Impacts on Health, Well-Being, and Cognitive Function

Ontario Society of Professional Engineers Special Topics in Indoor Air Quality Report: Impacts on Health, Well-Being, and Cognitive Function

Published:
July 2025

www.ospe.on.ca

ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Acknowledgements

This report was developed through the collaborative efforts of dedicated members of Ontario's engineering community. OSPE gratefully acknowledges the contributions of the following individuals:

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Background

The spread of COVID-19 in poorly ventilated indoor spaces, coupled with the increasing frequency of wildfire-related smoke pollution, has heightened concerns around **Indoor Air Quality (IAQ)** and **Indoor Environmental Quality (IEQ)**. Air pollution impacts human health and well-being in a variety of ways. To date, much research, monitoring, and enforcement efforts have been devoted to outdoor air pollution and the associated health effects on the population. Accordingly, many jurisdictions have set national ambient (outdoor) air pollution standards based on health and welfare considerations[1,2] and a multitude of research and monitoring efforts have estimated population health impacts. For example, the **Government of Canada** estimates that specific outdoor air pollutants (e.g., fine particulate matter, PM2.5; ground-level ozone, O3; and nitrogen dioxide, NO2) are related to 15,300 premature mortalities, 2.7 million asthma symptom days, and 35 million acute respiratory symptom days each year across Canada.[3]

While considerable attention is devoted to the health impacts of outdoor air pollution, historically, there has been an unfortunate lack of emphasis on indoor air pollution and its associated health considerations. Indoor air pollution may be variable, but in general, it is pervasive across various types of buildings. Often, the concentration of a specific pollutant is elevated indoors relative to outdoors.[4,5] Regardless of the indoor-outdoor concentration comparison, when considering the amount of time individuals spend indoors, it is estimated to be over 90% for the average North American.[6] When considering these factors, it becomes apparent that time spent in buildings has a significant impact on health and well-being. Indoor air dominates human exposure to air pollution, and over half of the body's intake over an average lifetime is attributable to the home environment alone.[7] Accordingly, the need to promote indoor air quality for human health and well-being is essential.

In addition to a robust body of evidence on the impact of ambient air pollution on human health, there is a growing body of research that has established various effects of indoor air quality on human physiology, cognition, and overall well-being.[8,9,10] These health impacts range in terms of temporality, from acute to chronic, and in terms of intensity, from minor to severe, based on the specific pollutant, the exposure concentration and time, and individual differences. These indoor air pollutant

[1] EPA, "FY 2022-2026 EPA Strategic Plan," 2022.
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[4] L. Wallace, "Indoor Particles: A Review," *J Air Waste Manage Assoc*, vol. 46, no. 2, pp. 98–126, Feb. 1996, doi: 10.1080/10473289.1996.10467451.
[5] L. A. Wallace, E. D. Pellizzari, T. D.Hartwell, C. M. Sparacino, L. S. Sheldon, and H. Zelon, "Personal exposures, indoor-outdoor relationships, and breath levels of toxic air pollutants measured for 355 persons in New Jersey," *Atmospheric Environment (1967)*, vol. 19, no. 10, pp. 1651–1661, Jan. 1985, doi: 10.1016/0004-6981(85)90217-3.
[6] N. E. Klepeis et al., "The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants," *Journal of Exposure Science & Environmental Epidemiology 2001 11:3*, vol. 11, no. 3, pp. 231–252, Jul. 2001, doi: 10.1038/sj.jea.7500165.
[7] J. Sundell, "On the history of indoor air quality and health," *Indoor Air*, vol. 14 Suppl 7, no. SUPPL. 7, pp. 51–58, 2004, doi: 10.1111/J.1600-0668.2004.00273.X.
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[10] J. M. Cox-Ganser et al., "Respiratory morbidity in office workers in a water-damaged building," *Environ Health Perspect*, vol. 113, no. 4, pp. 485–490, Apr. 2005, doi: 10.1289/EHP.7559.

exposures result from various built environmental factors, including building design characteristics, such as envelope tightness; operational factors, such as ventilation system type, run-time, schedule, and filtration; indoor sources, such as the use of consumer products, occupancy, and occupant activities.[11,12,13] In the following sections, the most common of the various health impacts from indoor air pollutant exposures are presented.

Impact of IAQ on Human Health

There are extensive associations between exposure to indoor air pollutants and impacts on human physiology. The following examples are intended to be illustrative, rather than exhaustive, of some common occurrences found in typical Canadian and other North American indoor environments and the need to consider human health in building design and operation. The examples are presented according to the associated method(s) of indoor air quality improvement and listed in descending order of recommended prioritization and general effectiveness: (i) source control, (ii) ventilation, and (iii) filtration and air cleaning.

1. Source Control

The first line of defence in ensuring good indoor air quality is controlling the source of any potential pollutants in an indoor space. An integral building envelope and attention to construction materials and consumer products are ideal measures to promote indoor air quality. Unfortunately, in practice, deficiencies in building envelopes and emissions from construction and consumer products typically degrade indoor air.

Previous research has revealed that envelope airtightness has a direct impact on indoor air quality. The airtightness of single-family houses and apartments has been measured using the fan pressurization method, and the mean air leakage rate of the building envelope has been found to range from 3 to 7 **Air Changes per Hour (ACH)**.[14] Leakier envelopes result from unintended openings, which create pathways for the ingress of moisture and various contaminants from the outdoors.[15] Studies have investigated the presence of symptoms, with skin, eye, throat, nose, and general res-piratory irritation being commonly reported issues, particularly in office environments where oc-cupants have less control over indoor settings.[16,17] While there are a range of factors that could and likely influence this occurrence, both low and high levels of indoor moisture, attributable to de-fects in exterior

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[11] S. Dedesko and J. A. Siegel, "Moisture parameters and fungal communities associated with gypsum drywall in buildings," *Microbiome*, vol. 3, p. 71, Dec. 2015, doi: 10.1186/S40168-015-0137-Y.
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[15] N. B. Hutcheon and G. O. Handegord, *Building Science for a Cold Climate*. Ottawa: National Research Council of Canada, 1995.
[16] J. M. Cox-Ganser et al., "Respiratory morbidity in office workers in a water-damaged building," *Environ Health Perspect*, vol. 113, no. 4, pp. 485–490, Apr. 2005, doi: 10.1289/EHP.7559.
[17] P. Wolkoff, "Indoor air humidity, air quality, and health – An overview," *Int J Hyg Environ Health*, vol. 221, no. 3, pp. 376–390, Apr. 2018, doi: 10.1016/J.IJHEH.2018.01.015.

envelopes and insufficient indoor humidity control, are commonly cited sources of the problem.[18,19]

Elevated levels of various volatile organic compounds, attributable to building materials (e.g., paints, coatings, finishes) and consumer products (e.g., stationery, cleaning products, textiles),[20] can also result in the aforementioned irritation and symptoms[21,22] in addition to more severe health effects, such as neurotoxicity, reproductive and developmental effects, and internal lesions (e.g., nasal, respiratory epithelial), depending on the specific volatile organic compound and expo-sure characteristics.[23]

While volatile organic compounds are pervasive in indoor settings, they are just one example of emitted pollutants from consumer products. There are a range of other pollutants, commonly categorized as compounds of concern (e.g., phthalates, flame retardants, dioxins) based on their physiochemical properties, that have also been found to be pervasive in consumer products and more persistent in indoor settings, contributing to numerous negative health impacts, such as asthma symptom exacerbation as well as endocrine and reproductive system effects.[24,25,26,27]

2. Ventilation

Even with a high-quality building envelope, clean ambient outdoor air, and attention to material and product selection, common daily activities such as cooking[28] and cleaning[29] introduce a range of particle and gaseous pollutants into indoor spaces that result in a range of outcomes, from the aforementioned symptom-based irritation, to exacerbated asthma symptoms and decreased lung

[18] P. Wolkoff, "Indoor air humidity, air quality, and health – An overview," *Int J Hyg Environ Health*, vol. 221, no. 3, pp. 376–390, Apr. 2018, doi: 10.1016/J.IJHEH.2018.01.015.
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[28] R. E. Militello-Hourigan and S. L. Miller, "The impacts of cooking and an assessment of indoor air quality in Colorado passive and tightly constructed homes," *Build Environ*, vol. 144, pp. 573–582, Oct. 2018, doi: 10.1016/J.BUILDENV.2018.08.044.
[29] C. Arata et al., "Volatile organic compound emissions during HOMEChem," *Indoor Air*, vol. 31, no. 6, pp. 2099–2117, Nov. 2021, doi: 10.1111/INA.12906.

function.[30] For most, these routine activities and the common use of products such as household cleaners may seem inconsequential, but can result in many unintended consequences.

Many studies have found that cooking produces elevated levels of gaseous pollutants such as nitrogen dioxide and particulate matter. These pollutants are attributable to the type of cooking element, the food being cooked, and the range hood ventilation in place. Interestingly, concentrations of cooking-related pollutants often exceed ambient air pollution thresholds set for health and welfare considerations. A simulation-based study estimated nitrogen dioxide levels resulting from cooking with a natural gas stove to exceed the recommended 1-hour ambient exposure thresholds set in both Canada and the United States.[31] For electric-based stoves, laboratory and field studies have revealed elevated levels of fine particulate matter (PM2.5) produced from cooking often exceeding acute ambient exposure thresholds.[32,33] Nitrogen dioxide is known to cause respiratory illness,[34] and numerous studies have elucidated the prominent and pervasive health impacts associated with fine particulate matter. Logue et al. (2012) estimated the ill health impacts from indoor air pollutants in the United States and found fine particulate matter, such as the particulate matter produced by cooking, to result in the greatest ill health burden.

Proper ventilation is a highly useful strategy for promoting indoor air quality, particularly for regular and necessary indoor activities such as cooking. Ventilation focuses on lowering the concentrations of various indoor air pollutants by bringing outdoor air (that is ideally cleaner) into the space. Past investigations and reviews on this topic have found evidence of reduced “sick building syndrome”, respiratory infections, asthma symptoms, and sick leave[35,36] with improved cognitive function, performance, and overall comfort, satisfaction, and well-being.[37,38,39]

3. Filtration and Air Cleaning

Along with source control and ventilation, further improvements can be made with filtration and air cleaning. High-performance media-based particle filters, such as **High-Efficiency Particulate Air (HEPA)** filters, are effective in reducing indoor particulate matter concentrations. This can be particularly

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[30] J. Ware, K. Snoww, B. Gandek, and M. Kosinki, “(PDF) SF36 Health Survey: Manual and Interpretation Guide.” Accessed: Mar. 13, 2024. [Online]. Available: https://www.researchgate.net/publication/247503121_SF36_Health_Survey_Manual_and_Interpretation_Guide
[31] J. M. Logue, N. E. Klepeis, A. B. Lobscheid, and B. C. Singer, “Pollutant exposures from natural gas cooking burners: A simulation-based assessment for Southern California,” *Environ Health Perspect*, vol. 122, no. 1, pp. 43–50, Jan. 2014, doi: 10.1289/EHP.1306673/SUPPL_FILE/EHP.1306673.S001.508.PDF
[32] R. E. Militello-Hourigan and S. L. Miller, “The impacts of cooking and an assessment of indoor air quality in Colorado passive and tightly constructed homes,” *Build Environ*, vol. 144, pp. 573–582, Oct. 2018, doi: 10.1016/J.BUILDENV.2018.08.044.
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[36] J. Sundell et al., “Ventilation rates and health: multidisciplinary review of the scientific literature,” *Indoor Air*, vol. 21, no. 3, pp. 191–204, Jun. 2011, doi: 10.1111/J.1600-0668.2010.00703.X.
[37] W. J. Fisk, “The ventilation problem in schools: literature review,” *Indoor Air*, vol. 27, no. 6, pp. 1039–1051, Nov. 2017, doi: 10.1111/INA.12403.
[38] O. A. Seppänen and W. J. Fisk, “Summary of human responses to ventilation,” *Indoor Air*, vol. 14, no. SUPPL. 7, pp. 102–118, 2004, doi: 10.1111/J.1600-0668.2004.00279.X.
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helpful in reducing allergy and asthma symptoms among individuals with such underlying conditions and sensitivities, as well as populations residing in urban environments with high levels of ambient particle pollution.[40] While effective under general circumstances, these technologies also offer an added layer of protection during extreme weather events, such as wildfires, and for infection control, such as during the COVID-19 pandemic.[41] Concerning wildfires, some studies have demonstrated that high-performance particle filters can reduce indoor concentrations of fine particulate matter, with measured reductions ranging from 61-85%, over short periods (e.g., 12 hours) in houses with wood-burning stoves.[42] However, more recent evidence suggests that the long-term performance of many filters that use an electrostatic charge may degrade considerably during extended smoke events, due to the smoke particles negating the electrostatic charge, a component of their filtration effectiveness.

In addition to particle filtration, other technologies exist to target other pollutants, such as activated carbon filters to remove gaseous pollutants and ultraviolet light-based technologies to primarily target microorganisms.[43] The latter became increasingly popular during the COVID-19 pandemic, and much attention went to the application of in-duct and upper room **Ultraviolet Germicidal Irradiation (UVGI)** systems, applied at a new wavelength (i.e., 222 nm Far-UVC), to remove and inactivate bioaerosols.[44,45]

The COVID-19 pandemic also saw the rise of various emerging “electronic air cleaning” technologies that are commercially available, but do not undergo standardized testing that other proven technologies do (e.g., media-based particle filters). Therefore, these products can have unintended and undesirable consequences.[46] Many emerging, non-filter-based technologies rely on chemical reactions that can reduce levels of some indoor air pollutants while increasing the levels of other indoor air parameters, which often are not measured or evaluated as part of continuous building monitoring or as part of system evaluation. Unfortunately, some investigative studies have found the unintended generation of various pollutants that can result in respiratory irritation and worsened respiratory symptoms.[47,48] There is a need for standardized performance testing, similar to media filters, to verify the effectiveness and safety of emerging technologies.

Collectively, source control, ventilation, and filtration are necessary as a layered approach to enhance indoor air quality and related health outcomes. The examples mentioned above are common

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[40] S. Z. Deng, B. B. Jalaludin, J. M. Antó, J. J. Hess, and C. R. Huang, “Climate change, air pollution, and allergic respiratory diseases: a call to action for health professionals,” *Chin Med J (Engl)*, vol. 133, no. 13, p. 1552, Jul. 2020, doi: 10.1097/CM9.0000000000000861.

[41] D. Jones, R. D. Neal, S. R. G. Duffy, S. E. Scott, K. L. Whitaker, and K. Brain, “Impact of the COVID-19 pandemic on the symptomatic diagnosis of cancer: the view from primary care,” *Lancet Oncol*, vol. 21, no. 6, pp. 748–750, Jun. 2020, doi: 10.1016/S1470-2045(20)30242-4.

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[44] E. Kujundzic, M. Hernandez, and S. L. Miller, “Ultraviolet germicidal irradiation inactivation of airborne fungal spores and bacteria in upper-room air and HVAC in-duct configurations,” *Journal of Environmental Engineering and Science*, vol. 6, no. 1, pp. 1–9, 2007, doi: 10.1139/S06-039.

[45] D. Welch et al., “Inactivation Rates for Airborne Human Coronavirus by Low Doses of 222 nm Far-UVC Radiation,” *Viruses*, vol. 14, no. 4, p. 684, Apr. 2022, doi: 10.3390/V14040684/S1.

[46] J. A. Siegel, “Primary and secondary consequences of indoor air cleaners,” *Indoor Air*, vol. 26, no. 1, pp. 88–96, Feb. 2016, doi: 10.1111/INA.12194.

[47] D. B. Collins and D. K. Farmer, “Unintended Consequences of Air Cleaning Chemistry,” *Environ Sci Technol*, vol. 55, no. 18, pp. 12172–12179, Sep. 2021, doi: 10.1021/ACS.EST.1C02582/ASSET/IMAGES/LARGE/ES1C02582_0007.JPEG.

[48] Y. Zeng et al., “Evaluating a commercially available in-duct bipolar ionization device for pollutant removal and potential byproduct formation,” *Build Environ*, vol. 195, May 2021, doi: 10.1016/j.buildenv.2021.107750.

instances of less severe health effects caused by air quality in the built environment, but more serious impacts can also occur. Recent examples include the severe morbidity and mortality resulting from COVID-19 transmission in buildings with inadequate ventilation rates for controlling infection, as well as the burden associated with climate change-driven extreme weather events, such as wildfires. It is important to recognize that in many cases, the precise sources, exposures, and biological pathways are not fully understood due to the complex and dynamic nature of indoor environments and the difficulties in measuring and quantifying these occurrences comprehensively. While this presents a common challenge in indoor environmental research, it should not hinder action. Despite the complex pathways of exposure and health outcomes, and the significant variation in indoor environments, there is substantial evidence that improving indoor air quality through source control, ventilation, and filtration (e.g., managing indoor moisture and using low-emitting consumer products) appears to protect human health. Furthermore, evidence suggests benefits extend beyond physical health, with many studies, including recent research, reporting improvements in cognitive health, overall well-being, and satisfaction.

Impact of IAQ on Cognitive Health

There is emerging evidence that indoor air quality influences multiple domains of cognitive function and overall performance. Two main types of investigations have been undertaken on this topic:

1. **Experimental studies** that manipulate one or more specific indoor air pollutant to assess their direct effects.
2. **Observational studies** that evaluate indoor environmental factors without experimental intervention, such as measuring ventilation rates or indoor carbon dioxide concentrations as an indicator of ventilation. Unlike experimental studies, these assessments account for variations in multiple pollutants influenced by ventilation and CO_2 levels.

The collective results from the first study method, involving control of one or more indoor air pollutants, have been mixed.[49] Several experiments have observed impaired cognitive function resulting from short-term exposure to artificially elevated indoor carbon dioxide concentrations, within the range of 600-2,500 ppm.[50] However, others have found the opposite, with no effect of artificially elevated carbon dioxide on cognitive function.

Several studies employing the second study method of examining fluctuations in indoor pollutants focus on the measurement of carbon dioxide concentration, which is dependent on changes in building ventilation and the number of occupants. The collective results from such studies have been more consistent and suggest that lower indoor carbon dioxide, achieved through improved ventilation, is associated with improved cognitive function. One study assessed real-world building operation and indoor environmental quality in six countries (China, India, Mexico, Thailand, the United States of America, and the United Kingdom), and the associations with both indoor fine particulate matter and carbon dioxide concentrations, and cognitive function among 302 adult worker participants.[51] Overall,

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[49] US EPA, "Controlling Pollutants and Sources: Indoor Air Quality Design Tools for Schools." Accessed: Feb. 24, 2024. [Online]. Available: https://www.epa.gov/iaq-schools/controlling-pollutants-and-sources-indoor-air-quality-design-tools-schools

[50] U. Satish et al., "Is CO2 an indoor pollutant? direct effects of low-to-moderate CO2 concentrations on human decision-making performance," *Environ Health Perspect*, vol. 120, no. 12, pp. 1671–1677, 2012, doi: 10.1289/EHP.1104789/ASSET/A9DE3656-EC97-43C4-891C-302C70259346/ASSETS/GRAPHIC/EHP.1104789.G002.JPG.

[51] J. G. Cedeño Laurent et al., "Associations between acute exposures to PM2.5 and carbon dioxide indoors and cognitive function in office workers: a multicountry longitudinal prospective observational study," *Environmental Research Letters*, vol. 16, no. 9, p. 094047, Sep. 2021, doi: 10.1088/1748-9326/AC1BD8.

higher fine particulate matter concentrations and higher carbon dioxide concentrations, a proxy for lower ventilation rates, were associated with slower response times and reduced accuracy for eight out of ten scored metrics from two cognitive tests. Moreover, further analysis and statistical modeling showed a linear, no-threshold association between indoor carbon dioxide and cognitive function (based on metrics incorporating response time and/or accuracy from a specific test) at carbon dioxide concentrations below a commonly cited industry standard of 1,000 ppm. This suggests that there are cognitive benefits to improved ventilation and indoor air quality.

Another study examined carbon dioxide concentrations in classroom settings and found attention processes of children to be significantly slower at high classroom carbon dioxide concentrations. This means that students in these settings had hindered focused attention and, likely, impairment to overall learning.[52] Children in classrooms with elevated carbon dioxide (mean of 2,909 ppm compared to 690 ppm) experienced roughly a 5% decrease in scores on a "Power of Attention" test used to assess focused attention. The researchers contextualized this as being equivalent to the observed magnitude of detriment among children who miss class.

Concerning fine particulate matter, past investigations have found impaired cognitive function among older adults with exposure to indoor fine particulate matter from the use of solid fuel combustion and open fires indoors.[53,54,55]

Adding to the overall evidence is a multitude of outdoor air pollution studies, which again observe impaired cognitive function in relation to various ambient air pollution markers.[56,57] Although others have noted variations in observed effects among studies, individuals, and indoor environmental parameters[58], there is growing evidence that various indoor air pollutants and ventilation and filtration schemes influence cognitive function. This is further supported by a generous body of research on ambient air pollution that shows impacts on cognitive health even from distant exposures.

Conclusion

Indoor air quality is essential for both physical health and cognitive function. Effective management through source control, ventilation, and filtration is crucial for maintaining healthier indoor environments. As scientific research continues to highlight its impact, the urgency for strong IAQ policies and proactive interventions becomes increasingly clear.

[52] D. A. Coley, R. Greeves, and B. K. Saxby, "The effect of low ventilation rates on the cognitive function of a primary school class," *International Journal of Ventilation*, vol. 6, no. 2, pp. 107–112, 2007, doi: 10.1080/14733315.2007.11683770.
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[55] J. L. Saenz et al., "Household use of polluting cooking fuels and late-life cognitive function: A harmonized analysis of India, Mexico, and China," *Environ Int*, vol. 156, p. 106722, Nov. 2021, doi: 10.1016/J.ENVINT.2021.106722.
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