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Connecting the Building Sciences and Health Sciences in Canada: Research Gaps

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Abstract: Canadians spend most of their time indoors. There is mounting evidence that the conditions they experience — air, light, sound, interior design, materials, and architectural features — influence their health. These effects may disproportionately occur in vulnerable populations, defined by individual, socioeconomic, cultural or geographic characteristics. In November 2008, the First Canadian Building and Health Sciences Workshop brought together Canadian researchers to identify the state of the science on buildings and health and to identify a way forward to improve the state of knowledge in Canada. This paper summarizes the state of knowledge and identifies research gaps as a first step in that process.

Résumé: Les Canadiens passent la plupart du temps à l'intérieur. Il est de plus en plus prouvé que les conditions dans lesquelles ils vivent ont une influence sur leur santé (l'air, la lumière, le bruit, la conception intérieure, les matériaux et l'architecture). Ces conséquences peuvent être particulièrement graves auprès des populations les plus vulnérables, définies ainsi suivant leurs caractéristiques individuelles, socio-économiques, culturelles ou géographiques. En novembre 2008, le premier atelier canadien sur les sciences du bâtiment et de la santé a permis de regrouper des chercheurs canadiens pour identifier l'état des sciences du bâtiment et de la santé et mettre au point une façon d'améliorer l'état des connaissances au Canada. Cet article résume l'état des connaissances et identifie les lacunes dans la recherche en tant que première étape de ce processus.

Introduction

Canadians spend close to 90% of their time indoors (Leech, Nelson, Burnett, Aaron, & Raizenne, 2002). The conditions created by and existing in buildings as they are designed, constructed, operated and inhabited, are those to which we are exposed most often and for the longest duration. The need to improve the scientific understanding of the health effects associated with buildings, and to understand how building design, construction, and operation influence the physical conditions in buildings, was the impetus that led the hosts to organize the First Canadian Building and Health Sciences Workshop. Although there are several international organizations, conference series, and expert meetings concerning health and buildings, there has been no concerted effort to bring together Canadian researchers. This has limited the possibility of collaborations among Canadian researchers and reduced the quantity of research on Canadian building and climate conditions and in the Canadian population. Better knowledge of building-health relationships in the Canadian context is needed for the development of appropriate Canadian solutions.

The scope of the workshop was intentionally broad: To consider buildings in all their aspects, including but not limited to air, light, sound, interior design, materials, and architectural features, as they could affect the health of people. We adopted the World Health Organization (WHO) definition of health: "…a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity" (WHO, 1948). We intended to address the health needs of people taking into account all of their individual and collective characteristics, abilities, and states, including (but not limited to) their age, developmental state, socioeconomic status, sex, personality, and cultural differences.

The goals for the workshop were:

- To review the state of the science on buildings and health;
- To identify research gaps, particularly those relevant to the Canadian context;
- To develop next steps leading to filling the gaps;
- To identify barriers that limit knowledge transfer and the development of interdisciplinary research collaborations, and to begin to break them down.

This paper addresses the first two goals of the workshop; a separate workshop summary paper (Veitch, 2008a) addresses the last two goals. This summary of the state of the science is based on all of the information

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associated with the workshop: the formal presentations, the panel discussions, the breakout group feedback, and the participants' selected bibliography (Appendix A, this volume), as well as a limited literature review of work published after the workshop.

Building Effects on Health

Respiratory Exposures and Ventilation

The air in buildings can contain chemical, microbial, and particulate contaminants, the exposure to which may affect human health. Dumont (2008, this volume) reviewed some of the sources: occupants; tobacco smoke; wood smoke; off-gassing from building materials, finishes, and furnishings; combustion appliances; and microbial contamination. The effects of indoor air quality on health, and the links between ventilation strategies and indoor atmospheric conditions, are the dominant research area at the intersection of the building sciences and health sciences. Indeed, for many the phrases "indoor air quality" and "indoor environment" are synonymous. Among the 54 articles proposed by workshop participants as valuable reading at the intersection of the building sciences and health sciences, 21 focused on this topic. Concern about possible adverse effects of the air we breathe indoors has increased in recent years with the recognition that there may be conflicts between the goal of tightening buildings to improve the energy-efficiency of heating and cooling systems, and the need for clean air to breathe.

Not surprisingly, the dominant focus in this area has been on respiratory health. Dales, Liu, Wheeler, and Gilbert (2008) reviewed the literature to provide guidance to the medical community concerning when to suspect residential indoor air quality as the source of a respiratory health problem, and how to advise patients and the public on how to improve the conditions in spaces they inhabit. More comprehensive reviews have been conducted in the U.S. by the National Center for Healthy Housing (NCHH) (2009) and the National Academies of Science Institute of Medicine (IOM) (2000). These reviews have concluded that there are strong or causal relationships between certain exposures and clinical conditions (e.g., environmental tobacco smoke and lung cancer; dust mites and asthma), whereas there is correlational evidence for associations between other allergens and clinical conditions (e.g., mould, cockroaches and asthma). Volatile organic compounds found in cleaning products are associated with various respiratory symptoms (Dales et al., 2008) and endotoxin burdens have been linked to infant respiratory health (Dales, Miller, Ruest, Guay, & Judek, 2006). For formaldehyde and radon, there is sufficient evidence of health effects indoors to support regulatory guidelines (Health Canada, 2006, 2007). For certain semi-volatile and non-volatile plasticizers, there is suggestive evidence of an effect on respiratory health and function, and on allergies, but this needs further study (Dales et al., 2008; Mendell, 2007).

Dales et al. (2008) highlighted a controversial issue that remains to be resolved: Some evidence supports the notion that early exposure can prevent sensitization and the subsequent development of allergy and atopy; other evidence suggests that early exposure can increase the risk of subsequent problems. Furthermore, avoidance of allergens (e.g., endotoxins, dust mites) is recommended for people with known sensitivities, but effects of allergen exposures on people who have not been sensitized are unclear (Dales et al., 2008).

Several investigations have assessed airborne contaminants in Canadian houses, with studies having focused on Prince Edward Island (Dales et al., 2006; Gilbert et al., 2005), Quebec City (Gilbert et al., 2006), and Baffin Island (Kovesi et al., 2006; 2007). Other investigations have assessed ventilation rates and practices in Ontario, Quebec, and Saskatchewan (Fugler, 2008, this volume). Taken overall, it appears that on the order of one third of homes are underventilated compared to North American norms; that is, they receive fewer than 0.5 air changes per hour most of the time (e.g., Canadian Commission on Building and Fire Codes (CCBFC), 2005), which would contribute to adverse health outcomes because of contaminant exposures.

Source control, dilution through ventilation, and pollutant removal through filtration are the three broad strategies available to reduce unwanted exposures. The National Center for Healthy Housing review, released after this workshop, outlined interventions that have been shown to be effective ways to address health problems in houses (NCHH, 2009), as well as those for which evidence of their effectiveness is weaker or nonexistent. Increasing residential ventilation was judged to require more field evaluation regarding its effectiveness in limiting exposure to biological toxins, and to require formative research in relation to chemical toxins. For example, multifactorial interventions (including both source control and ventilation components) can improve asthma symptoms and quality of life (Krieger, Takaro, & Rabkin, 2008, this volume), but residential ventilation rates alone are not clearly associated with health outcomes (NCHH, 2009). Filtration alone has shown mixed results with respect to allergy and asthma symptoms, partly because of research design limitations

(McDonald et al., 2002), and the NCHH did not consider the evidence sufficient to justify filtration alone as an intervention (NCHH, 2009). Further investigation of these issues is clearly justified: Wu and Takaro (2007) have argued using the data on asthma interventions that such interventions are cost-effective. The cost of disease associated with mould and dampness in U.S. homes has been estimated as ~ US$ 3.5 billion per year (Mudarri & Fisk, 2007).

Exactly how best to deliver healthful indoor air quality in Canadian homes is an active research topic. Leech, Raizenne, and Gusdorf (2004) provided limited evidence that ventilation practices in new, energy-efficient homes improved a number of comfort symptoms. However, the housing stock in Canada is diverse, as are regional climatic conditions. Different strategies will be required for existing older homes of varying ages and from one region to another.

Current Canadian research addresses the effects of indoor air quality on the development of asthma and allergy. The Canadian Healthy Infant Longitudinal Development (CHILD) Study (http://www.canadianchildstudy.ca/), funded by the AllerGen National Centre of Excellence http://www.allergen-nce.ca/Research/Network-Wide_Research.html) and the Canadian Institutes of Health Research, began in 2008 as a pilot, MiniCHILD. This study will ultimately involve 5,000 children born in four provinces across Canada over the next 20 years. This will cover environmental, clinical and genetic determinants of respiratory diseases. The National Research Council Canada Institute for Research in Construction (NRC-IRC) Indoor Air Initiative (http://irc.nrc-cnrc.gc.ca/ie/iaq/initiative_e.html), a partnership between NRC-IRC and l'Institut national de santé publique du Québec (INSPQ), with support from Health Canada and others, includes investigations into the effects of residential indoor air conditions on childhood asthma and the effects of various ventilation strategies on indoor air quality parameters.

It is well known that poverty increases exposures to toxins and stressors of all kinds (Evans & Kantrowitz, 2002; Wu, Jacobs, Mitchell, Miller, & Karol, 2007). There also exist geographic and cultural dimensions to this problem. For instance, Kovesi and colleagues (2006; 2007) found that among Inuit homes on Baffin Island, 94% had resident smokers and 80% had ventilation rates lower than recommendations. Infants in homes with higher concentrations of carbon dioxide and more occupants were more likely to develop severe respiratory tract infections. These illnesses require hospitalization in a distant city, an expensive problem for the health-care system and an expensive and distressing one for families.

Despite the extensive activity in Canada and elsewhere directed at understanding the effects of airborne exposures on health, there remain many unanswered questions. Comparatively few diseases have been studied, and predominantly those with obvious connections to respiratory health. Thus, present-day work emphasizes asthma and allergy, often in children because they are at greater risk (Bearer, 1995). Since the SARS epidemic in 2003, there has been a renewal of interest in the role of ventilation in the spread of infectious disease (e.g., Li et al., 2007). There exists little work addressing other diseases, particularly those of adulthood (e.g., cardiovascular disease; cancers; neurological disorders; behavioural and mental health problems; diabetes). There appear to be no studies that have attempted to associate indoor air conditions with positive well-being.

Extensive exposure monitoring took place in six European cities under the EXPOLIS project (http://www.ktl.fi/expolis/index.php?id=0) and in the USA in three states under the NHEXAS project (http://www.epa.gov/heasd/edrb/nhexas.htm). Total exposures of Canadians to airborne contaminants found in homes, nonindustrial workplaces, transport and outdoors are poorly understood. A few studies have undertaken extensive monitoring of indoor air quality in Canadian homes (e.g., Dales et al., 2006; Gilbert et al., 2006; Gilbert et al., 2008; Héroux et al., 2008; Kovesi et al., 2006; Stocco et al., 2008), but there is little information concerning exposures in non-residential, non-industrial buildings, and no evidence concerning the total exposure individuals experience throughout a day as they pass through various spaces. The vast array of substances that may occur in buildings, and the cost of assays for them, makes exposure monitoring a particularly difficult challenge (IOM, 2000).

Other Material Exposures

Inhabitants of buildings are also exposed to chemical, biological, and mineral contaminants through routes other than respiration. Exposures may occur through the skin and by ingestion. These exposures may affect infants and children more than adults, both because they are more likely to manually and orally explore surfaces and because the effects may be greater on developing bodies (Bearer, 1995; Canadian Partnership for Children's Health and Environment (CPCHE), 2005). The effects of some substances are well understood, with the result that standards and practices have changed. This has resulted in regulatory changes, such as banning lead additives for gasoline. Lead-based paints have been prohibited for some time; however, exposures to lead from building sources persist in homes built before 1980 (Rasmussen, 2004; Rasmussen et al., 2008;

Rasmussen, Subramanian, & Jessiman, 2001; Wu et al., 2007). There are inadequate data in Canada to assess the scope of this problem.

Aside from allergens, endotoxin and glucan, Canadian house dust can contain high concentrations of metals other than lead, flame retardants, perfluorosulfonates and particulate matter (PM) from wood stoves and automobile traffic (Harrad et al., 2008; Kubwabo, Stewart, Zhu, & Marro, 2005; Miller, Dugandzic, Frescura, & Salares, 2007; Rasmussen, 2004; Rasmussen et al., 2008; Rasmussen et al., 2001; Wilford, Shoeib, Harner, Zhu, & Jones, 2005). The health effects of these remain to be properly elucidated and the geographic distribution of data within Canada is limited.

Both in the general media and in the scientific literature there is controversy over the suggestion that organohalogen compounds such as flame retardants could have adverse health effects. These compounds have been suggested as possible influences on the occurrence of attention-deficit hyperactivity disorder (ADHD) and Parkinson's Disease, both of which have increased in incidence over the period during which these substances have been in use. There is some evidence that brominated flame retardants might adversely affect neurological development, possibly through effects on dopaminergic neurons (Lilienthal, van der Ven, Piersma, & Vos, 2009). Dust ingestion has been suggested as an important mechanism for human exposures (Abdallah et al., 2008; Harrad et al., 2008), but it remains far from clear what effects, if any, might relate to these exposures.

Research in this area is challenging because the exposures to any one substance are low, but many exposures occur simultaneously. The effects of various exposures could be additive, and some effects may develop in response to cumulative, not acute, exposures. Moreover, there are hundreds of man-made substances that may be involved, and the effects are likely to be the result of interaction with genetic factors (Mariussen & Fonnum, 2006).

Light and Lighting

A transformation is under way in lighting research, bringing together the international communities of researchers in photobiology and architectural lighting applications. The discovery of a separate retinal sensory system transducing information about light and dark (Berson, Dunn, & Takao, 2002; Hattar, Liao, Takao, Berson, & Yau, 2002) was revolutionary. Afferents from the newly-identified intrinsically photoreceptive retinal ganglion cells (ipRGCs) lead to, among other brain structures, the suprachiasmatic nucleus of the hypothalamus and from there to the pineal gland (Commission Internationale de l'Eclairage (CIE), 2004). The connection to the pineal gland is important for the regulation of the hormone melatonin, which regulates many circadian rhythms (CIE, 2004). Extensive research into acute melatonin suppression by nocturnal light exposure has resulted in an understanding that light in the region of 454-484 nm is most effective at influencing various indices of circadian phase (Brainard & Provencio, 2006). However, we do not yet have a clear understanding of the effects of polychromatic (white) light on human physiology, nor do we have a complete understanding of the effects of daytime light exposure on human physiology and behaviour (Brainard & Veitch, 2007).

Separate lines of research suggest that people in industrialized countries may not experience sufficient daily light exposure for optimal health (Espiritu et al., 1994; Jean-Louis, Kripke, Cohen, Zizi, & Wolintz, 2005; Leppämäki, Partonen, & Lönnqvist, 2002; Partonen, Leppämäki, Hurme, & Lönnqvist, 1998; Partonen & Lönnqvist, 2000), and Canadian researchers are active in this area. Residents in Montreal are exposed, on average, to 2 hours 26 minutes of light over 1000 lx in summer, and 24 minutes in winter (Hébert, Dumont, & Paquet, 1998). Social interactions may be more cooperative and less competitive immediately following bright light exposure (aan het Rot, Moskowitz, & Young, 2008). Moreover, studies in an Edmonton hospital revealed associations between sunny hospital rooms and lower mortality rates among cardiac patients (Beauchemin & Hays, 1998) and faster symptom remission for depressive patients (Beauchemin & Hays, 1996).

There are two responses to this information among those interested in lighting (Brainard & Veitch, 2007): some are enthusiastic about making immediate changes to lighting design and practice (e.g., Bommel & Beld, 2004). Others are more circumspect, recommending more thorough investigation (e.g., Boyce, 2006; Veitch, 2005). The International Commission on Illumination has a technical committee (TC 3-46, chaired by this author) charged with the development of a research roadmap to define the knowledge needed to develop lighting applications based on the effects of light on human physiology and behaviour.

Noise

Although few Canadian researchers are active in the field, there is growing evidence from international sources that chronic noise exposure has adverse effects on cardiovascular health, respiratory illness, depression, and interpersonal communication in both children and adults, and children's language development (e.g., Evans,

Hygge, & Bullinger, 1995; Evans & Maxwell, 1997; Ising & Braun, 2000; Ising & Kruppa, 2004; Niemann et al., 2006). The European Regional Office of the WHO is developing guidelines for urban noise levels based on this research (WHO Europe, 2007).

Noise annoyance is a predictor of health symptoms (Niemann et al., 2006), providing a non-invasive means of assessing the likelihood of problems in a given neighbourhood. Health Canada is in the process of developing guidelines based on noise annoyance that could be used for environmental assessments of planned projects in Canada (Michaud, Bly, & Keith, 2008). Canadians' annoyance with road traffic noise correlates with the distance to a heavily-travelled road and to community size (Michaud, Keith, & McMurchy, 2008). Further research is needed to identify the building and infrastructure characteristics (e.g., noise barriers) that could reduce noise exposure and mitigate health effects.

Architectural Features

The effects of architectural features of the built environment on health and well-being have been the target of many studies over the past fifty years (Gifford, 2007). At the most general level, the evidence shows that the objectively-assessed quality of housing improves health outcomes. Evans, Wells, Chan, and Saltzman (Evans, Wells, Chan, & Saltzman, 2000) conducted a prospective longitudinal study of mothers moving into new housing, and found that the improvement in housing quality reduced mothers' psychological distress. In a cross-sectional sample from this data set, they found that housing quality predicted mothers' mental health after controlling for income. A cross-sectional study of families in Quebec and British Columbia found that the quality of the home's interior, exterior, and neighbourhood positively predicted children's socioemotional health as rated by their parents, after controlling for parental income, parental education, parental mental health status, the child's sex, and the family's tenure in the house (Gifford & Lacombe, 2006). Such studies emphasize the importance of the characteristics of the physical environment, but provide little direct guidance for designers or policy-makers because it is impossible to identify the specific features that have the strongest connection to health outcomes from the generalized objective checklists.

Among the most important specific architectural features influencing health are windows. They exert their influence through the admission of light (see above), and by providing a view of outdoors. The value of the view is most beneficial when the view includes natural elements, such as trees and grass (Talbot & Kaplan, 1991; Ulrich, 1984).

The availability of nature near home has additional benefits, findings that have implications for landscape design and neighbourhood planning. Living near to natural features can improve psychological functioning and coping in adults (Kuo, 2001), and adults in neighbourhoods with more greenery have lower rates of obesity (Ellaway, Macintyre, & Bonnefoy, 2005). Playing in more natural settings can reduce symptoms of ADHD in children with the disorder (Kuo & Taylor, 2004; Taylor, Kuo, & Sullivan, 2001), and improves cognitive functioning and coping ability in children generally (Wells, 2000; Wells & Evans, 2003). The effects of both a natural window view and access to nature are thought to be related to attention restoration and the reduction of mental fatigue (Kaplan, 1995).

Specific architectural elements within homes also influence health. As Fernie, Dutta, Li, and Hsu (2008, this volume) observed, falling is one of the major causes of death among seniors. Research programs during the past three decades have led to interventions that reduce pain, suffering, and health care costs (Sleet, Moffett, & Stevens, 2008). As Syme (2008, this volume) observed, interventions aimed at training or changing the individual will need to be repeated for each cohort; architectural interventions will endure. New technologies are under development to reduce the risk of falls (e.g., Scovil et al., 2007), and much is known about accessibility features for new buildings (Fernie et al., 2008, this volume), but less is known about practical means to retrofit such features into existing homes. The National Center for Healthy Housing concluded that more field evaluation is needed to document the effectiveness of such interventions for fall prevention (NCHH, 2009). Moreover, injuries from falls are not the only health outcome affected by architectural features in homes, nor are the elderly and their caregivers the only populations needing attention.

Population Health

Housing and Neighbourhoods

Although one can consider dwellings in terms of building features, a separate body of research takes a population health perspective on housing, with a focus on socio-economic, geographical, and psychological contributors to health (Fuller-Thomson, Hulchanski, & Hwang, 2000; Hartig & Lawrence, 2003). This body of

work has demonstrated that being of low socio-economic status exposes individuals to both physical and social stressors, including higher levels of toxins and higher noise levels along with fewer buffers against stress, such as social support (Evans, 2004; Fuller-Thomson et al., 2000). These many and varied demands and exposures contribute to the poorer health status of residents in lower-income neighbourhoods (Caspi, Taylor, Moffitt, & Plomin, 2000; Dunn & Hayes, 2000).

Several reviews of the literature have appeared in recent years (Cummins & Jackson, 2001; Fuller-Thomson et al., 2000; Lawrence, 2002, 2006; Saegert, Klitzman, Freudenberg, Cooperman-Mroczek, & Nassar, 2003). Although they vary in emphasis, all agree that progress in understanding the relationships between housing characteristics and health, and demonstrating the importance of interventions in a way that is amenable to policy-makers and practitioners, requires interdisciplinary collaboration. Methodological weaknesses have limited the strength of conclusions in this field (Evans, Wells, & Moch, 2003; Saegert et al., 2003), and Dunn (2008, this volume) has called for more theoretical rigour and the development of integrated models to improve our understanding of the effects of housing and home on health outcomes. For detail concerning research methods applicable in this domain, see Sadish, Cook, and Campbell (2002). Gifford (2008, this volume) provided an overview.

Rates of obesity are rising dramatically in Canada and elsewhere (Starky, 2005). The causes are multifactorial, but one contributor is inactivity. Neighbourhood design is one focus of research attention. In particular, some have suggested that suburban designs that place homes far from shopping, schools, and amenities contribute to inactivity by making it more difficult to residents to walk or cycle to their daily activities. No consensus has emerged as yet, with some studies finding positive relationships between neighbourhood characteristics and either activity levels or obesity rates (Heinrich et al., 2008), and others finding no relationship or findings in unexpected directions (Atkinson, Sallis, Saelens, Cain, & Black, 2005; Wells & Yang, 2008). The diversity of neighbourhood characteristics used as predictor variables, as well as the diversity of neighbourhoods, likely explains the lack of consensus. Further investigation and theoretical development are needed in this area.

Interactions — Individual and Group Differences

As is clear from the literature cited above, the effects of building conditions on individuals are not necessarily simple main effects that are observable in all people. Researchers have focused on a limited subset of individual differences that moderate effects, but more attention is required.

Developmental effects have been, and continue to be, an important research focus. Infants and children, because of their lower mass and rapid growth, are likely to be more strongly affected than adults by various exposures (Bearer, 2005). For instance, Abdallah et al. (2008) calculated that the infant dose of the brominated flame retardant hexabromocyclodecane may fall within the range of occupational exposures of workers in a polystyrene plant. Little is known about the consequences in humans of such exposure at an early age, but one study found that rats receiving high doses during early development showed adverse effects in dopamine-dependent behaviour (Lilienthal et al., 2009).

Important effects also occur at the other end of the life span. Increasing light exposure during the day can improve mood and cognitive functioning and reduce night-time restlessness among nursing-home residents with dementia (Riemersma-van der Lek et al., 2008; Someren, Kessler, Mirmiran, & Swaab, 1997).

Failing to examine differential effects across age groups can mask interesting effects. The effects of electromagnetic fields (EMF) on health is a contentious topic. Some have suggested that EMF exposure might contribute to the development of cancers and other diseases (Ahlbom et al., 2001; Brainard, Kavet, & Kheifets, 1999), although there are few empirical studies showing such effects. Davis and Mirick (2007) found no association between household EMF exposure and breast cancer incidence among adult women. If the effects exist, disruption of the melatonin cycle is thought to be a possible underlying mechanism. Levallois et al. (2001) found no simple main effects of EMF exposure on melatonin secretion, but age and EMF exposure had an interactive effect. This led them to suggest that the effects of EMF exposure could be greater for vulnerable subpopulations. Further investigation of this effect would be required to address this particular question. More generally there have been few attempts to elucidate interactions between interior conditions and occupants' age or other individual differences.

Group-level interactions also warrant attention. These may include genetic differences associated with particular subpopulations, or cultural and geographic influences. Kovesi et al. (2006; 2007) studied the incidence of respiratory illness in the Canadian north because of a known public health problem: a high rate of serious illness among Inuit children in that region. The interior conditions that contribute to these illnesses have multiple determinants that include poverty, high occupant density, cultural practices contributing to interior

conditions, and the extreme climate. Developing effective interventions for such problems requires a better understanding of the relative importance of these various influences.

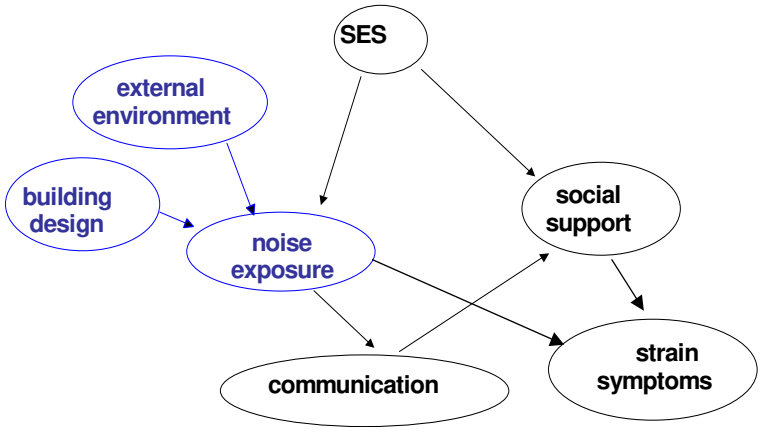
Building Systems

Sustainable development and health are intertwined. The report of the United Nations World Commission on Environment and Development (the "Brundtland Report") defined sustainable development as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987). To design buildings and to plan communities following this definition means to strive to create conditions that support human health today without compromising the health, broadly construed, of future generations. Thus, a healthful building must also be an energy-efficient one, and its construction and operation ought not to consume resources that future generations will require, nor to result in the creation of conditions that will impair their health. Kesik (2008, this volume) provided an overview of sustainability as it applies to buildings and in particular their energy consumption.

Much is known about how to design, construct, and operate buildings to create healthful conditions without being wasteful, and bodies of research also address the development of healthful, sustainable communities. Several journals publish the research of building scientists worldwide that document the development of design processes, building technologies, and operating strategies to improve building performance (e.g., *Building and Environment; Building Research and Information*; *Energy and Buildings*; *Indoor and Built Environment*; *Intelligent Buildings International*), and others are devoted to the community level (*Environment and Planning B: Planning and Design*; *Urban Studies*); there are also several conferences each year devoted to the topic. Loftness, Hakkinen, Adan, and Nevalainen (2007) briefly reviewed building design and construction choices that can lead to buildings that are both sustainable in the long run and healthy for their current inhabitants. Fazio (2008, this volume) described practical aspects of building design, construction, and operation that have limited our success in applying this information.

The research gap lies not in understanding fundamental building physics, but in the integration of separate lines of knowledge. Following the first energy crisis of the 1970s, building air tightness was increased to reduce the energy required for building heating and cooling. This resulted in unintended consequences related to indoor air quality. Contemporary homes in most of Canada require mechanical ventilation in order to achieve acceptable air change rates, and the standard practices for this ventilation are not as energy-efficient as they could be (Fugler, 2008, this volume). Further research is needed to develop integrated solutions for new buildings that will resolve these issues — that is, how to solve one problem without creating new ones. Moreover, solutions are needed that will result in renovations to ensure healthful and sustainable conditions in the existing buildings that comprise the majority of the building stock in all building types.

Figure 1. *An example of an integrated model involving building sciences and health sciences. Building science contributions are shown in blue, and health sciences in black.*



In order to address system issues, there needs to be integration of building sciences and health sciences, the very topic of this workshop. There are few, if any, fully integrated models that reveal how building systems create interior conditions and how, in turn, those interior conditions influence health. For example, Veitch (Veitch, 2008b) described a possible model for the effects of noise on cardiovascular health (Figure 1).

Evidence exists for the various steps in the relationship,

but there is not enough detail available to connect the building science and health science components in order to derive practical recommendations. Although this example concerns noise exposure, the same could be said for most other topics described in this review.

In short, we need to know what conditions Canadians are exposed to in their built environments; what the results might be of that exposure; and, what are the relative costs/benefits of those results, in order to determine where to place specific research efforts and applications. This exposure information needs to be applicable to all building types, to various populations, and tailored to individual cultural and geographic needs.

In all the areas investigated, authors have advocated interdisciplinary or transdisciplinary research as a necessary activity in advancing efforts to ensure the design, construction, operation, and habitation of healthful buildings in a healthful environment. Syme (2008, this volume) opened the First Canadian Building and Health Sciences Workshop with an inspiring call for Canadian scientists to work together, to lead the way. This review will, we hope, provide guidance to Canadian researchers in this endeavour.

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