A Review of Research Investigating Indoor Environmental Quality in Green Buildings

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ABSTRACT: Although it has been claimed that green buildings offer improved indoor environmental quality (IEQ) over conventional buildings, there is little empirical evidence in the literature to substantiate these claims. This research aimed to review the literature on IEQ in green buildings. The literature was analyzed based on parameters such as the literature's country of origin, year of publication, type and sample of buildings studied and specific IEQ aspects studied. The review showed the need for research that analyzed larger green building samples, that relied on on-site physical measurements and that focused on buildings other than office buildings. Papers reviewed showed consensus among researchers on how green buildings improved air quality, and worsened acoustics, but less consensus on how thermal comfort and lighting performed. Green building occupants were also found in general to be more satisfied with thermal comfort and air quality but less satisfied with acoustics than occupants in conventional buildings.

1 INTRODUCTION

Although there are claims to the improved indoor environmental quality (IEQ) of green buildings, there is little empirical evidence in the field to substantiate these claims. This is because most research and industry practices seem to have focused on energy as the main driver to building green; and thus on improving the energy-effectiveness of green buildings with little consideration to other aspects such as IEQ.

This research is based on the premise that assessing and improving IEQ in green buildings is a necessity given the growth of the green building market. Since the foundation of the Canada Green Building Council (CaGBC) in 2002 more than 4400 buildings have registered for Leadership in Energy and Environmental Design (LEED) certification, with more than 1200 projects already certified (CaGBC,2013). This focus on IEQ is also needed to address the weaknesses of the literature on the topic. Only small-scale post occupancy surveys about IEQ appear to have been conducted up to this point, raising concerns about the accuracy of their results and the ability to extend them to other green buildings (Birt and Newsham 2009). These results have also sometimes been contradictory, reinforcing the need for more research in the field (Issa et al., 2011).

The goal of this research is to conduct a thorough review of the literature on IEQ in green buildings to establish benchmarks about their performance and pave the way for further research in the field. The review will investigate the location and timing of relevant research studies and analyze methods used to conduct them as well as the results put forward by them. It should provide researchers and practitioners interested in the post-occupancy evaluation of green buildings with a better understanding of knowledge gaps in the field as well as the literature's strengths and limitations.

2 RESEARCH METHODS

The research involved identifying the literature focusing on IEQ in green buildings; three databases were investigated: Scopus, Science Direct, and Compendex Web; using the keywords "Indoor Environmental Quality", "Green Buildings", and "Occupant Satisfaction". Given the resulting large number of journal and conference papers, the search was limited by combining keywords together (e.g. "Indoor Environmental Quality" & "Green Buildings"), and skimming through the papers' abstracts to determine their relevancy. Papers were included in the analysis if they focused on investigating one or more IEQ aspects. They were discarded if they did not focus on green buildings specifically. This resulted in a total of 18 papers that focused on both IEQ and green buildings.

The research involved developing a database to analyze these papers based on the parameters in Table 1. In addition to these parameters, Table 1 also includes the section or subsection within the paper where every parameter is addressed, and the figure(s) if applicable depicting the analysis of every parameter.

Table 1. The parameters of analysis.

Parameters	Section	Figures
Country of origin and year of publication	3.1	1 and 2
Building types	3.2.1	3
Number of green versus non-green buildings	3.2.2	4
Rating systems	3.2.3	5
Methods and data	3.3.1	6
Specific IEQ aspects	3.3.2	7
Results	3.4	8

3 ANALYSIS RESULTS AND DISCUSSION

This section presents the literature review results as per the parameters in Table 1.

3.1 *Country of origin and year of publication*

The review involved analyzing research studies based on their country of origin. As shown in Figure 1, two countries seem to lead research in the field. More than 40% of studies on the topic were carried out in The U.S. (e.g. Abbaszadeh et al., 2006 and Kelting & Montoya, 2011), Australia came in second, with approximately 27% of all papers identified (e.g. Gou et al., 2013and Paul & Taylor, 2008). Only two studies were conducted in Canada (Issa et al., 2011 and Newsham et al., 2012), highlighting the need for more research on Canadian green buildings.

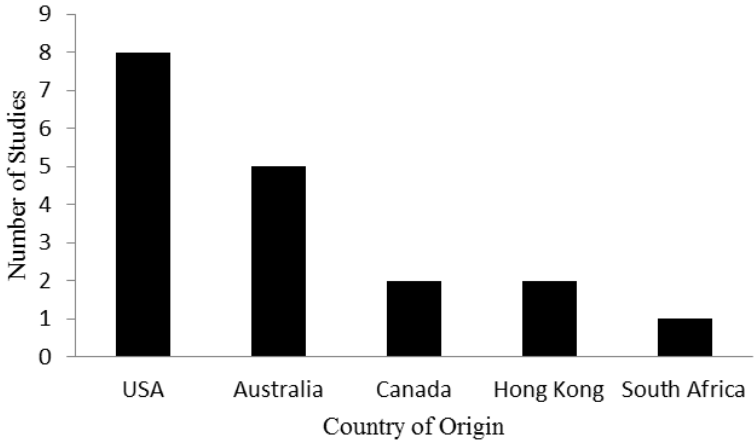

Figure 1. Distribution of research studies per country of origin.

The reviewed papers were also analyzed per year of publication. Figure 2 shows how the number of relevant papers increased significantly over the last three years, reflecting an increasing interest in green building research.

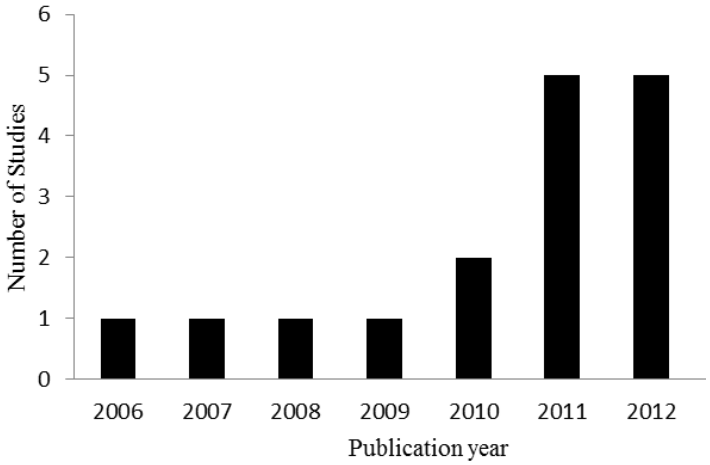

Figure 2. Distribution of research studies per year of publication.

3.2 *Buildings analyzed*

This subsection focuses on analyzing the specific types of buildings investigated in the studies reviewed, their level of greenness and the rating systems used to certify them.

3.2.1 *Building types*

As depicted in Figure 3, almost 50% of all buildings analyzed were office buildings (e.g. Singh et al., 2010 and Thatchera & Milner, 2012); a result hardly surprising given that office buildings tend to make up the majority of the building stock in the developed world, including Canada (CaGBC, 2013). This focus on office buildings could be due to the potential financial implications of doing. There are claims made by green building proponents that improving these buildings' IEQ would improve employees' health and productivity, and thus decrease related long-term business costs (Newsham et al. 2012) making their analysis of critical importance.

Twenty percent were institutional buildings (i.e. schools and universities) (e.g. Baker, 2011 and Issa et al., 2011), reflecting an interest in these buildings that could be due to the long-term goal of improving students and teachers' health, performance, and well-being (Issa et al. 2011).

About 17% of all studies investigated samples of different building types (e.g. Leaman et al., 2007 and Brager & Baker, 2009). Very few studies focused on residential buildings (e.g. houses and condominium buildings), the lack of focus on residential buildings could be due to the erroneous perception that those buildings do not have the same long-term financial implications as office buildings, highlighting the need for more research on residential buildings. This perception ignores the evidence in the literature linking improved IEQ in homes to improved occupants' health and the potential long-term health savings derived from doing so (Kovesi et al., 2007).

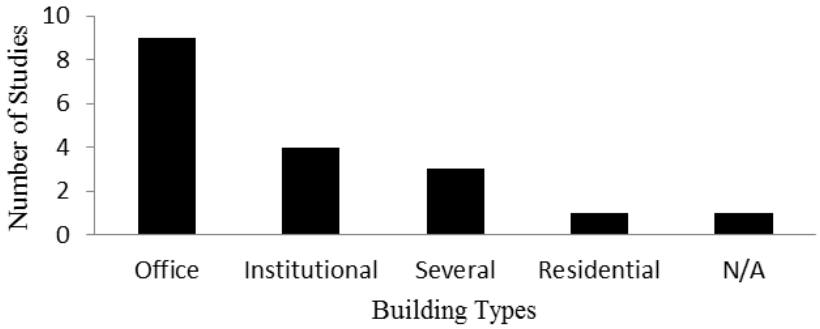

Figure 3. Distribution of research studies per building type.

3.2.2 *Number of green versus non-green buildings*

Fifty percent of all studies reviewed compared green buildings to non-green ones (e.g. Abbaszadeh et al., 2006 and Baker, 2011) with the other half focusing on assessing IEQ in green buildings solely (e.g. Singh et al., 2010 and Thatchera & Milner, 2012). A total of 140 buildings versus 650 non-green buildings were analyzed in all papers: an imbalance most probably due to the relative small ratio of green buildings to total existing buildings. Figure 4 shows how 60% of all studies used small sample sizes of less than 10 green buildings (e.g. Paul & Taylor, 2008 and Konis, 2013). This highlights an important limitation of existing research that makes it difficult to generalize existing results and reinforces the need for research evaluating larger building samples.

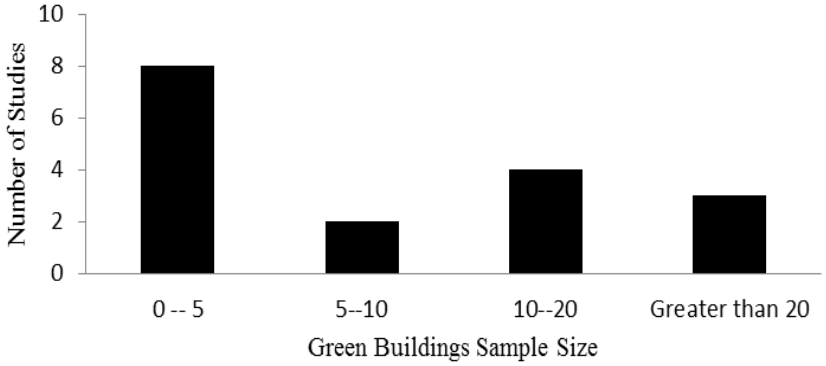

Figure 4. Distribution of research studies per number of green buildings.

3.2.3 *Rating systems*

Figure 5 shows how more than 50% of the studies reviewed focused on analyzing LEED buildings (e.g. Issa et al., 2011 and Singh et al., 2010). Seventy-five LEED buildings were analyzed in total in all studies; an indication of the popularity of the system in the green building market. The analysis also showed how green buildings certified using other rating systems received a lot less attention in the literature. Two studies focused on green buildings using the Green Building Label system (GBL) (e.g. Gou et al., 2013); another two on buildings using Green Star (Cladingboel et al., 2011 and Thatchera & Milner, 2012), and another two on buildings not accredited using any existing rating system (Abbaszadeh et al., 2006 and Baker, 2011).

Surprisingly, a number of studies did not specify the rating system used to certify buildings analyzed. Only one study (Gou et al. 2012a) analyzed green buildings certified using different rating systems at the same time. Despite the popularity of the Building Owners and Managers Association Building Environmental Standards (BOMA BESt) in North America, surprisingly, no research seems to have assessed these buildings' IEQ. These results highlight the need to consider buildings using other rating systems in order to enable IEQ cross-system comparisons.

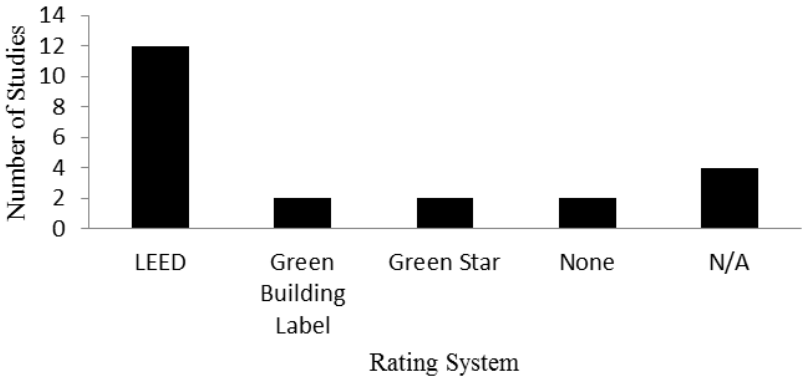

Figure 5. Distribution of research studies per rating system used.

3.3 *Research methods*

This subsection focuses on analyzing the specific research methods used to investigate green buildings' IEQ and the specific IEQ aspects analyzed in the studies reviewed.

3.3.1 *Methods and data*

As depicted in Figure 6, occupant surveys seemed to be the main method used to investigate IEQ in green buildings. Seventy percent of all studies used occupant surveys (e.g. Paul & Taylor, 2008 and Beauregard et al., 2011). Approximately, 40,000 occupants were surveyed in all of these studies, with one study alone (Abbaszadeh et al., 2006) surveying over 33,300 occupants.

Twenty six percent of the studies used the Building Use Studies (BUS) Occupant Survey Method; a benchmarking comprehensive method originally developed in the UK and used to assess users' needs in a range of building types (Gou et al., 2012b).

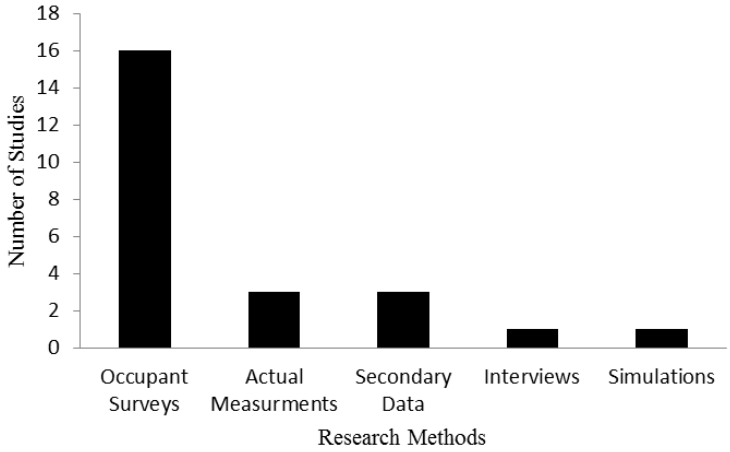

Figure 6. Distribution of research studies per methods and data.

Surprisingly, only three studies relied on actual physical measurements (Konis, 2013, Deuble & de Dear, 2012 and Newsham et al., 2012), highlighting the need for research that focuses on validating IEQ using on-site physical measurements due to their objective nature. The lack of actual physical measurements could be due to the fact that these require time, effort, and money; with the need for specialized equipment, personnel training, and field work; making them more difficult to conduct. The three studies that relied on them complemented and validated them with actual occupant surveys. Only one study (Cladingboel et al., 2011) relied on computer design simulations to test the thermal efficiency of their design.

Fourteen of the eighteen studies reviewed used statistics to analyse the results, highlighting an important strength of the existing literature.

3.3.2 *Specific IEQ aspects*

Four main IEQ aspects were assessed in the studies reviewed: Thermal comfort, Air quality, Lighting, and Acoustics. Figure 7 depicts the number of studies investigating each aspect.

More than 50% of the studies reviewed investigated the four aspects together (e.g. Issa et al., 2011 and Singh et al., 2010). Every other study assessed either one or two aspects at most (e.g. Cladingboel et al., 2011 and Lee, 2010). While there is value to investigating the four aspects together to get a comprehensive understanding of how they vary in relation to one another, focusing on every aspect separately allows for a more in-depth assessment of each. Thermal comfort appeared to be the IEQ aspect the most researched in the literature, most probably due to the tight relationship between thermal comfort; heating, ventilation, and air-conditioning; and energy consumption as the main driver to building green.

Lighting and Acoustics appeared to be the ones the least investigated at 65% and 60% respectively. This could be due to the fact that very few green building rating systems emphasize these aspects in general, thus the need for further research on them.

Given the tight link between IEQ and building occupancy, all studies extended to analyzing building occupancy through occupant surveys. The popularity of occupant surveys could be due to the relative ease of conducting them in comparison to other research methods. These surveys involved assessing aspects such as overall occupant satisfaction, productivity, performance, and health. Only 35% of the studies investigated all of those aspects together (e.g. Abbaszadeh et al., 2006 and Baker, 2011); the remaining focused only on occupant satisfaction with the overall indoor environment.

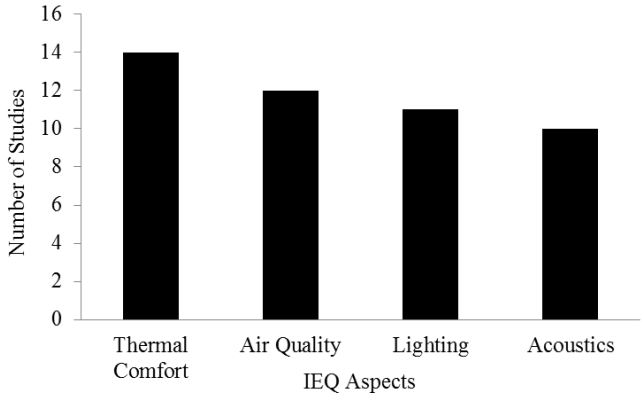

Figure 7. Distribution of research studies per IEQ aspects.

3.4 *Results*

This section presents a review of the studies' results to better understand how IEQ varies in green buildings and its effects on building occupants. Figure 8 summarizes these results.

Seven out of ten studies found air quality to have improved in green buildings (e.g. Gou et al., 2012b and Leaman et al, 2007). This was the aspect occupants were most satisfied with and the one that was found to have improved in most studies, showing a high level of agreement among researchers over its performance. Only five out of eleven studies showed an improvement in lighting (e.g. Konis, 2013 and Kelting & Montoya, 2011), demonstrating a lack of consensus over its performance and thus the need for more research on it. Only six studies out of twelve found that thermal comfort had improved in green buildings (e.g. Abbaszadeh et al., 2006 and Issa et al., 2011). The other six studies found thermal comfort in green buildings to either be on par with thermal comfort in conventional buildings or worse, suggesting the need for further research to reach more definitive conclusions. These results also reinforce the need to examine more closely the variations in performance across the different studies to better explain them. For the studies that used both physical measurements and occupant surveys, the results were surprisingly not always in line. Deuble & de Dear (2012) compared a mechanically ventilated green building to a naturally ventilated one and found that although the mechanically ventilated building performed better, occupants in the naturally ventilated one were more satisfied.

This shows the need to make the distinction between objective assessments of IEQ performance and subjective occupant perceptions of performance as those do not always match.

On the other hand, acoustics was found to be worse in six out of eight studies (e.g. Gou et al., 2013, Leaman et al, 2007). Lee Y. (2010) compared acoustics in five different office layouts in LEED buildings and found that high cubicle offices showed significantly lower levels of occupant satisfaction with acoustics, with low cubicle offices showing the lowest satisfaction levels of all. This dissatisfaction could be due to that fact that this aspect tends to be deemphasized, if not completely ignored in existing rating systems, reinforcing therefore the need for further research on it to improve its performance.

Given how the studies reviewed linked improved IEQ to improved satisfaction, comfort and performance, the research entailed reviewing results involving occupants. More than 90% of all occupants surveyed in these studies were satisfied with their green buildings' IEQ (e.g. Abbaszadeh et al., 2006 and Thatchera & Milner, 2012), showing high levels of consensus over occupants' perception of their indoor environment. Other studies noticed an improvement in occupants' well-being, productivity, and performance (e.g. Singh et al., 2010 and Issa et al., 2011). Despite some dissatisfaction from some occupants with some IEQ aspects (e.g. acoustics), occupants generally tended to forgive the inadequacies of their environments (Gou et al., 2013).

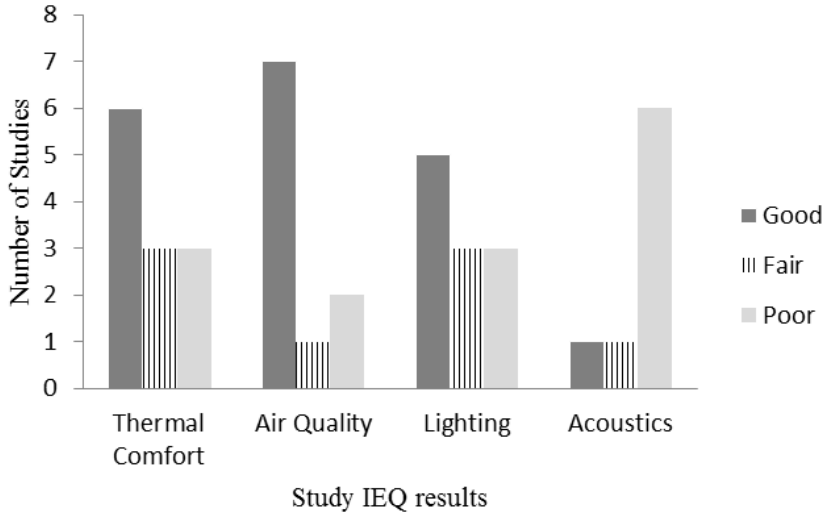

Figure 8. Distribution of research studies per IEQ results.

4 CONCLUSION

Despite the increasing interest in green buildings, there are only a few studies investigating their IEQ, and providing empirical evidence to their superiority over conventional buildings. This literature review showed how green building occupants tended to be on average more satisfied with thermal comfort and air quality than occupants in conventional buildings but largely dissatisfied with acoustics, highlighting the need for more research on acoustics.

This literature review also revealed the need to increase research in the field by analyzing larger samples of green buildings and using actual empirical data in the analysis. Larger-scale studies using on-site physical measurements are needed to reach consensus and allow researchers to draw broader conclusions about the green buildings' IEQ. There is also a need to focus on evaluating buildings other than office buildings to better understand how IEQ varies across different building types and industry sectors.

REFRENCES

Abbaszadeh, S., Zagreus, L., Lehrer, D. & Huizenga, C. 2006. Occupant Satisfaction with Indoor Environmental Quality in Green Buildings. *Proceedings of Healthy Buildings*, (pp. 365-370). Lisbon.

Baker, L. 2011. *Summary Report: Post-Occupancy Evaluation Surveys in K-12 Learning Environments.* UC Berkeley: Center for the Built Environment.

Beauregard, S.J., Berkland, S. & Hoque, S. 2011. Ever green: a post-occupancy building performance analysis of LEED certified homes in New England. *Journal of Green Building*.

Birt, B. & Newsham, J.R. 2009. Post-occupancy evaluation of energy and indoor environment quality in green buildings: a review. *3rd International Conference on Smart and Sustainable Built Environments*, (pp. 1-7). Delft, Netherlands.

Brager, G. & Baker, L. 2009. Occupant satisfaction in mixed-mode buildings. *Building research & Information 37(4)*.

CaGBC. 2013. Retrieved May 27, 2013, from Canada Green Building Council: http://www.cagbc.org/

Cladingboel et al. (2011). Six green stars in a warm tropical climate - William McCormack place phase 2 - case study.

Deuble, M.P. & de Dear, R.J. 2012. Green occupants for green buildings: The missing link? *Building and Environment 56*.

Gou, Z., Lau, S.S. & Jie Shen, J. 2012a. Indoor Environmental Satisfaction in Two LEED Offices and its Implications in Green Interior Design. *Indoor and Built Environment*.

Gou, Z., Lau, S.S. & Zhang, Z. 2012b. A Comparison of Indoor Environmental Satisfaction between Two Green Buildings and a Conventional Building in China. *Journal of Green Building, Volume 7, Number 2*.

Gou, Z., Prasad, D. & Lau, S.S. 2013. Are green buildings more satisfactory and comfortable? *Habitat International*.

Hoppe, P. 2002. Different aspects of assessing indoor and outdoor thermal comfort. *Energy and Buildings*, 661-665.

Issa, M.H., Rankin, J.H., Attalla, M. & Christian, A.J. 2011. Absenteeism, Performance and Occupant Satisfaction with the Indoor Environmental of Green Toronto Schools. *Indoor and Built Environment*, 511–523.

Kelting, S. & Montoya, M. 2011. Green Building Policy and School Performance. *Integrating Sustainability Practices in the Construction Industry.*

Konis, K. 2013. Evaluating daylighting effectiveness and occupant visual comfort in a side-lit open-plan office building in San Francisco, California. *Building and Environment 59*.

Kovesi, T., Gilbert, N.L., Stocco, C., Fugler, D., Dales, R.E., Guay, M. & Miller, J.D. 2007. Indoor air quality and the risk of lower respiratory tract infections in young Canadian Inuit children. *CMAJ. 177*(2):155-60.

Leaman, A., Thomas, L. & Vandenberg, M. 2007. 'Green' buildings: what Australian building users are saying? *EcoLibrium*.

Lee, Y. 2010. Office layout affecting privacy, interaction, and acoustic quality in LEED-certified buildings. *Building and Environment 45*.

Newsham, G., Birt, B., Arsenault, C., Thompson, L., Veitch, J., Mancini, S., Galasiu, A., Gover, B., Macdonald, I. & Burns, G. 2012. *Do green buildings outperform conventional buildings? Indoor environment and energy performance in North American offices.* National Research Council Canada.

Paul, W.L. & Taylor, P.A. 2008. A comparison of occupant comfort and satisfaction between a green building and a conventional building. *Building and Environment.*

Singh, A., Syal, M., Grady, S.C. & Korkmaz, S. 2010. Effects of Green Buildings on Employee Health and Productivity. *American Journal of Public Health*.

Thatchera, A. & Milner, K. 2012. The impact of a 'green' building on employees' physical and psychological wellbeing. *Work: A journal of Prevention, Assesment and Rehabilitation*.