and workers may be missing from institutions' balance sheets. Indeed, public health should be considered a sufficient sole reason to maintain optimal ventilation, heating and cooling of occupied indoor environments.

An outcome-based ventilation costing framework to comprehensively assess performance, health and energy impacts was used to examine a database of U.S. commercial office space.[11] Profitability was optimized by minimizing losses (e.g., costs for heating and ventilation) while maximizing profitability (e.g., work performance and lower absenteeism) in the context of air quality parameters known to affect health (ozone and particulates).[11] Using mid-range values in the model, maximum profits based on occupant health were realised with very high ventilation rates exceeding 45 L/s per person, while the most conservative model indicated an optimum at 17 L/s. This is twice the recommended American Society for Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 62.1 guidance of 8.5 L/s per person.[11] The bottom line is that health-based outcomes (well-being, absenteeism, and learning and work) offer substantial value compared with energy costs. Ventilation is discussed further in section 3.1.1.

Environmental performance and resilience of buildings affect mental health in tangible and intangible ways. Indoor contaminants and noxious stressors may affect directly the brain and nervous system, while individuals may also suffer "eco-anxiety" and wish to study, work and live in spaces that reflect key priorities and values.[10]

2.2.2. Options for IEQ

Facing climate imperatives, energy use is top of mind. Numerous eco-standards for design, construction, and operation of buildings (see Section 7) offer a wealth of options to reduce heat loss. These may be considered throughout concept, siting (e.g., optimization of solar gain during winter), design (e.g., Net Zero goal, and choice of durable, low-carbon-footprint and high-carbon-content materials), construction (e.g., enhanced insulation, high thermal mass, methods to avoid heat bridges across the building envelope, and meticulous vapour seals), fitting and commissioning of the finished building (e.g., blinds and curtains to reduce heat loss through windows during the winter, and to reduce solar gain and warming during summer), operation of building systems, and maintenance.

IEQ is affected by, and broader than energy efficiencies. Comparisons of eco-standards may help to identify options and to select priorities (see Section 7 for resources). For example, cognitive and well-being benefits of green buildings (e.g., with natural light, views of nature, and vegetation elements in addition to efficiencies of heating and air conditioning) exceed those of high performance buildings (i.e., energy-efficient with superior air quality, and other features). It has been suggested that the breadth, complexity and inter-relatedness of design and operational aspects contributing to building performance be understood as "buildingomics", akin to studies of complex determinants of health such as genomics.[6] Indeed, an environmentally superior building in terms of energy efficiency and IEQ, per international green building standards, may represent a competitive advantage, attracting and retaining high quality employees and preferred clientele, and optimizing performance of buildings and productivity of occupants.[12,13]

2.2.3. Responses to climate crises

Climate crises are driving rapid revolution in all aspects of buildings, from concept to renovations to operations. ASHRAE states, "Climate change is the most formidable environmental challenge ever faced by society. Opportunities exist … to provide solutions to reduce GHG emissions."[14] Opportunities arise during design and construction, maintenance, renovation, and equipment replacement and retrofitting, to improve resilience and to modernize building systems and controls. Taking advantage of these opportunities can result in savings from improved efficiencies, as well as from design features that ease maintenance and avoid problems in heating, ventilation and air-conditioning (HVAC) systems.[6,15]

Endeavours to combat climate change must not repeat the unfortunate consequences of ventilation reductions in response to the Gulf Oil crisis of the 1980s, including dampness, poor indoor air quality and "sick building" symptoms (Module 13, *Addressing Chemical Sensitivities* [1]).

Multiple strategies for buildings and occupants will be necessary, to adapt to climate changes. International research examining human performance under different environmental conditions has spawned interest in adaptive capabilities of individuals, and in broadening acceptable thermal and energy use ranges for IEQ. This requires re-examination of physical conditions that support excellence in workplace productivity and in educational achievement.

2.3. How to use this guide

This guide provides an overview of IEQ considerations to improve environmental performance as well as individuals' productivity and well-being in educational facilities and workplaces. The guide discusses progressive options for building owners, facility managers, building operators, occupants, businesses, education providers and governments, as well as architects and designers, in the context of numerous priorities focused on energy efficiencies, infrastructure resilience and health.

3. Indoor Environmental Quality (IEQ) and Productivity

IEQ includes indoor air quality as well as numerous factors covered in this section, including lighting, acoustics, water, ergonomics, aesthetics and site-related factors, and information technology.

Optimization of indoor air quality has largely been covered in the preceding CCIAQ modules, including design, monitoring, maintenance, renovations and eliciting cooperation among occupants.[16] Module 13, *Addressing Chemical Sensitivities*,[1] concluded: "Improving IAQ in ways that would address chemical sensitivities can improve health and productivity of others in the shared environment,[9] thereby helping to protect the most vulnerable (e.g., the developing foetus and child) [17,18,19] as well as contributing to broader environmental objectives such as reduction of pollution and greenhouse gasses.[20]"

In this section, distinctions are made between measurements that can be readily taken in educational facilities and workplaces, and the fuller picture. For example:

- the actual air quality including all chemicals is only partially represented by measured markers (typically CO_2, or total volatile organic compounds [TVOCs]);
- air temperature, humidity and velocity alone do not predict thermal comfort, because occupants may wear temperature-appropriate clothing, or experience radiant heat; and
- perceived comfort or environmental quality may not always predict students' or workers' performance.

Many elements of comfort (e.g., perceived versus actual indoor air quality, noise, lighting, aesthetics, amenities) interact with individuals' preferences and priorities to determine ultimate satisfaction. Finally, the nuances of comfort and acceptability of IEQ parameters, in relation to productivity at school or work, are summarized.

3.1. Indoor air quality, carbon dioxide (CO_2) and other contaminants

Poorer indoor air quality may result when natural ventilation in older "leaky" buildings is reduced via renovations that tighten the building envelope, especially if mechanical ventilation is also restricted to reduce energy used for heating, cooling and air handling. Some older buildings, such as schools using radiators, may have limited ventilation and air conditioning.

Optimizing a building's indoor air quality requires efforts to minimize and mitigate contaminants from the building structure and contents. For example, design, construction and renovation choices must aim to minimize off-gassing of materials, water infiltration and dampness indoors. In operation, buildings must capture and vent at source the emissions from processes and equipment such as printers, or in kitchens, and products that are free of volatile organic chemicals (VOC-free) must be used for cleaning and maintenance.

Chemicals from occupants and visitors are inevitable. We all breathe in oxygen and exhale CO_2, that builds up in indoor air. CO_2 is also a reliable marker for other bioeffluents such as chemicals in breath and body odours.[2,21] In a given venue, CO_2 levels may also reflect potentially avoidable VOCs from individuals' use of scents, and chemicals from personal products and habits (e.g., residues of smoke); however, CO_2 is unrelated to off-gassing from building elements (e.g., structure, carpeting, furnishings, etc.) and activities (e.g., cooking, photocopying, etc.). Chemicals originating from the building and maintenance are nevertheless important; for example, children sitting on carpets and breathing dust close to the floor are both more highly exposed and more vulnerable to adverse effects of chemicals in building materials, furnishings, and cleaners and pesticides used indoors. [1,22,23,24,25,26]

Optimizing indoor air quality with attention to these types of details is discussed in Module 13, *Addressing Multiple Chemical Sensitivities*.[1]

With high occupancy in enclosed spaces and/or insufficient outdoor air supply, conditions of elevated indoor CO_2 (plus unmeasured bioeffluents and other contaminants) can engender fatigue and impair critical thinking and cognition.[27,28] In multiple studies, CO_2 levels correlated with performance on cognitive and decision-making tasks,[8] while experimental supplementation of CO_2 in the outdoor air supply revealed direct impairment of skills for office work associated with CO_2 itself, apart from other VOCs.[9,27]

CO_2 levels may be used in mathematical models of occupancy, ventilation and room volume as a surrogate for numerous occupant-related air contaminants.[29] Models relate occupants' responses in test situations to air quality and associated ventilation rates.

Researchers also aim to distinguish effects of CO_2 from other unmeasured bioeffluent air contaminants, that increase along with CO_2. A multi-faceted review of dozens of studies reported physiological mechanisms and effects of inhaled CO_2, and effects of indoor air supplemented with various levels of CO_2.[30] Cardiovascular changes were observed to increase between 500 ppm and 5000 ppm, and "building related symptoms" (e.g., dry cough, eye irritation, headache, fatigue, dizziness) increased above 700 ppm.[30] Children in daycares and schools also experienced dry cough, rhinitis (runny nose) and wheezing. Short-term exposure to 1000 ppm CO_2 resulted in poorer psychomotor performance in research with young adults exposed to constant ventilation, with CO_2 levels manipulated via addition of ultrapure gas. Authors concluded that addressing atmospheric CO_2 is urgent because in addition to climate disasters, current trends may result in ambient indoor levels that are detrimental with chronic exposure, even with rates of ventilation that would be sufficient to dilute other bioeffluents.[30] Atmospheric CO_2 surpassed 400 ppm in 2015, and continues to climb.[31]

Notably, included in the above extensive review are short-term experimental studies in young college students, showing that physiological effects related solely to CO_2 did not translate into impaired productivity.[32,33] Exposure over 2.5 hours to clean air containing very low levels of bioeffluents, supplemented with pure CO_2 up to 3000 ppm or 5000 ppm (the occupational exposure limit), increased blood pressure and stress biomarkers in blood and saliva, but had little short-term effect on results of cognitive tests and tasks resembling office work. Productivity impairment and adverse physiological responses during different sessions with lower air exchange were related to the totality of bioeffluents, rather than only CO_2 concentration.[32,33,34] It is unclear how results in young students would translate to effects in mature workers.

The bottom line is that while low-emission structures, furnishings and practices (e.g., use of scent-free cleaning products) are important for indoor air quality, ventilation using outdoor air is essential to optimize productivity by diluting CO_2, bioeffluents and other personal chemicals. Energy use for heating and cooling while ventilating during extremes of outdoor temperatures can be reduced via heat exchangers/economizers exchanging energy between exhaust and incoming air.[35]

3.1.1. Ventilation for air quality

Maximizing energy efficiency to address climate imperatives will include optimization of the building ventilation system.

Ventilation, exchanging indoor for outdoor air, is essential to exhaust bioeffluents as well as building- and activity-related airborne substances. ASHRAE has summarized that for low-activity occupants, 7.5 L/s per person ventilation with outdoor air will maintain CO_2 levels approximately 700 ppm above outdoor levels.[36] This translates into over 1100 ppm at time of writing – a level known to cause physiological, and potentially cognitive effects.[30]

When occupants are more active CO_2 is produced more rapidly, requiring higher ventilation rates to maintain low levels and healthy indoor air quality.[36] Since ventilation rates are on a per-person basis, crowded environments require proportionally higher volume exchange rates, as well as good mixing of the air. Thus, higher activity levels and more crowded spaces require larger numbers of vents to ensure adequate, uniform air quality, and thermal and acoustic comfort.

Ventilation rates in research studies range from less than 3 L/s per person to tens of L/s per person, with CO_2 levels ranging from 500 ppm (not substantially higher than current average outdoor air levels, that have surpassed 400 ppm [37]) to thousands of ppm. As global CO_2 levels increase, surpassing 400 ppm, 500 ppm indoor CO_2 levels become more difficult to achieve, and schools may continue to greatly exceed this achievement-based optimum.[3]

Higher ventilation rates are necessary to support students' and workers' performance. A study of workers randomized and blinded to different air quality on various days found that compared with a conventional office, the Green (low VOC) environment resulted in 61% higher cognitive function scores, whereas a high-ventilation Green environment resulted in 101% higher scores.[9] In a large review demonstrating significant incremental improvements in workplace productivity at ventilation rates up to 17 L/s per person, this represented at the time, a CO_2 level of 500 ppm.[8] In another study, an outcome-based ventilation costing framework modelled real-time data from U.S. offices.[11] Using mid-range values for costs (wages, absenteeism), health (as impacted by ozone and particulate pollution) and energy (electricity and natural gas), an optimum based on occupant health was identified for very high ventilation rates, exceeding 45 L/s per person.[11]

"Natural" or passive ventilation is common particularly in schools that are minimally occupied during the heat of the summer. Canadian schools may have either no air conditioning (A/C) nor air exchange equipment, or A/C is partially retrofitted (e.g., present in the gym and/or library) in response to increasing temperatures. Passive ventilation occurs via air exchange through cracks in buildings, and open windows and doors. As discussed below, IEQ expectations, satisfaction, productivity and academic results may be achieved over the greater range and variability of temperature observed when indoor and outdoor temperatures trend similarly, and when occupants have some control over the environment (e.g., opening windows, lowering shades, or operating fans) as with passive ventilation.

Indoor air quality is more challenging when outdoor air used for ventilation has been degraded by urban pollution, industrial emissions or substances related to disasters such as wildfire smoke or microbial growth in wet buildings. Thus, creating and maintaining healthy IEQ requires addressing interrelated design and operational challenges for resilience, energy efficiency, air exchange, control of humidity and removal of pollutants. Timing peak ventilation rates may reap benefits, such as ventilating during times of low levels of traffic or smoke, or overnight to take advantage of lower temperatures during seasons when cooling is required.[38] Filters may be fitted to air intakes, or be considered for particular rooms.[35]

Optimizing ventilation algorithms to improve indoor air quality was investigated in a large experimental and modelling study of small to medium-large U.S. offices.[11,39] Subjects' performance was tested under a variety of IEQ conditions, and public health effects were related to particulate and ozone concentrations. Using measurements of outdoor and indoor temperature and air quality, along with 19 building parameters, modellers manipulated timing of ventilation to take advantage of outdoor air temperature, drew in outside air in response to indoor CO_2 levels, economized on heating and cooling using heat exchangers, filtered particulate pollution, and in some cases doubled the baseline ventilation rate to reduce CO_2. This mathematical modelling identified potential savings of up to $28 billion U.S. annually via refined ventilation strategies for the optimum energy savings scenario, and $55 billion U.S. annually for the scenario optimizing worker productivity and health (a composite of decision-making test data, absenteeism, and sick building syndrome symptoms).[39]

Reduction of airborne viruses and bacteria is aided by high air exchange (ideally complete replacement with no recycling) and high efficiency, well-maintained filters.[40,41,42] Although 100% outdoor air supply would not be used routinely, this capacity should be a design consideration for epidemic preparedness.[42] A further option is to exhaust air from washrooms and to draw air from less- to more-contaminated environments.[42] Infectious particles may be shed in faeces and become airborne when toilets are flushed (using lids on toilets helps to reduce this), and be mobilized by air hand drying devices when hands are poorly cleaned. This results in washrooms being the most highly contaminated rooms, as detailed in a study of COVID-19 in Wuhan, China.[42] Other measures for infection control, including design and amenities, ease and practice of maintenance, and water and waste are described further below.

3.1.2. Temperature and relative humidity

Canadian buildings provide hospitable environments, despite extremes of outdoor temperatures spanning 60 Celsius degrees or more, and relative humidity covering the full scale from cold, dry winter air to near saturation during sweltering summers.

Warmer air can hold much more water vapour than cooler air, so water content is measured relative to the capacity of the air at a given temperature, known as relative humidity. Relative humidity is important both for comfort, as occupants feel warmer and sweaty at warmer temperatures and higher humidity; higher temperatures are more tolerable with lower relative humidity air. As detailed in previous CCIAQ modules,[16] dampness must be prevented, including condensation on cooler surfaces and overnight, and in air handling systems, to prevent microbial growth, deterioration of structure and contents, and impaired indoor air quality.

Heat recovery ventilators (HRVs) transfer heat between outgoing and incoming air, and energy recovery ventilators (ERVs) also capture the considerable energy from condensation of water. These recapture heat in the winter, decrease the temperature and humidity of incoming air during the summer, may be fitted or accompanied with particulate filters, may also control relative humidity, and substantially decrease net energy needed for heating, cooling and dehumidification.

Depending upon climate and indoor activities, humidification during winter may help to decrease dryness in skin, eyes and mucous membranes. Contagions tend to persist longer under cold, dry conditions; relative humidity between 40 percent and 60 percent may be optimum to minimize persistence, such as of SARS-Co-2 on surfaces.[42]

The energy required to change the temperature of air is much less than that for solids and liquids, so air temperature is very responsive to heating or cooling while structures that store heat can buffer indoor air temperature.

The apparent temperature is the result of personal warming and cooling according to numerous parameters.[43] Online tools supported by Berkeley University Center for the Built Environment (CBE) enable prediction of comfort over a broad range of humidity, air temperature, radiant temperature (determined by the temperature of walls, floor and ceiling) and air flow rate.[44,45]

3.1.3. Infrared radiation

The heat of the sun, or warmth from a fire or stove, is largely infrared radiation. One parameter of IEQ is the "globe temperature," which is an indication of how warm one feels as a result of infrared radiation.

Buildings with predominately glass envelopes may receive greater heating from solar radiation, which can result in greater requirements for air conditioning during summer. Exterior shades may reduce insolation when the sun is high, while permitting warming during winter months when the sun is lower.

Infrared heaters may be used – often in garages, workshops and industrial workplaces, but possibly in other situations – to warm individuals without warming the entire structure or maintaining a high ambient air temperature.[46] Infrared heaters are fast, effective and energy efficient insofar as the heating is targeted, although thermal comfort may suffer with excessive warming of the head and cooler lower limbs when using overhead fixtures.[47]

The converse is that cool walls, floors and particularly windows result in inhabitants feeling cooler than they would otherwise despite ostensibly adequate air temperature. This radiative temperature is incorporated in the Berkeley CBE models.[44,45]

3.2. Comfort, productivity, and adaptation

IEQ research and assessments frequently determine comfort and acceptability of the indoor environment using surveys of occupants. While satisfaction is doubtless important, and more readily assessed (typically with a brief survey) than worker performance (requiring testing of subjects and instrumentation/sensors for various measurements), optimum productivity or learning may not correlate precisely with IEQ perceptions. Notably, optimum work can correspond to the sensation of being somewhat cool.[2,48]

Temperature sensation is the result of the net heating or cooling of the skin related to: conduction related to air temperature and speed; radiative heating or cooling; evaporative cooling related to air speed and relative humidity; and clothing.[43]

A long-standing prescriptive approach to a narrowly defined optimum temperature range is being challenged by an adaptive approach. Individuals may have a considerable, perhaps unrecognized ability to adapt to hot or cold conditions.[49] Research is identifying that occupants' expectations and adaptation according to outdoor temperatures influences comfort ranges, and that individuals may be productive under a wider range of thermal conditions than previously prescribed by ASHRAE and other authorities.[50,51]

Adventurers claim, "there is no bad weather – only bad clothing," and in that spirit "acceptable" temperature ranges may be extended by permitting clothing to address temperature ranges throughout the year.[14] Energy use is reduced when indoor temperatures trend according to outdoor temperatures. In this case, comfort must be assured with seasonal clothing.[14,50] For example, measured ranges of temperature acceptability among Taiwanese patients were much broader than ASHRAE curves.[52] In a study of Chinese school children,14^{o} C was identified as an optimum winter time temperature for learning.[53] A detailed study of clothing in India examined garment choices as an under-researched means to adapt to seasonal indoor environments in buildings without air conditioning.[54] Materials (e.g., loosely woven cotton versus modern synthetics that protect against draughts) plus style for modesty and to meet religious requirements may all factor into discussions and guidelines to achieve sufficient thermal comfort for high occupant productivity.

Numerous innovations permit both individual control over heating or cooling, and energy savings via local rather than building-wide systems. Some examples include an individualized clean (filtered) air supply that permits individual temperature control for heating or cooling,[55] providing local heating or cooling within an office chair [56] or using an infra-red heater.

3.3. Lighting

Visible light, at higher frequencies and shorter wavelengths than infrared, is the most commonly recognized form of electromagnetic radiation. Sources, intensity and colours of light all contribute to IEQ.

Daylight, the complete spectrum of visible light, is preferred over narrower spectra from high-efficiency lighting.[57] Research indicates that as long as there is control of direct light and glare, that work and patient outcomes in healthcare,[58] and student achievement in schools,[59,60] are better with more daylight and views outdoors, particularly of natural ("green") landscapes and activity. Student attentiveness is further improved following outdoor education sessions.[61] Some educational facilities and workplaces may also feature small windows and minimal natural light or views to the outdoors, particularly on northerly walls.[62] Windows and "light pipes" offer advantages in terms of light quality and potential savings in bulbs and tubes, and high efficiency windows, appropriately shaded and with blinds, are efficient and featured in recent Net Zero buildings.

Lighting can consume substantial energy in buildings, which is culminating in shifts to high efficiency light-emitting diode (LED) bulbs. Incandescent bulbs are being phased out, and halogen lights and compact fluorescent lights (CFLs) and tubes are being replaced. Fluorescent lights have received attention because they can result in voltage spikes, sometimes called "dirty electricity." CFLs also contain mercury; Canada has ratified the Minamata Convention against this global pollutant.[63]

LEDs were originally sold with an external rectifier to transform the alternating current (AC) to direct current (DC), and DC systems offer economies of materials and energy.[64] Today's drop-in substitute bulbs are of wide-ranging quality, potentially with undesirably high levels of blue light or magnetic fields. Direct current power for lighting and other applications may be preferred in new builds or renovations.[64]

Visible light has important biological effects including regulation of the circadian cycle, as the natural waning particularly of blue light at the end of the day triggers healthy production of the "sleep hormone" melatonin.[65,66] Beyond normal, restful sleep, melatonin has many beneficial effects for cellular repair, detoxification and rejuvenation for the next day, and even prevention of chronic disease and cancer.[67,66,68] Night time workers are at risk, as shift work has been recognized to increase risks of obesity, chronic diseases, and cancer.[69] Artificial light when working at night was identified as potentially promoting and accelerating breast cancer in young women co-exposed to carcinogenic engine exhaust at Canadian border crossings.[70]

The majority of the population is predominantly exposed to indoor lighting. Higher-intensity lighting (measured in lumens) is common in warehouses and workshops, where brighter light assists with performance of fine tasks, and increases alertness. Bright light does not, however, necessarily translate into improved performance. In a study of simulated driving, blue-enriched bright light increased arousal, increased driver errors, and did not improve reaction time.[71]

Bright bulbs and screens may appear bluish as they emit violet and sometimes ultraviolet light. Ultraviolet (UV) light in sunshine is known for sunburn and damage to the skin and eyes, and long-term, low level exposure from indoor lighting may cause cumulative damage. Canadian optometrists consider modern "warm spectrum" LED bulbs to be a great advance for eye health.[72] Light from screens on electronic devices, also has biological effects, such as cataracts, age-related macular degeneration, eye strain, delayed and lower melatonin output, and sleep issues.[72] Yellow-tinged or blue-reflective glasses may be used, although efficacy is under debate. A French government review of health effects of blue light from LEDs and screens found that children were particularly vulnerable both to eye damage and modulation of melatonin. The government issued guidance to limit children's screen time, particularly before bedtime, and to use options that emit lower levels of blue light.[73]

Computer-related vision syndrome,[74] including blurred vision, eye strain, headaches and other physical symptoms associated with ergonomics of prolonged work on computers will undoubtedly impact productivity. This syndrome may be related to: light quality from the screen and ambient light (vicinity and task lighting of similar brightness as the screen, and natural lighting); air humidity, air velocity and particulate levels; and ergonomic factors. Reduced blinking, poor posture, lack of movement and prolonged focus close up, age-related changes in tear composition as well as contact lens use and maintenance,[75] may all contribute to symptoms. The 20/20/20 recommendation is every 20 minutes to focus at least 20 feet away for 20 seconds [76] (for a bonus, blink 20 times). Compensatory actions include adjusting screen brightness, contrast, colour and font size.

For energy savings, turning off lights, screens and equipment when not needed is naturally included in any energy efficiency program, with sophistication ranging from reminder stickers on light switches to motion detectors, timers and remote controls.

UV light and daylight shortens persistence of airborne contagions. Natural light is encouraged, and UV fixtures shielded from direct sight to protect vision may be used in air ducts or carefully deployed in clinical settings to reduce airborne viruses and bacterial loads.[42,77]

3.4. Acoustics

The World Health Organization (WHO) identified that, "Environmental noise is an important public health issue, featuring among the top environmental risks to health. It has negative impacts on human health and well-being and is a growing concern among both the general public and policy-makers in Europe."[78] Guidelines were developed based on a series of systematic reviews examining effects of noise on annoyance, cardiovascular effects, obesity and metabolic effects (such as diabetes), cognitive impairment, sleep disturbance, hearing impairment and tinnitus, adverse birth outcomes, quality of life, mental health, and wellbeing.[79]

Indoor environments have characteristic "soundscapes" arising from building operations and occupants' activities indoors, plus from traffic, aircraft, trains and activities of people outdoors.[80] "Sound pressure" refers to the total sound as experienced by the occupant (noise), while "sound power" is measured at the source. Both are expressed as decibels (dB).

Excessive noise from HVAC systems may be addressed with maintenance, repairs and updating. Noise can also be blunted with carpeting, sound-proofing in and above ceiling tiles and panels between office cubicles, or nearly eliminated in rooms for special applications (e.g., sound recording, or hearing testing), but quiet is uncommon in educational facilities and workplaces.

Regardless of the origin, be it the HVAC system [81] or external sound from trains, airplanes or traffic,[82] noise affects the ability to understand speech, as well as occupants' concentration and levels of accomplishment, with marked differences in response according to physiology, sensitivities and personality, such as among introverts versus extraverts.[83]

Sounds that may be distracting or distressing include intelligible conversation,[84] high pitched "whining" sounds, sudden sounds, and rumbling that may also be sensed as vibration, such as from a subway or construction/demolition/blasting activities.

Intelligibility of speech is a key parameter causing distraction and annoyance among adult co-workers in open-plan offices, where a limited amount of "white noise" may mask intermittent noises and bolster office work productivity (excessive noise may, however, be counter-productive as it leads to louder speech).[84,85] In classrooms, however, being able to discern speech2 is necessary to optimize learning. Thus, extraneous noise must be minimized.[81,82,86]

A review of the effects of noise on school children found that, "general effects of chronic noise exposure on children are deficits in sustained attention and visual attention; poorer auditory discrimination and speech perception; poorer memory for tasks that require high processing demands of semantic material; and poorer reading ability and school performance on national standardised tests."[86] Acceptable sound pressure in classrooms was reported to range from 30 to 45 dB. Reverberation – the tendency of sound to echo in spaces with hard surfaces, particularly with low occupancy – is also measured and reported and should be minimized in classrooms and workplaces.

Design of noise abatement requires care, as carpeting and panels that absorb sound may carry harmful chemicals such as flame retardants, stain-resistance chemicals, and materials that absorb and re-emit VOCs and semi-VOCs (e.g., pesticides) used indoors.

3.5. Design, ergonomics

"Design" is a broad concept, ranging from siting, landscaping and architecture, outdoor views and natural light, to space allocation for various activities (e.g., meetings, group activities, solitary desk work), to building systems and to details of equipment, furnishings and setup. IEQ for students and workers also includes amenities such as washrooms, kitchen facilities, group eating areas, showers and bicycle storage to enable active commuting, or exercise equipment and space. Security services, parking and availability of public transportation also affect occupants' and visitors' perception of the facility.

The Canadian Committee for Occupational Health and Safety (CCOHS) defines "work space" as "any location where a person's work is performed, including traditional office spaces and non-traditional office spaces (e.g., home offices, vehicles, and temporary locations), as well as the furniture, accessories, equipment, environmental conditions, and psychosocial workplace factors within these locations."[87]

Over the decades, workspace areas have been tending to shrink. CCOHS references the Government of Canada Workplace 2.0 Fit-up Standards for *maximum* areas in enclosed offices, workstation and meeting spaces;[87] however, other standards internationally recommend *minima* that are substantially greater.[88] For employees carrying out individual work, many factors may impact performance, including privacy, stress, noise at close proximity, and ventilation requirements to maintain air quality in more highly occupied spaces. A large longitudinal survey of IEQ found that allocated area (cubicle or office) was among the top three concerns of 15 factors queried.[89]

One solution to multiple concerns – workplace crowding (limiting physical distancing), the environmental footprint of commuting, and different needs during solitary work versus group meetings – is "hoteling" of office space, whereby workers tele-commute (work from home or off-site via the Internet) part of the time, and use a shared work station during days in the office, outside of meeting times. Telework is addressed further in section 4.3.

Aspects of design that contribute to efficiencies and reduce risks of work-related harms, including lighting and other topics addressed previously, are often grouped as "ergonomics."[90] CCOHS, however, defines "ergonomics" more narrowly as the science of matching the job to the worker, and the products and tools (e.g., chair and computer setup) to the user, for the purposes of injury prevention.[91]

With work increasingly centred on computer and web-based activities, the Workers' Compensation Board of Alberta [92] and the Occupational Health Clinics for Ontario Workers [93] offer detailed resources addressing setup and use of computer workstations to minimize long-term stress (repetitive strain) injuries. These include: physical layout; desk and chair to encourage good posture and eye alignment; lighting to minimize glare, blue light, and eye strain; and even desks that adjust for use sitting or standing to prevent and address back and other musculoskeletal problems.[94] For example, productivity was improved in a call centre with implementation of stand-capable desks that reduce sitting time.[95] Cognitive and performance improvements were seen across two job categories, with productivity 23 percent higher after one month, and 53 percent higher after six months, compared with sedentary co-workers.[95] Physical activity and fitness, from programs during or outside of the work day, are well known to reduce illness-related absenteeism from work.[96]

With sufficient space, design details may reduce frequently touched surfaces, such as elimination of washroom doors as seen in airports.

3.6. Resilience, setting and aesthetics

Extreme weather may result in more than extreme and fluctuating temperatures that represent challenges to operation of buildings. Design conditions are changing in densely populated areas due to global warming. Flooding can impact structural integrity of surroundings and buildings. Resilience of the building design and features of the site, both to withstand and to moderate adverse events, are practical necessities as well as a source of reassurance for occupants. This is important to consider during buildings' initial design and in any future renovations.

Exterior elements and the setting of the building have impacts on IEQ, environmental impacts and occupants' perceptions. These include: [97,98]

- built features that blunt urban "heat islands" and incorporate natural systems such as:
    - light-reflective exterior surfaces (e.g., roofs and solid surfaces);
    - natural elements such as green roofs or living walls (indoors or outdoors) that cool by evapotranspiration through leaves;
    - naturalization of surroundings with deciduous trees to the south and coniferous trees to the north to protect from northerly winds and to moderate insolation during summer months (n.b., loss of solar gain from limited shading during winter months is less significant than warm-season cooling and other benefits);
    - vegetation and water/wetland features to moderate temperatures, as well as to support wildlife such as pollinators, predators of pests such as dragonflies, birds, amphibians and other species;
- design to minimize bird strikes, including window glass that is visible to birds;[99] and
- awareness of glare to or from nearby buildings, at particular angles of the sun.[100]

Another challenge to resilience is fire, which threatens landscapes, infrastructure, buildings and air quality (potentially addressed with indoor air filtration). Although a landscape of concrete and stone will not burn, it will also not absorb CO_2 nor provide natural cooling, water retention or support ecosystems, as vegetation does. Numerous measures may address fire potential such as sprinkler systems, water features, choices of plants that are slower burning (e.g., poplar, birch or hardwood rather than conifer trees) and a metal roof.

3.7. Water

Clean drinking water is a basic human need, and unfortunately is a long-standing issue in some Canadian communities. Meanwhile, droughts and floods have elevated water to a central concern with climate change. Drinking water supply quantity and quality, conservation and re-use, water features onsite, and resiliency against floods, are all important elements of buildings' environmental quality.

Water supplies are generally high-quality in Canadian cities, although some establishments may choose to filter drinking water for chlorination by-products, residual contaminants and lead. Drinking water supplies are governed more strictly than bottled water, so water bottle/cup refilling stations are preferred over supplying bottled water and disposing of the plastic with its significant environmental footprint.

In Canadian cities and rural areas, lead supply pipes and lead-containing pipes, solder and fixtures occasionally remain in place and can result in elevated lead body burden.[101] Lead is a toxic metal that bio-accumulates in bone and organs; low levels of exposure impair early development, learning and executive function; the resulting lower impulse control predisposes young adults to violence; and in older adults lead causes chronic cardiovascular, neurological and metabolic diseases.[102,103,104] Lead infrastructure may not be catalogued by local governments or building owners and operators, so supply pipes must be scoped by owners, tenants and renovators of older properties, and drinking water tested according to Canadian standards.[102] Of note: lead is also in older paint [105] and must be abated using protective protocols.[106]

Other desirable features include water re-use such as greywater recycling for toilets or watering outdoors, rainwater collection, permeable parking surfaces and landscaping to maximize infiltration and to slow migration of water across the landscape during precipitation, and storm water retention areas and water features that also provide habitat, for biodiversity.

Bacteria and viruses may be shed into urine and feces, contaminate aerosols from flushing of toilets, and result in higher loads of contagions in washrooms.[42] Use of a toilet lid helps, while lower turbulence fixtures merit investigation. Forced-air hand dryers also mobilize fine aerosols with contagions when hands are not well washed; paper towels do not pose this risk.

3.8. Maintenance/cleanliness

Health, well-being and productivity are supported in a clean, organized, and uncluttered environment.

When HVAC equipment and building interiors are easily maintained, ease of routine maintenance supports IEQ and air quality. Numerous modules in the CCIAQ collection address relevant topics.[16]

Minimizing waste via re-use (e.g., water bottle refilling stations, and reusable dishes and a dishwasher in kitchen facilities), composting of organic materials and recycling also feature among priorities for IEQ.

Frequent cleaning, particularly of frequently touched surfaces and bathrooms, helps to intercept contagion transmission.[40] Soap and water is effective against SARS-Co-2 (the virus causing COVID-19), while peroxide-based cleaners are odourless and may be better tolerated than chlorine-based bleach or ammonium-based cleaners.

3.9. Interactions among IEQ factors

Sensations and demands upon students and workers are integrated by the individual, so it is not surprising that effects of IEQ factors interact, such that discomfort as a result of one factor may be expressed by individuals as dissatisfaction with another. The following are some examples.

The volume and type of sound (music, water, babble or a fan) interact with the level of illumination, with females being more sensitive or perceptive.[107] In further examination of IEQ (thermal comfort, as well as illumination and sound), the acoustic environment had the greatest effects on overall comfort under thermal-neutral conditions (25 °C, 45% relative humidity).[108]

Another office-based study of IEQ perception in terms of air temperature, globe temperature (radiative heat), relative humidity, carbon dioxide concentration, illumination and background noise level, found interactions between temperature and perceived acceptability of other parameters. Office work productivity was best at neutral and slightly cool temperatures.[48]

A large survey-based study of satisfaction that included interactions of 15 parameters of IEQ reported that the most important factors were the amount of space (cubicle or office size – not gross space), noise level, and visual privacy.[89] Participants in this observational study of established workplaces were exposed to a narrower range of temperatures, so the thermal interaction was not as predominant.

Successfully implemented "green" offices, schools and housing [109] can result in lower indoor air contaminants, and superior health, learning and productivity. The perception that the building is "green" may, however, skew subjective survey responses. Individuals who self-identify as being concerned about the environment are more likely to find higher temperatures "acceptable" when a building has a "green" designation,[110] although more detailed research finds that symptoms related to temperature are driven by established physiological as well as psychological factors.[111] Nevertheless, public health must be a prominent consideration when establishing thermal comfort and indoor air quality.

4. Evolving Issues

4.1. Net zero buildings

Imperatives to curb climate crises, along with the significant GHG footprint of buildings, have resulted in considerable focus on improvements in energy efficiencies. The ultimate goal for Net Zero buildings is to offset their (low) energy use with emission-free electricity, while achieving excellent IEQ. This entails improvements in insulation and air tightness, efficiencies in all systems (e.g., illumination, heating, cooling, ventilation, equipment, and information and control technologies), use of efficient technologies (e.g., heat pumps) and solar electricity on-site or generated elsewhere. Net Zero buildings culminate from attention to many details, catalogued for example in Advanced Energy Design Guides for offices,[12] and for schools.[13] These guides include advice for design and services (e.g., hot water, heating, air exchange), advanced "as needed" operations (e.g., switches to turn off unused equipment, dimming or turning off lights when not needed), and systems to ensure proper operation (e.g., alarms for unlatched doors). Emphasis may be placed on thermal mass to slow changes in temperature, and to ensure that no "thermal bridges" exist that can transfer heat more readily across the building envelope. The clear tension between energy efficiency and ventilation must be addressed to the extent possible by improving energy recovery rather than compromising air quality by restricting ventilation.

Strategies for Net Zero buildings vary according to climate and site, responding to the greatest needs for energy (e.g., heating in cooler climates versus cooling in more temperate areas). At COP25, the Government of Canada committed to legislating the Net Zero goal by 2050, with 5-year goals and reporting of progress.[112]

4.2. Electronic interconnectivity

Information technology (IT) increasingly underpins large building control systems and is central to office workplaces and common in education.

Interconnected sensors and controls are aimed at improving energy use and indoor air quality, and efficiency and effectiveness of complex building control systems.[113] Sophisticated machine learning has been applied to refine HVAC control algorithms, by anticipating demands and measures of occupancy based upon motion, voice and CO_2, indoor and outdoor temperatures and humidity, and individuals' preferences.[114] Energy savings of 7 to 52 percent were achieved by applying adaptive cooling in offices and meeting rooms, chiefly with lower occupancy.[114] The fashion of extensive IT surveillance and control may be tempered over time, as local controls offer security, controls and resources at lower costs than operating via "the cloud," and promised savings with high tech and machine learning to improve building efficiencies may be over-stated for expensive networks of sensors and controls.[115]

IT equipment choices present opportunities to optimize IEQ and improve energy efficiency, resilience and security by minimizing wireless and maximizing use of wired options. [116,117] Signals between numerous small radio transmitters and receivers require more energy to broadcast signals than is needed to send information through a wire or fibre.[116] Wireless solutions may be implemented quickly out-of-the-box, but other environmental drawbacks include that devices require non-renewable resources, many have relatively short lives, and rather than electricity from mains they rely upon batteries that may be difficult to recycle.

The best broadband includes fibre or wire to and throughout buildings for Internet access and IT connections (e.g., to smartboards, fax machines, scanners, printers, projectors, mouses, keyboards, speakers/headphones or microphones) for students, employees and visitors; and a modicum of wired "smart" control of building systems to optimize IEQ, energy efficiency and performance. Indoor "microcells" – radios for internet access via small hotspots when needed – offer advantages in terms of energy and lower exposures to radiofrequency radiation. The "Internet of Things" for "smart" devices, buildings and cities is often promoted in a wireless format, but most devices in the workplace and educational institutions can and should be connected physically with wire and fibre. After all, building systems are not mobile.

Advances in wireless communications have increased ambient levels of modulated radiofrequency radiation, for wireless mobile communications and Internet access (Wi-Fi). Further increases in present day and additional frequencies are being rolled out for fifth generation or 5G systems, [118] while 6G is being envisioned.

The evidence demonstrating harms of radiation from wireless devices is sufficient to routinely take precautions to minimize emissions and thereby exposure. Canadian exposure limits for radiofrequency and lower frequency non-ionizing radiation (Safety Code 6 [119]) aim to avoid overt heating of tissue, and electrical shock respectively. Assessment does not yet incorporate scientific research indicating effects on biochemistry, membrane permeability and DNA, or human reproduction, early development, chronic conditions and cancer, that occur at commonly encountered radiofrequency exposure levels.[117,120,121]

Cell phones are increasingly common even among pre-teens, and phones are highly distracting in the classroom. This led the Ontario government to restrict their use to teacher-initiated learning applications, as assistive devices for those with handicaps, and for emergency communication. When used or carried against the body cellphones may exceed exposure guidelines under Canada's Safety Code 6 [122] or France's *Agence Nationale des Fréquences*.[123] Electronic devices being used for non-classroom activities such as gaming or checking social media distract and result in poorer learning and exam performance by both the user and neighbours.[124] A London School of Economics analysis of results of standardized testing in U.K. schools showed that banning cellphones in classrooms resulted in improved test scores.[125] Improvements were greatest among students who had previously been performing poorly, resulting in improved equity.[125]

Apart from the technology, subtle effects of wireless radiation may be difficult to discern but have large impacts on public health and successes across society. Low-level ongoing exposure may impair brain development, memory and behaviour, [117,120,121] including increasing reaction speed, and decreasing accuracy (characteristics of impulsivity) and memory in school children.

Wireless radiation affects membranes in cells, potentially making chemicals, such as neurotoxic lead, additionally harmful. Effects seen in dozens of animal studies [126] have been replicated, for example, in a study of 2,244 elementary school children. Students with higher than average blood lead levels (typical of Canadian children) who also made three or more cellphone calls per day, exhibited significantly greater symptoms of attention deficit hyperactivity disorder (ADHD).[127]

Indoors, radiofrequency radiation reflects off structures, metallic coated windows and furnishings (particularly metal such as appliances and file cabinets).[117] When cellular technology (including fifth generation or 5G) is deployed with wireless infrastructure rather than fibre, anomalous high exposures from permanent installations within and in the vicinity of buildings (e.g., transceivers for cellular services, and Wi-Fi) may be detected with an electromagnetic survey using specialized meters. Health may deteriorate with long-term exposure (e.g., if a desk is unfortunately placed in an invisible "hotspot"), but these exposures are preventable by choosing wired connections over wireless.

Lower-frequency magnetic fields may result from wiring deficiencies, some motors or some (not all) high-efficiency light bulbs. Once identified by experts, correction of wiring and substitution of alternative lighting are straightforward solutions.

Overall, testing is essential to detect and resolve electromagnetic fields that are generally not felt, tasted, seen or heard. There are numerous lower-energy, safer, more secure and sustainable IT solutions. [116,117]

4.3. Paradigm shifts in the workplace and classroom

The COVID-19 pandemic resulted in rapid conversion and adaptation to telework, e-learning or telecommuting. This hinges upon availability of high-bandwidth Internet, and can result in time efficiencies and convenience. While potentially saving energy and resources, telework, web conferencing and e-learning also facilitate interactions with individuals and experts outside a particular institution or locale. Teleworking, at least part-time, may increase efficiencies (particularly with online cloud-based collaborative tools and suites of programs).[128] It also allows learning and work to continue during periods of disruption of travel routes or responses to pandemics. Remote work also offers opportunities to optimize Internet connectivity (see section 4.2).

Employees and students working and studying in their own space, often at home, may save employers and school boards the costs to provide, ventilate, heat, cool and maintain office and classroom facilities. Working and learning from home or off-location may reduce transportation and related CO_2 emissions if entire days are spent away from the office or classroom. Working and learning from home will result in increased residential heating/cooling costs since programmable thermostats are unlikely to be operating with the same temperature setbacks during periods of working/learning from home.

Not all outcomes of telecommuting are desirable. Differences in productivity with telework or e-learning may not be apparent in terms of work or test scores; however, decreased personal interactions may have negative impacts on satisfaction and intangible factors related to interpersonal interactions.[129,130] Ontario's high school e-learning course requirement was scaled back from four to two courses in November 2019 following public outcry; nevertheless, remote e-learning will continue to feature in advanced education and was rapidly developed and adopted in response to shut-downs due to COVID-19.

If attendance in-person is reduced, then time in school or the workplace may focus more on activities such as hands-on learning and work, and in-person collaboration. These may require more use of communal spaces rather than individual desks in rows, or office cubicles. Thus, while the modes of work change, the design of learning and workspaces will also evolve according to activities and to needs for personal distancing.

It is important to set boundaries for telework, since working from home may devolve into "always being at work." CCOHS summarizes numerous considerations, including recommendations for routines, avoidance of distractions, communications and that all workplaces should be equally safe – furnished and set up adequately for extended periods of work.[131]

5. Discussion and Conclusions

Repercussions of increasing greenhouse gases on ecosystems, agriculture, oceans and fisheries, fires and weather, are driving the need for rapid, wise changes in Canadians' lives, and in environmental best-practices and resilient construction in response to climate change. Considerable work, ingenuity and attention to detail are required to reduce and replace with efficiencies and renewable energy, the roughly one-third of Canada's energy use presently consumed to ventilate, heating, cool, light and operate buildings. The public health emergency resulting from COVID-19 also brings focus on importance of design, material selection for efficient cleaning, amenities (particularly in bathrooms) and maintenance to minimize contagions that are airborne and on surfaces.[42]

This brings focus to the challenge for buildings to efficiently provide healthy, safe environments that promote the well-being and productivity of occupants, particularly at work and at school. It is crucial not to repeat the mistakes of the 1980s when energy restrictions were met with tightening building envelopes and reducing ventilation rates, resulting in sickness and disability. Overwhelming evidence from controlled research, to surveys of hundreds of buildings, indicates that learning and work productivity improve with ventilation rates exceeding ASHRAE recommendations, as CO_2, bioeffluents and building-related air contaminants all diminish health, learning and productivity. Indeed, internationally, current operations of some educational facilities and offices, with increasing occupancy rates, exceed CO_2, bioeffluent and other contaminant levels, with negative impacts on learning and performance.[3,4] Weighing employee productivity, student learning and achievement, physical and mental health, absenteeism and wages, against costs for building operations, reveals the false economy of sub-optimal indoor air quality, and more broadly IEQ.[2,11] Typically businesses spend roughly 1% of their expense budgets on energy, 9% on rental costs, and 90% on salaries.[132] Although it is important to reduce heating and cooling costs, they are generally a very small percentage of overall operating costs, and hence maintaining building ventilation is important to maintain indoor air quality.

The World Green Building Council, a coalition with representatives from 94 countries is listed among exemplary organizations, in part 7, Resources. It has published a business case for Green Buildings, and collections of case studies of both new construction and renovations that result in "wins" all around, with lower or Net Zero emissions, and improved employee health, satisfaction and productivity.[133,134] Some projects were even led by tenants.

Net Zero, the evolving building guidelines to meet climate challenges, place high priority on IEQ and resilience for schools [13] and offices.[12] While Net Zero and Passive House initiatives and standards that include the siting and planning of new construction are strengthened and proven in practice (see part 7 Resources), a large challenge is the current building stock. Recent decades have seen major advancements in energy exchange between intake and exhaust air, and modern sensors and control algorithms can control building HVAC, lighting and other systems to optimize efficiencies. Simple, inexpensive measures are possible, such as local climate control, or insulating blinds to improve insulation and/or control solar gain.

Norms and requirements for IEQ are also evolving. Indoor climate control is progressing from maintaining a constant indoor temperature year-round, to trending with annual and daily temperature. Adaptive behaviours and clothing choices can contribute to maintaining productivity and good air quality with less heating and cooling.

Telecommuting for work or education offers time and energy efficiencies, as well as opportunities for collaborations and learning beyond the locale. Important considerations include maintaining a quality workspace and routine, and setting limits in the face of constant connectivity. Use of wires and fibre for IT connectivity (for both building systems and Internet) saves energy both on- and off-site, is more secure and resilient, and results in lower exposures to potentially harmful non-ionizing radiation.

Environmental quality is a broad, many-faceted topic, and this module is intended to whet the appetite rather than provide comprehensive advice. Many leading organizations are listed in the Section 7, and the hope is that with solid science and pragmatic approaches Canadians can work and learn in high-quality indoor environments, while respecting the limits of the Earth.

The collection of CCIAQ guidance documents address relevant topics.[16] *CCIAQ's Module 4 – Recognizing and Addressing IAQ Problems* that assists with identification of deficiencies in fresh air supply as well as quality, and *CCIAQ's Module 9 – Indoor Air Quality and Energy Efficiency* offers recommendations to maintain indoor air quality in buildings while implementing various methods and systems to reduce energy consumption. Section 7 catalogues standards and initiatives advancing energy-efficient, healthy buildings.

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7. Resources: Environmental Quality of Buildings - Organizations and Research Groups, and Domains of Guidelines

Organization	Domains
American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) https://www.ashrae.org/technical-resources/standards-and-guidelines	Detailed guidelines and predictive methods for heating, cooling, ventilation, thermal comfort, and energy efficiency targets in new and existing buildings of various types in a variety of climates.
Baubiologie MAES https://buildingbiology.com/site/wp-content/uploads/randbedingungen-2015-englisch.pdf and https://buildingbiology.com/site/wp-content/uploads/richtwerte-2015-englisch.pdf	**Fields, Waves, Electromagnetic Radiation** Toxins, pollutants, Indoor climate Fungi, Bacteria, Allergens
BOMA BEST Building Owners and Managers Association Canada bomacanada.ca/bomabest/aboutbomabest/ See extensive series of links	Energy, Water, Air, Comfort, Health and Wellness, Purchasing, Custodial, Waste, Site, Stakeholder Engagement
BREEAM International planning and certification for communities, infrastructure, new construction, commercial buildings, and refurbishment www.breeam.com/discover/technical-standards/ https://www.bregroup.com/news/connected-cities-start-with-connected-homes/	Similar topics, notably including ***connected cities and buildings, using hard (not wireless) connections to avoid difficulties with energy efficiency materials interfering with signals***

Organization	Domains
Building Biology Institute (International) buildingbiologyinstitute.org Numerous links, notably https://buildingbiologyinstitute.org/wp-content/uploads/2019/05/Indoor-Climate-Fact-Sheet.pdf https://buildingbiologyinstitute.org/course/electromagnetic-radiation/	Indoor Environmental Quality: IAQ, Managing moisture; Vetting / choosing materials; Water quality and treatment; Finishes Indoor climate (includes electromagnetic qualities); Ventilation Electromagnetic Radiation: Lighting; Microsurge ("dirty electricity); Photovoltaic electrical systems; Communications tech; Research and solutions; Minimizing radioactivity
Built Green Canada www.builtgreencanada.ca [advertising vehicle for products] www.builtgreencanada.ca/i-envelope-and-energy-systems www.builtgreencanada.ca/ii-materials-and-methods numerous others	Energy Water (heat recovery) Durable materials Materials include recycled content Damp proofing Waste – On site composting or collection of compost materials for off-site composting where offered Permeable paving
Canada Green Building Council www.cagbc.org www.cagbc.org/makingthecase	Making the case for **building to zero carbon –** large report Advances LEED and zero carbon building standard LEED - Site (e.g., brownfield), stormwater, irrigation, water use, **heat island reduction**, light pollution, transportation alternatives and cycling support, energy, materials and waste, **lighting including daylight**, materials emissions and IAQ
Canadian Centre for Occupational Safety and Health https://www.ccohs.ca/oshanswers/chemicals/iaq_intro.html	IAQ Noise Thermal comfort Ergonomics Lighting
Energuide (any home) Energy Star (new construction) www.nrcan.gc.ca/energy-efficiency/energuide-canada/energuide-energy-efficiency-home-evaluations/20552 www.nrcan.gc.ca/energy-efficiency/energy-star-canada/18953	Energy efficiency for renovations Energy efficiency for new homes, buildings, workplace, products

Organization	Domains
Envirohome Account and resources are available only to members of the Canadian Home Builders' Association.	R2000 + Canadian Mortgage and Housing Corporation's (CMHC) Healthy Housing initiative, such as: occupant health, energy efficiency, resource efficiency, environmental responsibility, and affordability.
EQuilibrium CMHC demonstration initiative publications.gc.ca/site/eng/9.857925/publication.html http://publications.gc.ca/collections/collection_2018/schl-cmhc/nh18-1-2/NH18-1-2-196-2013-eng.pdf publications.gc.ca/collections/collection_2018/schl-cmhc/nh18-1-2/NH18-1-2-196-2013-eng.pdf	Water and energy saving + photovoltaic generation demonstration projects
Green Globes http://www.greenglobes.com	BOMA BEST + ECD Energy and Environment Canada Ltd
Green Building Canada - resources greenbuildingcanada.ca	Resources, coordinating and educational organization
Leadership in Energy and Environmental Design (LEED)	see CaGBC
International Living Future Institute Living-future.org Living Building Challenge "A Visionary Path to a Regenerative Future" (notes slow progress to date, and need to accelerate) https://living-future.org/wp-content/uploads/2019/08/LBC-4_0_v13.pdf	Energy Water Light Healthy interior and exterior (largely air quality) Materials and sourcing Biophylic design Education and inspiration
Novoclimat	Quebec, energy efficiency in buildings, transportation Goal is to reduce energy use at least 1% per year
Passive House Alliance (US) www.phius.org www.phius.org/phius-2015-new-passive-building-standard-summary www.phius.org/phius-certification-for-buildings-products/project-certification/documents-for-download	**Aiming for net zero houses / buildings** High standard
R2000 https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/files/pdf/2012%20R2000%20Standard%20EN.pdf	Energy efficiency, air tightness, environmental responsibility in new construction

Organization	Domains
City of London, UK Design Guidance (largely exterior) www.cityoflondon.gov.uk https://www.cityoflondon.gov.uk/services/environment-and-planning/planning/design/Pages/design-guidance.aspx	Wind microclimate Solar glare Solar convergence Sunlight Major utility connections, including telecommunications
 ALSO *Conference Paper:* *Testing the correlation between indoor environmental quality and productive time* *https://open.library.ubc.ca/cIRcle/collections/52660/items/1.0076354*	Thermal, Air quality, Ventilation Light, visual comfort Noise Sound privacy Visual privacy Amount of space / crowding Ease of interactions among occupants & IT Comfort, adjustability of furnishings Building and workspace cleanliness and maintenance