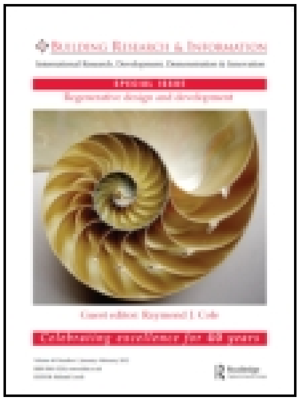

Building Research & Information

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/rbri20

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Published online: 13 May 2013.

To cite this article: Guy R. Newsham, Benjamin J. Birt, Chantal Arsenault, Alexandra J. L. Thompson, Jennifer A. Veitch, Sandra Mancini, Anca D. Galasiu, Bradford N. Gover, Iain A. Macdonald & Gregory J. Burns (2013) Do 'green' buildings have better indoor environments? New evidence, Building Research & Information, 41:4, 415-434, DOI: 10.1080/09613218.2013.789951

To link to this article: http://dx.doi.org/10.1080/09613218.2013.789951

BRI Building Research & Information, 2013
Vol. 41, No. 4, 415–434, http://dx.doi.org/10.1080/09613218.2013.789951
Routledge Taylor & Francis Group

RESEARCH PAPER

Do ‘green’ buildings have better indoor environments? New evidence

Guy R. Newsham[1], Benjamin J. Birt[2], Chantal Arsenault[1], Alexandra J. L. Thompson[1], Jennifer A. Veitch[1], Sandra Mancini[1], Anca D. Galasiu[1], Bradford N. Gover[1], Iain A. Macdonald[1] and Gregory J. Burns[1]

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A post-occupancy evaluation (POE) of 12 green and 12 conventional office buildings across Canada and the northern United States was conducted. Occupants (*N* = 2545) completed an online questionnaire related to environmental satisfaction, job satisfaction and organizational commitment, health and well-being, environmental attitudes, and commuting. In each building on-site physical measurements at a sample of workstations (*N*= 974) were taken, including: thermal conditions, air quality, acoustics, lighting, workstation size, ceiling height, window access and shading, and surface finishes. Green buildings exhibited superior performance compared with similar conventional buildings. Better outcomes included: environmental satisfaction, satisfaction with thermal conditions, satisfaction with the view to the outside, aesthetic appearance, less disturbance from heating, ventilation and air-conditioning (HVAC) noise, workplace image, night-time sleep quality, mood, physical symptoms, and reduced number of airborne particulates. A variety of physical features led to improved occupant outcomes across all buildings, including: conditions associated with speech privacy, lower background noise levels, higher light levels, greater access to windows, conditions associated with thermal comfort, and fewer airborne particulates. Green building rating systems might benefit from further attention in several areas, including: credits related to acoustic performance, a greater focus on reducing airborne particulates, enhanced support for the interdisciplinary design process and development of POE protocols.

Keywords: building performance, environmental assessment, green buildings, indoor environment, Leadership in Energy and Environmental Design (LEED), occupant satisfaction, post-occupancy evaluation

Il a été mené une évaluation après occupation (POE) de 12 immeubles de bureaux verts et 12 immeubles de bureaux classiques répartis à travers le Canada et le nord des Etats-Unis. Les occupants (*N* = 2545) ont rempli un questionnaire en ligne portant sur la satisfaction environnementale, la satisfaction au travail et l’implication organisationnelle, la santé et le bien-être, les attitudes environnementales, et les trajets réguliers. Dans chaque immeuble, des mesures physiques in situ sur un échantillon de postes de travail (*N* = 974) ont été effectuées, comprenant : les conditions thermiques, la qualité de l’air, l’acoustique, l’éclairage, la taille des postes de travail, la hauteur de plafond, l’accès aux fenêtres et leur occultation, et les finitions de surface. Les bâtiments verts ont affiché des performances supérieures par rapport aux bâtiments classiques similaires. De meilleurs résultats ont été obtenus concernant la satisfaction environnementale, la satisfaction à l’égard des conditions thermiques, la satisfaction à l’égard de la vue sur l’extérieur, l’aspect esthétique, la diminution des perturbations liées aux bruits provenant du chauffage, de la ventilation et de la climatisation (CVC), l’image du lieu de travail, la qualité du sommeil nocturne, l’humeur, les symptômes physiques, et la réduction du nombre de particules en suspension dans l’air. Différentes caractéristiques physiques ont conduit à une amélioration des résultats pour les occupants dans tous les immeubles, concernant notamment les conditions liées à la confidentialité des conversations, les niveaux inférieurs de bruit de fond, les niveaux de luminosité plus élevés, l'accès accru aux fenêtres, les conditions associées au confort thermique, et le nombre moindre de particules en suspension dans l'air. Les systèmes de notation des bâtiments verts pourraient bénéficier d'une plus grande attention apportée à plusieurs domaines, s'agissant en particulier des crédits relatifs aux performances acoustiques, d'un accent accru sur la réduction des particules en suspension dans l'air, d'un soutien renforcé en faveur du processus de conception interdisciplinaire et du développement de protocoles POE.

Mots clés: performances des bâtiments, bilan environnemental, bâtiments verts, environnement intérieur, Leadership in Energy and Environmental Design (LEED), satisfaction des occupants, évaluation après occupation

Introduction

At the time of writing, more than 3600 projects had been registered for LEED (Leadership in Energy and Environmental Design) certification by the Canada Green Building Council (CaGBC) (2012), and more than 32 000 commercial building projects had been registered for LEED certification by the US Green Building Council (USGBC) (2012a) since the introduction of the system in 1998. An increasing number of jurisdictions now require such certification for their own new buildings (*e.g.* Government of Manitoba, 2006; Treasury Board of Canada Secretariat, 2012), or new buildings in their region (San Francisco Department of Building Inspection, 2011). However, in most cases these buildings are judged on their 'greenness' at the time of their design, and there has been little follow-up to determine whether post-occupancy performance meets expectations.

Energy performance

All green building rating systems provide credits for energy-efficient design, and in most cases this is the largest credit category. Given the focus of this paper, prior research on green building energy performance is only briefly summarized. Most work has shown that green buildings do use less energy than conventional counterparts, but analysis has been limited by small sample sizes (Center for Neighborhood Technology, 2009; Newsham, Mancini, & Birt, 2009). A study based on one year of data from 100 LEED-certified commercial buildings in North America suggested that, on average, LEED buildings used 18–39% less energy than conventional counterparts, but many individual LEED buildings performed poorly. Further, measured energy performance had little correlation with the number of LEED energy credits achieved at design time (Newsham, Mancini, & Birt, 2009). Encouragingly, both the US and Canada Green Building Councils are placing additional emphasis on measured energy performance. In particular, certification under LEED EBOM (Existing Buildings: Operations & Maintenance) (USGBC, 2011) requires whole-year measured energy data to be submitted.

Indoor environment quality (IEQ)

There is abundant evidence that better indoor environments in office buildings are correlated with more satisfied occupants with higher levels of well-being, and thus to better outcomes for organizations (*e.g.* Newsham, Veitch, & Charles, 2008; Newsham *et al.*, 2009; Thayer *et al.*, 2010). However, there has been little formal investigation of whether green buildings specifically offer measurably better physical environments, and in turn if occupant environmental satisfaction, job satisfaction and health are benefitted.

Birt & Newsham's (2009) review concluded that, in general, occupants of green buildings had higher satisfaction with air quality and thermal comfort, whereas satisfaction with lighting showed little or no improvement. Conversely, there was a trend towards a decrease in acoustic satisfaction associated with green buildings. In North America, this might be a logical consequence of the prevailing LEED credit scheme, which offered credits for building design features such as low partitions to allow daylight to penetrate and allow views, and hard ceilings and floors to improve air quality. However. both these features have negative effects for acoustics (Bradley & Wang, 2001). This is compounded by the fact that no credits for acoustic performance existed. Subsequently, Singh, Syal, Grady, & Korkmaz (2010) conducted a pre-/post-study of people moving into two LEED buildings ($N = 56$ and 207, respectively) and found statistically significant improvements in asthma and depression symptoms, and perceived productivity.[1] In addition, Frontczak *et al.* (2012) reported that overall workspace satisfaction was higher in LEED buildings, based on survey data ($N > 40\ 000$) from more than 300 office buildings, of which around 50 were LEED certified. However, Gou, Lau, & Shen (2011) reported no difference in overall satisfaction with IEQ between two LEED offices and a sample of conventional offices in the same city, and called for more empirical studies of whether IEQ in green buildings is better from the occupants' perspective.

New post-occupancy evaluation (POE) research

Given the paucity of objective data in this domain, the goal of the current work was to collect comprehensive field study data, with a sample size and variety of outcomes not previously undertaken. The following hypotheses for green building performance, relative to conventional buildings, were developed:

- green buildings will produce higher ratings of occupant environmental satisfaction, except for ratings related to acoustics
- green buildings will produce higher ratings of occupant job satisfaction
- green buildings will produce higher ratings of occupant well-being
- green buildings will produce higher ratings of organizational commitment among employees
- green buildings will have lower levels of air pollutants
- green buildings will have temperatures closer to thermally neutral
- green buildings will have lighting conditions closer to recommended practice, and provide more access to daylight
- speech privacy will be lower in green buildings
- background noise levels will be higher in green buildings

Methods and procedures

The POE approach, described below, was approved by the research team's Research Ethics Board. For brevity, the approach is summarized in this paper; full details are available in Newsham *et al.* (2012).

Study buildings

Building pairs were sought, one green and one conventional, that were as similar as possible (*e.g.* of the same size and age, in the same climate zone, with the same owner, employer, and occupants doing similar work).[2] This provides confidence that any differences in the measured outcomes are due to 'greenness' rather than other factors. Table 1 shows summary physical characteristics of the buildings; Table 2 shows summary demographic characteristics of the occupants. Building pairs were closely matched on most criteria, and no obvious biases with respect to green buildings were observed.[3] Perfect matching is never possible in any practical sample of real buildings, and due to the historically recent development of the sustainable buildings movement, green buildings do tend to be newer than non-green buildings. This was controlled for as well as was practical given that matching the buildings on other factors was simultaneously desirable. A much larger sample of buildings would be necessary to examine the effect of age or any of the other matching characteristics.

On-site physical measurements

Physical measurements reported in this paper were made using a custom-built integrated sensor platform, referred to colloquially as the 'NICE Cart' (National Research Council Indoor Climate Evaluator) (Figure 1).

The NICE Cart was a mobile platform used to take a detailed snapshot of indoor environment conditions over a 10–15 min period at representative locations within a building. These measurements included temperature (at 0.1, 0.7, 1.1 and 0.9 m from the ground),[4] air speed (0.1, 0.7 and 1.1 m), relative humidity (RH) (0.9 m), formaldehyde (0.9 m), CO_2 (0.9 m), carbon monoxide (CO) (0.9 m), respirable particles (0.9 m), illuminance (desktop and cubic at 1.25 m), and luminance and sound pressure (third-octave bands). Cart-based measurements were made during normal working hours, in at least 25 office locations per site. Photographs for luminance mapping via high dynamic range photography (*e.g.* Inanici, 2006) were centred on the computer screen in an office, and taken from a distance to include surrounding surfaces. The remaining measurements were made with the cart at the location of a seated occupant (Figure 2). The researcher manually recorded other workstation characteristics, including the height of walls; length and width of the workstation; ceiling height; floor, ceiling and wall finishes; lighting type; distance to a window, window orientation, sky condition, and whether the window was open; distance to the printer/copier; shade type, opacity, and position. Supplementary information was also collected at a smaller set of representative locations, including photographs; furniture type; ceiling plan; and reflectance measurements of all major surfaces; luminaire and lamp type; air supply/return location; and window and shading type.

A structured interview with the building manager/operator was conducted to gather information on the following topics: building size and age; number and type of occupants; heating, ventilation and air-conditioning (HVAC) system type and operation; lighting system type and operation; use of sound masking; the complaint handling procedure; availability of energy data; occupant transportation options; major retrofits; and the availability of green building certification documents (if applicable).

Occupant questionnaire

All occupants at the study sites were invited to complete a confidential on-line questionnaire.

Table 1 Summary of the features of the study buildings

Site code letter	Type	Certificate (target/ obtained)	Distance apart (km)	Sector	Setting	CBECS Climate Zone[a]	Age	Size (m^2)	Interior layout	Measured dates	Number of survey responses (%)	Number of cart measures	Notes
A	Green	LEED Silver		Provincial government	Urban	1	1965 (LEED renovated 2009)	14 400	Mostly private	May 2010	160 (41)	53	
B	Conventional		260	Provincial government	Urban	1	1976	18 500	Mostly private	May 2010	147 (26)	41	
C	Conventional		4	Provincial government	Urban	1	1963	13 500	Mostly open	November/ December 2010	112 (33)	45	
D	Green	LEED Platinum		Provincial government	Urban	1	1968 (LEED renovated 2009)	3500	Mostly open	November/ December 2010	35 (29)	25	Two floors in a larger building
F	Green	LEED Platinum	1	Private, multi-tenant	Urban	2	2006	17 300	Two-thirds open	October/ November 2010	94 (49)	46	
G	Conventional			Private, multi-tenant	Urban	2	2000	9900	Two-thirds open	October/ November 2010	50 (47)	50	
H	Green	LEED Gold	1	State government	Suburban	1	2009	5100	Mix of open and closed	October/ November 2010	47 (39)	49	
I	Conventional			Federal government	Suburban	1	1978	26 500	Two-thirds open	October/ November 2010	266 (48)	38	Designed for high energy efficiency when built
J	Green	LEED Gold	16	Non-profit	Ex-urban	1	2007	2000	Mostly open	November 2010	43 (73)	26	
K	Conventional			University administration	Suburban	1	1967	7700	Mix of open and closed	January 2011	125 (40)	41	
LNP	Conventional		1	University departments	Suburban	3	1959, 1997, 1997	1300, 3900, 1300	Mix of open and closed	March 2011	56 (40)	47	Three small buildings on the same site
MOQ	Green	Various		University departments	Suburban	3	1996, 2005, 2000	2400, 6000, 1500	Mix of open and closed	March 2011	80 (20)	74	Three small buildings on the same site, one LEED Gold, others deemed green without a certificate
R	Conventional		3	Federal government	Urban	1	1958	10 500	Mostly open	June 2011	67 (30)	47	
X	Green	Go Green Plus		Federal government	Urban	1	1956 (renovated 1996)	38 500	Mix of open and closed	October 2011	242 (36)	69	
S	Green	LEED Platinum	5	Federal government	Urban	1	2009	4700	Open	June 2011	115 (42)	59	Three floors in a larger building
W	Conventional			Federal government	Urban	1	2003	20 000	Open	October 2011	273 (37)	69	
T	Green	LEED Gold	55	Private	Suburban	1	2008	27 900	Open	August/ September 2011	211 (31)	70	
UV	Conventional			Private	Suburban	1	1994, 1998	7400, 7400	Open	August/ September 2011	250 (38)	70	Two buildings on the same campus
E	Conventional			Provincial government	Urban	1	1967	21 600	Closed	October 2010	187 (35)	58	No pair, expected renovation did not occur as originally scheduled

Notes: Buildings are listed in pairs, with pairs separated by background shading. Building E, which had no pair, is listed at the bottom with a different background shading. CBECS = Commercial Buildings Energy Consumption Survey.
[a]1 = HDD65F > 7000; 2 = HDD65F 5500–7000; 3 = HDD65F 4000–5500.

Table 2 Demographic information for the occupants of the study buildings who completed the questionnaire

Site code letter	Type	Sex (%)		Age (%)					Job type				With current employer (years)					Highest education level (%)					Task split (%)
		F	M	18–29	30–39	40–49	50–59	60+	Administrative	Technical	Professional	Managerial	0–5	6–10	11–15	16–20	20+	Secondary/ high school	College/ technical	University bachelor's	Bachelor's degree	Graduate/ doctorate	Computer/ quiet work
All buildings		63	37	12	26	29	27	6	28	13	45	14	46	19	12	7	17	7	13	13	37	30	57
A	G	66	34	13	25	25	35	3	36	8	40	16	35	18	9	9	29	13	18	18	31	20	56
B	C	78	22	15	26	25	28	6	29	5	52	14	43	15	15	5	21	6	23	12	44	16	45
C	C	73	27	5	44	25	21	5	10	3	79	8	51	24	6	8	11	3	4	8	32	54	60
D	G	76	24	15	41	24	21	0	14	0	77	9	74	15	3	3	6	3	3	6	31	57	54
F	G	60	40	18	34	22	20	5	27	18	37	18	55	12	18	2	13	9	11	26	40	15	50
G	C	54	46	12	24	43	12	8	27	2	67	45	47	22	14	8	8	2	8	12	45	33	60
H	G	36	64	32	19	26	15	9	22	43	26	9	78	18	0	2	2	0	4	19	28	49	60
I	C	44	56	6	14	30	37	13	18	24	49	9	46	14	9	14	18	2	9	18	42	28	56
J	G	59	41	20	32	22	27	0	19	36	24	21	45	19	12	7	17	0	17	2	63	17	54
K	C	65	35	6	28	31	28	6	41	22	14	23	40	32	6	4	19	6	17	17	43	17	61
LNP	C	74	26	15	25	20	33	7	25	2	60	13	47	15	9	5	24	2	0	4	38	57	44
MOQ	G	65	35	21	34	23	16	6	29	10	49	12	66	16	5	4	9	1	3	8	19	70	60
R	C	55	45	23	25	23	23	6	20	17	54	9	63	17	8	6	6	9	5	6	20	60	63
X	G	70	30	15	30	32	21	2	35	5	47	13	52	19	14	6	8	12	20	9	21	38	62
S	G	67	33	24	32	21	18	5	23	0	53	24	78	12	2	2	7	6	10	6	37	42	58
W	C	63	37	8	22	36	29	6	45	3	36	16	42	18	11	5	24	15	17	9	33	26	60
T	G	51	49	9	18	29	35	9	16	32	39	13	25	14	23	8	30	7	5	21	50	18	56
UV	C	75	25	9	30	35	21	5	33	18	37	11	44	29	20	4	2	8	15	17	43	17	60
E	C	68	32	9	26	28	32	5	26	5	49	19	27	22	10	11	30	8	14	13	37	29	59

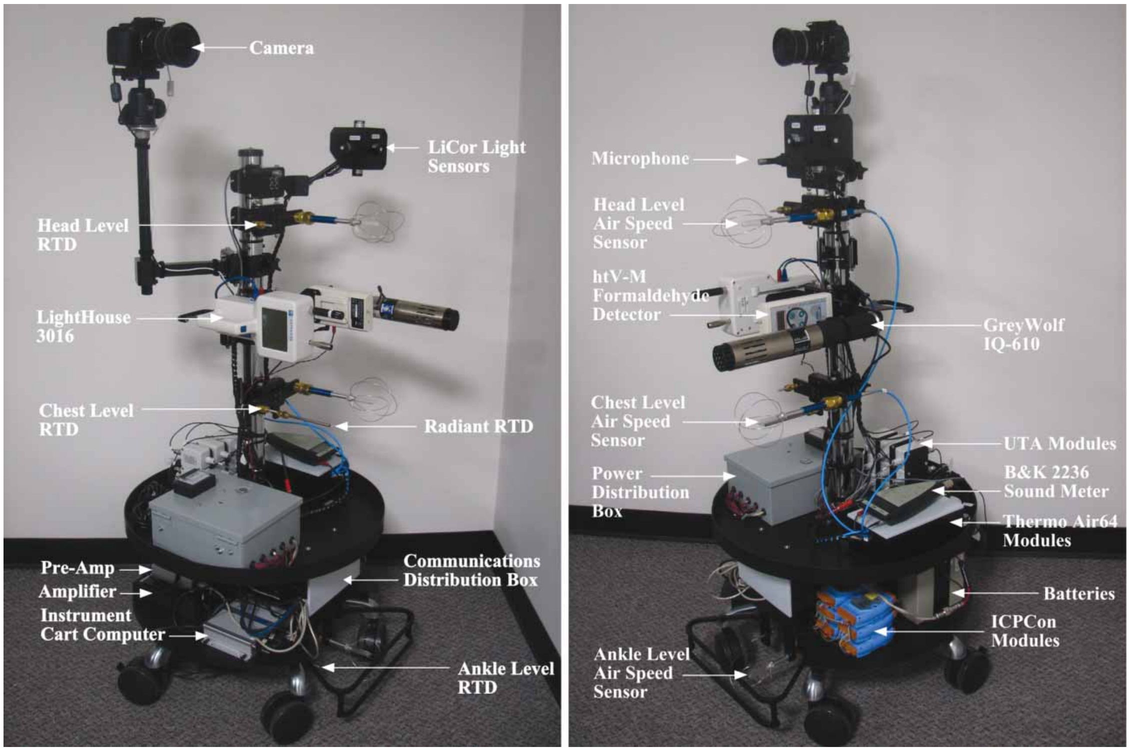

Figure 1 NICE Cart (height about 1.5 m) showing sensors and other system components

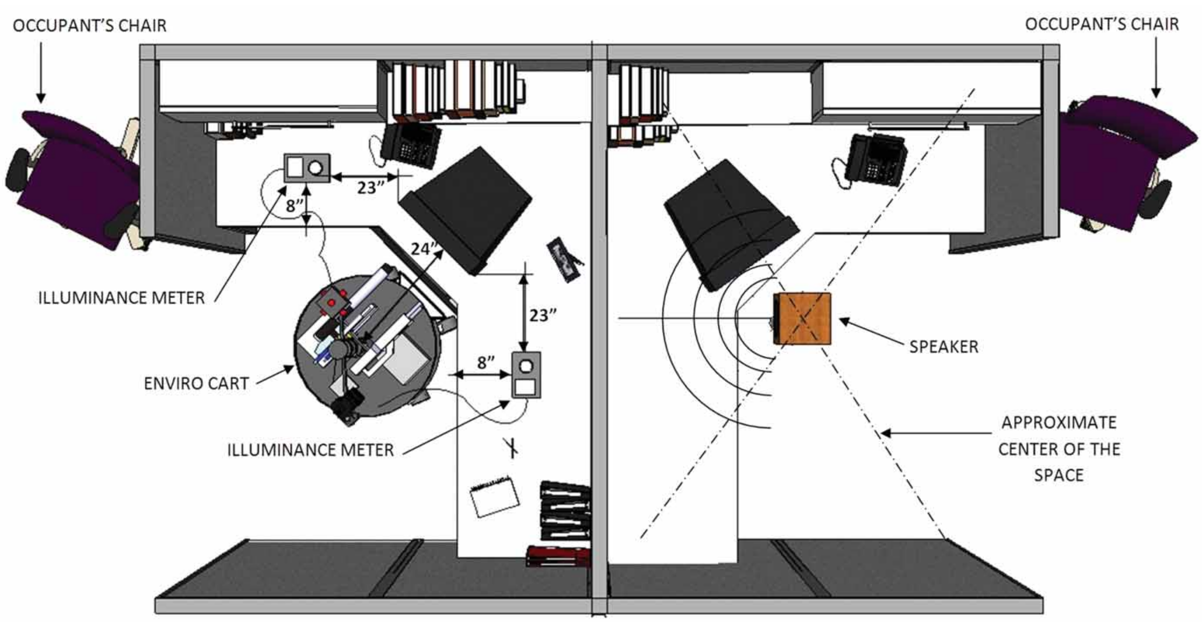

Figure 2 Schematic diagram of cart location during the majority of the measurement procedure

Questionnaire items addressed elements that green buildings are said to improve. The questionnaire was available in both English and French, where appropriate. The questionnaire was organized into seven modules; Table 3 gives a brief description of each module. All respondents were asked to complete the core module; they were then presented with two of the six other modules, randomly assigned. This approach was taken to keep the time burden reasonable for respondents, while preserving a valid sample

Table 3 Summary description of the questionnaire modules and number of responses for each module

Module	Number of items	Description	*N*
Core	35	Environmental and job satisfaction, demographics, job demands	2545
1	16	Organizational commitment, workplace image, internal communications	843
2	11	Acoustics	880
3	14	Thermal comfort	865
4	34	Chronotype, sleep quality, positive/negative feelings (affect)	876
5	13	Health	828
6	25	Commuting, environmental attitudes	798

size. The large majority of questionnaire items had been validated in prior studies, and are briefly described below.

Core module

The Environmental Features Rating (EFR) included items on 18 aspects of the work environment, scored on a seven-point scale from 1 (very unsatisfactory) to 4 (neutral) to 7 (very satisfactory), based on Stokols & Scharf (1990). Veitch, Charles, Farley, & Newsham (2007) demonstrated that the items formed a stable three-factor structure to create subscale scores for satisfaction with lighting (Sat_L), with ventilation and temperature (Sat_VT), and with privacy and acoustics (Sat_AP). Overall Environmental Satisfaction (OES) was the mean of two items on a seven-point scale, related to the effect on personal productivity, and satisfaction as a whole. A single-item measure of overall job satisfaction was used, based on Dolbier, Webster, McCalister, Mallon, & Steinhardt (2005), using the same scale as the EFR. Job demands were rated using the mean of four items (Lowe, Schellenberg, & Shannon, 2003), scored on a seven-point scale. Participants were asked to report their sex, age, job type, type of computer monitor, education, years of work experience and education. Participants were also asked to report the proximity of their workstation to a window to the outside; and the percentage of time at work spent doing various activities (Brill & Weidemann, 2001).

Module 1 (Relationships between the occupant and the organization)

The average of a six-item scale of affective organizational commitment was used (Meyer, Allen, & Smith, 1993) with a value from 1 to 7 (a higher score indicating greater commitment). Intent to turnover (leave the present employer voluntarily) was the average of a three-item scale developed by Colarelli (1984) with a value from 1 to 7 (a higher score indicating a greater likelihood to turnover). The Workplace Image scale was based on questions used by workplace design consultants (Laing, 2005); the average of three items had a value from 1 to 7 (a higher score indicating a better image). The four-item Communication and Social Support scale from Lowe *et al.* (2003) was used; the composite scale score was the average of the four items, with a value from 1 to 7 (a higher score indicating better communications).

Module 2 (Acoustics)

Eleven questions were developed for this study by members of the research team with acoustics expertise. Subscales were constructed from items related to speech privacy (Speech) and non-speech sounds (Non-speech), and speech privacy related only to overheard speech (Speech2). The subscales had values of 1 to 7, with a higher score indicating more disturbance.

Module 3 (Thermal comfort)

Individual thermal sensation items related to winter, summer and present conditions were scored on a seven-point scale from 1 (cold) to 4 (neutral) to 7 (hot). McIntyre's (1980) single-item thermal preference scale was also used. Further questions asked about frequency of adaptive responses used by occupants (Barlow & Fiala, 2007; Bordass, Leaman, & Willis, 1994; Brown & Cole, 2009; Huizenga, Abbaszadeh, Zagreus, & Arens, 2006): hot/cold drink, portable heater, portable fan, change thermostat, add/remove clothing, open/close window, adjust window shading, with response options coded from 1 (Never) to 7 (Several times per day). From these four subscales were created, taking the mean of actions that would use additional energy (Adap_Energy), would use no energy (Adap_NoEnergy), actions that affected the person only (Adap_Person), and actions that affected the indoor environment more generally (Adap_Enviro). Participants were also asked whether they had complained to a facility manager or supervisor in the current season about the thermal conditions or air quality in their workstation. Finally, participants were asked to indicate the clothing typically worn in their office in the current season, based on American

Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55 (ASHRAE 2004). This was used to estimate clothing insulation value, in clo units.

Module 4 (Effects of light exposure)

The Chronotype scale developed by Di Milia, Wikman, & Smith (2008) was used; the composite scale score was the sum of the six items with a value from 0 to 4 (a higher score indicating a preference for activity later in the day). The Groningen Sleep Quality Scale (Leppämäki, Meesters, Haukka, Lönnqvist, & Partonen, 2003) was used; the composite score was the sum of 14 individual true/false questions with a value from 0 to 14 (a higher score indicating more sleep problems). A scale by Diener *et al.* (2010) gauged mood (affect). Participants were asked to report how much they experienced each of 12 feelings (six positive and six negative). The individual items were scored from 1 (Very rarely or never) to 5 (Very often or always). Scores for positive and negative feelings were the sum of the associated items, and an affect balance score was the positive score minus the negative score. Participants with access to a window were asked to rate the view on an 11-point scale.

Module 5 (Health symptoms)

Visual discomfort was measured using a version of the scale developed by Wibom & Carlsson (1987). More general physical discomfort measures were adapted from the literature (*e.g.* Hedge, Erickson, & Rubin, 1992) and placed in the same format. A mean frequency for both visual and physical discomfort (VCF, PCF) was constructed, from 1 (Never) to 5 (Daily), and a mean intensity for each (VCI, PCI), from 1 (None) to 5 (Very uncomfortable). An overall discomfort score was the mean value of the frequency multiplied by intensity (VCOMF, PCOMF). Participants were asked to report on the number of work days missed in the past month (from 0 to 5+) due to personal illness, and due to any reason.

Module 6 (Transportation; environmental attitudes)

Participants were asked to report all modes of transport used to get to work, how often they used a mode, how long the journey took, and their reason for using this mode (Gardner, 2009; Gardner & Abraham, 2008; Verplanken, Walker, Davis, & Jurasek, 2008). The New Environmental Paradigm (NEP) Scale (Dunlap, van Liere, Mertig, & Emmet-Jones, 2000) was used; the composite NEP score was the average of the 15 items, with a value from 1 to 5 (a higher score indicating higher environmental concern).

Procedure

The month and year of each building visit is shown in Table 1. The NICE Cart measurements, supplementary physical data and interviews were collected over two to four days at each building. Typically, the first invitation to the on-line questionnaire was sent a few days before the site visit. Reminders were sent after one and two weeks; the questionnaire was closed a week after the final reminder.

Results

Statistical methods

Wilcoxon signed ranks tests were used to compare the performance of green versus conventional buildings on building-level average data. For each outcome the difference between paired buildings is calculated, and a statistic based on the number of differences favouring one building type, and the magnitude of the differences, was calculated. This is a non-parametric test, which is favoured over the corresponding parametric test (a paired *t*-test) when sample normality is difficult to establish or not expected (Siegel & Castellan, 1988). Moschandreas & Nuanual (2008) followed this approach for their green building study. Following these analyses univariate linear regression was used to evaluate the relationships between physical measurements and survey outcomes, again measured at the building level, regardless of the building type and pairing.

The results of statistically significant tests only are presented in tables in this section, and it is only these that are considered in interpreting study findings. Means for green and conventional buildings are reported in the text even when differences were not statistically significant, but only to illustrate the general conditions in the study buildings. Table A1 in Appendix A contains descriptive statistics of the primary variables collected via the questionnaire and NICE Cart.[5]

Conventionally, tests are considered statistically significant if $p \leq 0.05$. However, if an effect is expected in a specific direction, one can use the one-tailed p-value (half the two-tailed value) (Siegel, 1956). The hypotheses provided these expectations. Thus, outcomes of the Wilcoxon analyses may be statistically significant with two-tailed $p \leq 0.10$, provided the trend is in the hypothesized direction.

Green versus conventional buildings

Survey outcomes

Table 1 reports the number of completed questionnaires, and the associated response rates, at each site. Response rates across sites ranged from 20% to 70% (mean of 39%); response rates for similar on-line surveys in other recent studies fell within the range of response rates in the current study (Lee, 2011;

Table 4 Results of the Wilcoxon signed ranks test related to survey outcomes, and related means of building-level means for each building type

	Ranks		Sum of ranks				Mean rating	
Outcome	**Positive**	**Negative**	**Positive**	**Negative**	**Z**	**p**	**Green**	**Conventional**
Core module								
OES	8	1	42	3	−2.31	0.021	4.55	4.01
SatVT	8	1	44	1	−2.55	0.011	4.75	3.95
Aesthetic appearance ...	9	0	45	0	−2.67	0.008	5.55	4.34
Size of personal workspace ...	7	2	42	3	−2.31	0.021	5.44	4.80
Access to a view of outside ...	8	1	38	7	−1.84	0.066	5.18	4.58
Module 1								
Workplace image	9	0	45	0	−2.67	0.008	4.86	3.96
Module 2								
Noise from heating, ventilating and cooling systems?	1	8	5	40	−2.07	0.038	2.28	2.96
Module 3								
Prefer change in thermal conditions	2	7	8	37	−1.72	0.086	0.40	0.49
Adap.Energy	2	7	4	41	−2.19	0.028	1.47	1.93
Adap.NoEnergy	2	7	3	42	−2.31	0.021	2.83	3.12
Adap.Enviro	1	8	1	44	−2.55	0.011	1.53	1.95
Module 4								
Sleep quality at night	0	9	45	0	−2.67	0.008	3.99	4.85
Affect balance	6	3	39	6	−1.96	0.051	8.64	7.49
Module 5								
Visual discomfort frequency	2	7	7	38	−1.84	0.066	2.13	2.48
Physical discomfort frequency	3	6	6	39	−1.96	0.051	2.35	2.60

Note: Using OES as an example, 'Positive/negative' indicates that of the nine building site pairs, in how many cases did the green buildings have higher ratings (in this case better performance)? 'Sum of ranks' is the total of the positions after rank ordering the magnitudes of the rating differences between buildings. For example, OES has one negative rank, with a sum of negative ranks of 3, meaning that the negative rank was the third smallest absolute difference.

Monfared & Sharples, 2011). Table 4 shows the results of the statistically significant tests related to survey outcomes.

Core module

- *Job demands*

The results show no statistically significant difference between the building types, confirming (as desired) that similar work was being done across buildings. The building-level means for the green and conventional buildings were 4.28 and 4.47, respectively.

- *Environmental satisfaction*

OES was neutral for conventional buildings, but significantly higher for green buildings. For the individual EFR sub-scales, green buildings rated significantly higher for Sat_VT; overall, Sat_VT was neutral for conventional buildings, but above neutral for green buildings. There were no significant differences for Sat_L or Sat_AP. Mean values indicated a high overall level of satisfaction with lighting conditions (Sat_L, green = 5.36; conventional = 5.05), and overall impressions of acoustics and privacy on the satisfied side of neutral (Sat_AP, green = 4.43; conventional = 4.16). Tests on individual EFR items show some significant effects. Overall, building occupants were satisfied with the aesthetic appearance of their office and the size of their workspace, but ratings were significantly higher for green buildings. Similarly, building occupants were satisfied with their access to a view, but ratings were significantly higher for green buildings.

- *Job satisfaction*

  Job satisfaction was very high for both building types (green = 5.72; conventional = 5.57), with no statistically significant difference.

Module 1 (Relationships between the occupant and the organization)
Overall means indicated a high level of organizational commitment (green = 4.81; conventional = 5.00), low intent to turnover (green = 2.77; conventional = 2.71), and a very high level of satisfaction with internal communications (green = 5.73; conventional = 5.68), with no statistically significant differences between building types. Overall, workplace image was neutral for conventional buildings, but significantly higher for green buildings.

Module 2 (Acoustics)
For the individual items there was only one statistically significant effect: noise from HVAC systems was considered less disturbing in green buildings, although the rating was below the mid-point of the scale in both building types. There were no statistically significant effects on the subscales. Overall means indicated disturbance from non-speech sounds (Non-speech) below the mid-point of the scale (green = 2.56; conventional = 2.68), and concerns with speech privacy (Speech) above the mid-point of the scale (green = 4.71; conventional = 4.62).

Module 3 (Thermal comfort)
Thermal sensation items were re-coded in terms of distance from the middle of the scale. There were no statistically significant differences between building types. To take immediate thermal sensation as an example, overall means indicated an average distance from thermally neutral of about one scale unit (green = 0.88; conventional = 1.04).

For thermal preference the fraction of respondents preferring anything other than the current conditions was calculated. There was a statistically significant effect: occupants of green buildings were less likely to prefer a change (40% versus 50% of conventional building occupants).

For the thermal adaptation sub-scales there were three statistically significant effects, consistent in showing that green building occupants took fewer actions to secure their thermal comfort. There was no reason to believe that adaptation opportunities (*e.g.*, clothing changes, use of portable heaters, having a hot or cold drink) were fewer in green buildings, so these results suggest that green building occupants felt less need to exercise such opportunities, and were thus more thermally comfortable in general.

Module 4 (Effects of light exposure)
There were no differences between building types on chronotype (means, green = 9.84; conventional = 9.72), another confirmation that the building populations were similar. For occupants with a view to the outside, there was no difference between building types on rated view quality (green = 7.22; conventional = 7.11). Overall, occupants indicated modest sleep issues, and an overall positive mood; however, occupants of green buildings experienced significantly better sleep quality (fewer problems) and more positive feelings.

Module 5 (Health symptoms)
Both visual and physical symptom frequency were statistically significantly lower in green buildings, though occurring less than weekly for both building types. There was no effect of building type on visual (means, green = 1.87; conventional = 2.09) or physical (means, green = 2.19; conventional = 2.33) symptom intensity, means suggested relatively low intensity of discomfort. There was also no effect on days away from work for personal illness (means, green = 0.50; conventional = 0.60), or for any reason (means, green = 1.81; conventional = 1.86). The personal illness rates compare to the overall Canadian average for full-time workers in 2009 of 0.65 per month (Statistics Canada (StatCan), 2011).

Module 6 (Transportation; environmental attitudes)
No statistically significant difference in commuting distance was found (means, green = 18.1 km; conventional = 17.8 km), though the means were about double the Canadian median (Statistics Canada (StatCan), 2009).

No statistically significant difference in environmental attitudes was found (means, green = 3.67; conventional = 3.65). This is further confirmation that the building populations were similar and that the occupants of green buildings in the sample were not unusually motivated or biased (Monfared & Sharples, 2011).

NICE Cart outcomes
All analyses included tests for all workstation types combined, but for some variables tests for open-plan and private offices were conducted separately, as were some tests for windowed and non-windowed offices. For these latter tests, only building pairs in which there were at least ten measured workstations in each category for both buildings in the pair were included. Table 5 shows the results of the statistically significant tests.

Enclosure
This category included: average and minimum height of walls, floor area, and ceiling height. There were no

Table 5 Results of Wilcoxon signed ranks test related to cart outcomes, and related means of building-level means for each building type

	Ranks		Sum of ranks				Mean rating	
Outcome	Positive	Negative	Positive	Negative	Z	p	Green	Conventional
AI (private offices)	4	1	14	1	−1.75	0.080	0.17	0.15
Air speed (m/s) at head level	1	8	7	38	−1.84	0.066	0.106	0.122
Air speed (m/s) at chest level	2	7	6	39	−1.96	0.051	0.112	0.129
Number of particles ≥ 0.5 μm	2	7	8	37	−1.72	0.086	1782	6298
Number of particles ≥ 5 μm	3	6	8	37	−1.72	0.086	92	117
PM10 ($\mu g/m^3$)[a]	2	7	7	38	−1.84	0.066	21	29

Note: [a]Assuming a particle specific gravity (density) of 2800 kg/m^3, following the method of Levy, Houseman, Ryan, Richardson & Spengler (2000).

statistically significant differences on these variables. Using open-plan space as an example, overall mean values were: height of walls/partitions: green = 1.8 m, conventional = 1.74 m; workstation area: green = 6.64 m^2, conventional = 6.83 m^2; and ceiling height: green = 3.07 m, conventional = 2.95 m.

Sound

AI (Articulation Index), the ASTM standard for speech privacy (ASTM International, 2008), was calculated. A-weighted background noise (AW) was also examined. A statistically significant effect related to AI in private offices was found: green buildings performed slightly worse, although private offices in both building types, on average, were at or close to the level recommended for offices (0.15). AI in open-plan offices was poor in both building types (AI mean, green = 0.42; conventional = 0.38), and background noise, which may help to mask speech sounds, was relatively low (AW mean, green = 42.6 dBA; conventional = 43.1 dBA).

Lighting

The analysis was focused on desktop illuminance (the mean of two measurements per desk). The fraction of measurements per building below 300 lux and the fraction above 500 lux was derived, representative of typical recommendations that prevailed during the past two decades (American National Standards Institute/Illuminating Engineering Society of North America (ANSI/IESNA), various years). There were no statistically significant effects. For offices without windows, there were substantial numbers of workstations with illuminances outside of recommended practice (below: green = 0.37; conventional = 0.46; above: green = 0.24; conventional = 0.21). As expected, for offices with windows, there were fewer instances of illuminances below recommended practice (green = 0.15; conventional = 0.26), and more instances of illuminances above recommended practice (green = 0.61; conventional = 0.53). Illuminances above recommended practice might represent the potential for energy savings, depending on the lighting design and available control options.

Thermal conditions and air quality

Fanger's thermal comfort indices, PMV (predicted mean vote) and PPD (predicted percentage dissatisfied) (ASHRAE, 2004), were calculated for each cart measurement location. Air temperature and air velocity measured at chest level, and measured RH and radiant temperature were used, along with the reported building-level mean clothing insulation level (0.71–0.98 clo); the typical office metabolic activity level of 1.2 met was assumed. Separate tests on air speed were also conducted. For air quality metrics,[6] tests on particulates, total volatile organic compounds (TVOC) and CO_2 were conducted.

There was a statistically significant difference for air speed at both the head and chest level. The air velocity in green buildings tended to be lower. While very low air speeds can be interpreted as stagnant and problematic, the mean air speeds observed in this study were above the level where this would be a concern, and such that lower air speeds were positive because there was a lower draught risk. Nevertheless, ASHRAE Standard 55 (ASHRAE 2004) suggests that there is little draught risk below (approximately) 0.16 ms^{-1}, and in this regard both sets of buildings performed well, on average. The thermal comfort indices suggested that thermal conditions in both sets of buildings were good (PPD mean, green = 6.1%; conventional = 6.7%, standards are typically based on achieving average values below 10%; ASHRAE, 2004).

There were statistically significant differences related to particulates: on average, green buildings had lower particulate levels. Respirable particles in this size range have been associated with negative health outcomes (Health Canada, 1989). In the US the most

Table 6 Results of linear regression analysis related to acoustics

Dependent variable	Independent variable	R^2_{adj}	F	Constant	B (slope)
Sat_AP	AI	0.26	7.16	5.04	−2.36
Speech (disturbance)	AI	0.48	17.83	3.30	4.26
Speech (disturbance)	AI (private offices only)	0.38	8.33	3.58	5.20
Speech2 (disturbance)	AI	0.45	15.76	3.27	3.84
Speech2 (disturbance)	AI (private offices only)	0.48	12.22	3.35	5.94
Speech (disturbance)	Fraction Open	0.26	7.18	3.92	1.10
PCF	Fraction Open	0.28	7.81	2.83	−0.534
Absence (any reason)	AW	0.20	5.39	−2.65	0.050
Absence (any reason)	AW (open-plan offices only)	0.18	4.53	−0.509	0.055

stringent regulations require the mass of particulates ≤ 10 μm in diameter (PM10) to be less than 50 μg/m^3 for 1 year and less than 150 μg/m^3 for 24 h (US Environmental Protection Agency (USEPA), 2012), and in this regard both building types performed well. The average CO_2 concentrations in both building sets were well below the limits presented in ASHRAE Standard 62.1 (ASHRAE 2007) of 700 ppm above outdoor ambient levels (CO_2 mean, green = 628 ppm; conventional = 651 ppm).

Regressions across all buildings

Variable pairs were chosen based on theoretical expectations of a relationship to test individual physical conditions as potential influences on occupant outcomes. Both the predictor and outcome variables were averages over building sites. For these analyses no distinction was made between green and conventional buildings, and thus the sample size was expanded by including Building E ($N = 19$).

Sound

Table 6 shows that satisfaction with acoustics and privacy declined as AI increased. AI had a stronger negative effect on disturbance from speech sounds, as might have been expected; this relationship is illustrated in Figure 3. However, the effects of the acoustic environment extended beyond outcomes related directly to satisfaction with noise. Higher A-weighted noise was associated with more frequent absence from work. This is consistent with research on office noise and stress (Evans & Johnson, 2000).

Lighting

A variety of positive outcomes were associated with higher light levels (Table 7).[7] However, the effects of the lighted environment extended beyond outcomes related directly to satisfaction with lighting. OES and physical comfort also improved with higher light levels. It is interesting that lighting effects on physical comfort were observed, but not on visual comfort. Prior studies have shown that poor lighting may lead to the adoption of compensatory, but un-ergonomic, postures (Heerwagen & Diamond, 1992; Rea, Ouellette, & Kennedy, 1985). Further, absence from work was lower in buildings where occupants had greater access to windows from their desks. Windows, in addition to the well-documented multiple benefits of view (Farley & Veitch, 2001), are also generally associated with higher light levels.

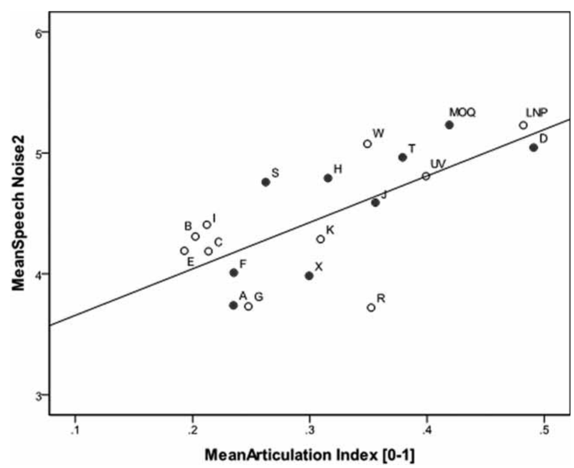

Figure 3 Rated disturbance from speech sounds versus measured articulation index (building-level means). The best-fit linear regression line is shown ($R^2_{adj} = 0.45$). Green buildings are shown with filled symbols

Thermal conditions and air quality

Satisfaction with ventilation and temperature increased the closer PMV was to neutral (or PPD was to zero), and the further physical thermal conditions were from predicted neutrality the more frequently building occupants took actions to improve their thermal comfort (Table 8). However, the effects of the thermal environment extended beyond outcomes

Table 7 Results of linear regression analysis related to lighting

Dependent variable	Independent variable	R^2_{adj}	*F*	Constant	*B* (slope)
Sat_L	IllumCubeFront (H removed)	0.19	4.89	4.65	0.002
Sat_L	IllumCubeLeft (H removed)	0.28	7.55	4.73	0.001
Sat_L	IllumCubeBottom (H removed)	0.18	4.73	4.75	0.004
OES	IllumCubeLeft	0.21	5.88	3.80	0.001
OES	IllumDeskRight	0.17	4.68	3.83	0.001
PCI	IllumCubeFront	0.16	4.44	2.51	−0.001
PCI	IllumCubeLeft	0.26	7.18	2.52	−0.001
PCI	IllumCubeLeft (H removed)	0.20	5.30	2.53	−0.001
PCI	Luminance above Monitor	0.22	6.00	2.45	−0.002
PCOMF	IllumCubeLeft	0.21	5.85	7.97	−0.003
PCOMF	IllumCubeLeft (H removed)	0.24	6.31	8.24	−0.004
Absence (any reason)	IllumOutsideRecommend	0.18	5.00	2.72	−1.29
Absence (any reason)	Fraction Windows in WS	0.16	4.43	2.16	−0.605
Absence (any reason)	Fraction Windows in WS/Next	0.19	5.34	2.27	−0.674

Table 8 Results of linear regression analysis related to thermal conditions and air quality

Dependent variable	Independent variable	R^2_{adj}	*F*	Constant	*B* (slope)
Sat_VT	PMV (abs. from neutral)	0.21	5.79	5.28	−0.504
Sat_VT	PPD	0.22	6.16	6.20	−0.301
Adap_Energy	PMV (abs. from neutral)	0.18	4.82	1.11	3.24
Adap_NoEnergy	PMV (abs. from neutral)	0.17	4.60	2.36	3.19
Adap_Enviro	PMV (abs. from neutral)	0.22	5.95	1.09	3.48
OES	PMV (abs. from neutral)	0.19	5.16	4.89	−3.22
OES	PPD	0.23	6.36	5.53	−0.198
PCI	PMV (abs. from neutral)	0.24	6.67	1.19	1.798
PCI	PPD	0.21	5.73	1.64	0.096
PCF	PMV (abs. from neutral)	0.16	4.49	2.16	1.67
PCF	PPD	0.18	5.03	1.85	0.099
PCOMF	PMV (abs. from neutral)	0.19	5.21	5.15	8.35
PCOMF	PPD	0.20	5.39	3.69	0.480
VCI	Air speed (head)	0.20	5.39	1.41	5.04
VCI	Air speed (chest)	0.21	5.74	1.18	6.63
Sat_VT	PM10	0.42	14.20	5.06	−0.031
VCI	PM10	0.38	12.19	1.71	0.010
PCI	PM10	0.32	9.30	2.03	0.009
VCF	PM10	0.52	20.63	1.91	0.016
PCF	PM10	0.49	18.15	2.19	0.012
VCOMF	PM10	0.45	15.85	3.95	0.072
PCOMF	PM10	0.25	6.99	5.70	0.041
Absence (illness)	PM10	0.40	12.81	0.283	0.011

Note: abs = absolute distance from neutral.

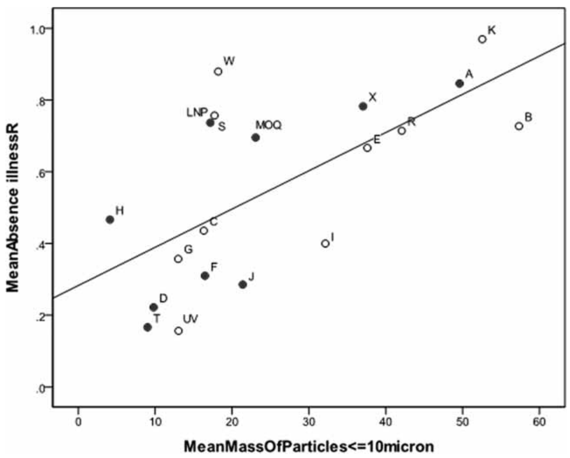

Figure 4 Days per month absent from work due to illness versus measured airborne particle mass (PM10). The best-fit linear regression line is shown ($R^2_{adj} = 0.40$). Green buildings are shown with filled symbols

related directly to thermal comfort. It was also found that the closer PMV was to neutral the higher was OES and the lower were physical symptoms. Higher air speed on the upper body was associated with higher intensity of visual discomfort symptoms, this might be expected as higher air speed would cause more rapid drying of eyes.

There was also a consistent pattern of relatively strong relationships related to airborne particulates. The relationships extended beyond the direct satisfaction outcome: higher particle mass was also associated with higher levels of visual and physical discomfort, and with higher absence from work due to illness (Figure 4). Figure 4 shows that there are some green buildings with relatively high levels of particulates, and relatively high levels of absence due to illness, this demonstrates that a green designation does not guarantee better absolute performance in all outcomes.

These regressions at the building level suggest some very intriguing and potentially important relationships for building design and operation. However, they are based on snapshot physical measurements that are compared with survey outcomes that in some cases may be integrated over longer time periods (*e.g.* work absences over a month). Therefore, these findings should be considered as preliminary and exploratory; it is hoped that the results will encourage future work with larger sample sizes and broader variable sets to explore more complex models of how these variables interrelate.

Discussion

The hypotheses from the Introduction are repeated here, and the results of the analyses are used to indicate whether or not each was supported:

- Green buildings will produce higher ratings of occupant environmental satisfaction, except for ratings related to acoustics.
  Supported. Green buildings exhibited higher levels of overall environmental satisfaction, and higher levels of satisfaction with: ventilation and temperature, aesthetic appearance, size of workspace, and access to a view of outside. Occupants of green buildings were less likely to prefer a change in thermal conditions, and took fewer actions to improve their thermal comfort.

- Green buildings will produce higher ratings of occupant job satisfaction.
  Not supported.

- Green buildings will produce higher ratings of occupant well-being.
  Supported. Occupants of green buildings reported a lower frequency of visual and physical discomfort symptoms, and reported better mood, and better sleep quality at night.

- Green buildings will produce higher ratings of organizational commitment among employees.
  Partially supported. No difference between building types on the specific organizational commitment measure was observed. However, occupants of green buildings indicated that their facilities offered a better workplace image.

- Green buildings will have lower levels of air pollutants.
  Supported. Specifically, green buildings exhibited lower levels of airborne particulates.

- Green buildings will have temperatures closer to thermally neutral.
  Partially supported. No difference between building types on measured temperatures, or on PMV was observed. However, green buildings did exhibit lower air velocities. Further, as described in Hypothesis 1, green building occupants had higher ratings of satisfaction with ventilation and temperature, were less likely to prefer a change in thermal conditions, and reported taking fewer actions to improve their thermal comfort.

- Green buildings will have lighting conditions closer to recommended practice, and provide more access to daylight.
  Partially supported. No difference between building types on any physical measure of the luminous environment was observed. However, as described in Hypothesis 1, green building occupants had higher ratings of satisfaction with access to a view of outside.

- Speech privacy will be lower in green buildings.
  Partially supported. No difference between building types on subjective measures of speech privacy was observed (it was poor in both building types). However, AI in private offices was higher in green buildings.

- Background noise levels will be higher in green buildings.
  Not supported.

The results suggest that, on the whole, both building types delivered indoor conditions that were acceptable to most people (with the exception of speech privacy), but that the indoor environments in green buildings were of higher quality. While there were many dependent variables for which there was no statistically significant difference between building types, when there was a difference, all but one of these favoured green buildings.

The superior performance of green buildings is good news for a society that is increasingly facilitating their development. However, this does not mean there is no room for improvement; moreover, not all green buildings may be delivering the energy and indoor environment performance expected by their owners, which may hamper green building uptake. Although broad in scope, the data did not allow us to provide a comprehensive analysis of the reasons for underperformance where it was observed.

Newsham, Mancini & Birt (2009) observed that while green buildings, on average, demonstrated superior energy performance, there was little relationship between the number of energy performance credits obtained at design time and post-occupancy energy performance. They speculated that it might be the process of designing green that is more important than the specific energy measures taken: a greater focus on energy use generally means that many actions are taken to improve energy performance, though some may not be eligible for credits in a rating system. The results of this field study suggest that a similar mechanism might prevail for indoor environment quality. Few substantial differences in the more commonly considered physical variables were observed between green and conventional buildings. Nevertheless, there were many important subjective measures that did indicate superior indoor environments in green buildings. Again, this might suggest that there is not necessarily a simple cause-and-effect relationship between individual design credits and resulting post-occupancy performance. Rather, it might be that the green building process leads to a greater focus on indoor environment quality in general. This might spawn technologies that garner credits, but it might also generate other actions that do not receive credits but nevertheless lead to improvements, and a general attitude that benefits performance in the longer-term. However, this is speculative, and it is hoped that future studies could explore this further.

The results of this study suggest potential modifications to existing green rating systems that could lead to improved post-occupancy performance:

- It is suggested that an acoustics credit be created to counterbalance design choices engendered by other credits that are detrimental for acoustics. There are acoustics credits in some green rating systems (*e.g.* BRE Global, 2012; Green Building Council of Australia, 2012), and proposals for a LEED credit (Jensen, Fischer, Wentz, & Camara, 2008; USGBC, 2012b, 2013). However, these existing and proposed credits do not place particular emphasis on reducing the propagation of speech sounds, which is the most problematic acoustics issue in offices.

- The data suggested that airborne particulates were particularly important for predicting satisfaction with ventilation, visual and physical comfort, and even absence due to illness. Under LEED-CI (USGBC, 2012c), for example, Construction IAQ Management Plan, Option 2 for compliance requires levels of PM10 below 50 $\mu g/m^3$ be demonstrated, among other pollutant tests. The credit on Indoor Chemical and Pollutant Source Control also states particulate reduction as one of the IAQ goals. A modification to these credits that elevated the importance of particulate reduction might be justified.

- The argument that the integrated design process is at least as important as specific, creditable, actions, suggests that a credit be developed that enhances such process. Perhaps this credit could reward documented interdisciplinary design team meetings, or documentation of all implemented measures intended to improve building performance, credit-eligible or not, or a specific mechanism to facilitate on-going performance review and continuous improvement.

- Mechanisms are already in place to require on-going quantitative energy performance criteria to be met to maintain green certification (*e.g.* LEED EBOM; USGBC, 2011). This approach could be extended to other aspects of green building performance, and resources should be devoted to developing an objective and subjective IEQ measurement kit and protocol. To have widespread applicability the toolkit must be affordable and straightforward to deploy. ASHRAE's Performance Measurement Protocols (ASHRAE, 2010) might play this role, but only time will tell if these are practical and will become routine.

The fact that very few differences were observed in the physical measurements between green and conventional buildings could have many explanations. Buildings can achieve a green rating with very few specific IEQ credits, and one could not expect physical differences if specific measures affecting physical characteristics were not taken. A study involving many more buildings, and with more detailed credit information, would be needed to examine this properly. Another possibility is that although a set of physical measurements consistent with recommended practice was chosen, a different set of metrics might have shown differences. Also, measurements were conducted over a short time period in each building, and it is possible that physical differences between building types would only become apparent over longer periods. Continuous monitoring, or frequent revisits to study buildings might address this. Recall that many differences were recorded in the questionnaire outcomes between building types. It is possible that in this context the building occupants are more sensitive 'instruments' for detecting multidimensional, long-term differences in indoor environments than any practical set of instantaneous physical sensors.

Conclusions

By analysis of original post-occupancy field study data, the following conclusions were drawn:

- Green buildings exhibited superior indoor environment performance compared with similar conventional buildings. A wide range of outcomes that were better in green buildings were observed, including environmental satisfaction, satisfaction with thermal conditions, satisfaction with a view to the outside, aesthetic appearance, less disturbance from HVAC noise, workplace image, night-time sleep quality, mood, physical symptoms, and a reduced number of airborne particulates.

- Analysis of data from across all buildings showed a variety of physical features that led to improved occupant outcomes, including better speech privacy, lower background noise levels, higher light levels, greater access to windows, better thermal conditions, and lower number of airborne particulates.

- Green building rating systems might benefit from a consideration of a credit related to acoustic performance; a greater focus on reducing airborne particulates; enhanced support for the interdisciplinary design process; development of POE protocols, and their integration into on-going certification systems.

Acknowledgements

This research was generously supported by: the National Research Council Canada; the Natural Resources Canada Program of Energy Research and Development (PERD); the Public Works and Government Services Canada; the governments of Alberta, Manitoba, Nova Scotia, New Brunswick, Ontario and Saskatchewan; BC Hydro; the Fonds en efficacité énergétique de Gaz Métro (Energy Efficiency Fund for Gaz Métro customers); Haworth; the Jim H. McClung Lighting Research Foundation, Inc.; and the University of Idaho – Integrated Design Lab. The authors also thank the people, too numerous to list, who facilitated the taking of measurements at each study building; and all the building occupants who participated in the physical or questionnaire measurements. The authors are grateful to the talented students who assisted with data collection and processing: Maude Chalin, Daniel Cormier, Aifei Lu and Elena Sanchez McAuley; and for the data collection support provided at specific sites by Kevin van den Wymelenberg, Gunnar Gladics, Jacob Dunn and Harshana Thimmanna.

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Endnotes

[1]There were some methodological issues with the study, and it is suggested that the results be treated as indicative only.

[2]In most cases green buildings either had, or were applying for, LEED certification; one had a very high BOMA Go Green Plus rating, and another two buildings, built prior to LEED, which were considered green by the owner compared with their typical building stock as a result of specific sustainability measures.

[3]For details of the formal statistical tests of equivalence, see Newsham *et al.* (2012).

[4]ASHRAE Standard 55 (ASHRAE, 2004) specifies that the measurement positions appropriate for thermal comfort variables for seated occupants are 0.1 m (ankle), 0.6 m (torso) and 1.1 m (head) for air temperature and air speed, and 0.6 m for RH. The measurement positions on the NICE Cart differed from these due to practicality; sensors beyond those for thermal conditions were included, and they could not be co-located due to size and interference issues. However, previous experience (Veitch, Charles, Newsham, Marquardt, & Geerts, 2003) suggested that such height variations are unlikely to have a large effect for typical office spaces.

[5]Means in the main body text and tables are means of building means; means in Table A1 in Appendix A are means of individual data points.

[6]Values for CO and ozone were very low in both building types (a good thing), and thus did not lend themselves to meaningful statistical tests. The formaldehyde meter was suspected to have had multiple malfunctions, and these data were not included in the analysis.

[7]Tests were repeated both with and without Building H, which had substantially higher mean illuminances and might be considered an outlier. For cubic illuminance variables the mean illuminance on all six faces was tested as a predictor as well as the individual faces; similarly, for desktop illuminance variables mean desktop illuminance was tested as a predictor as well as the two desk sides separately. The composite variables may be more reliable, but were not significant predictors. Nevertheless, the pattern of relationships using the individual metrics is consistent and suggests robust conclusions.

Appendix A: Overall descriptive statistics

Table A1 Summary descriptive statistics for the primary questionnaire and cart variables collected at the study buildings

	Total						Green						Conventional					
	N	Mean	SD	Minimum	Maximum	Medium	*N*	Mean	SD	Minimum	Maximum	Medium	*N*	Mean	SD	Minimum	Maximum	Medium
Questionnaire																		
%Computer & Quiet Work	2534	57.5	21.6	0	100	60.0	1011	57.6	21.4	0	100	60.0	1523	57.4	21.7	0	100	60.0
SAT_L	2540	5.12	1.17	1	7	5.40	1015	5.37	1.14	1	7	5.60	1525	4.96	1.16	1	7	5.20
SAT_VT	2542	4.18	1.52	1	7	4.33	1013	4.55	1.42	1	7	4.67	1529	3.94	1.54	1	7	4.00
SAT_AP	2544	4.28	1.31	1	7	4.30	1015	4.45	1.28	1	7	4.50	1529	4.17	1.32	1	7	4.20
OES	2544	4.22	1.43	1	7	4.50	1015	4.49	1.39	1	7	4.50	1529	4.03	1.43	1	7	4.00
Job demands	2537	4.36	1.39	1	7	4.50	1011	4.35	1.39	1	7	4.50	1526	4.36	1.39	1	7	4.50
Organizational commitment	838	4.88	1.29	1	7	5.00	329	4.81	1.29	1	7	4.83	509	4.93	1.29	1	7	5.00
Intent to turnover	835	2.69	1.59	1	7	2.33	327	2.74	1.56	1	7	2.67	508	2.66	1.61	1	7	2.33
Workplace image	839	4.20	1.52	1	7	4.00	330	4.71	1.40	1	7	4.67	509	3.86	1.50	1	7	4.00
Communication	840	5.67	1.16	1	7	6.00	331	5.69	1.10	1	7	6.00	509	5.65	1.19	1	7	6.00
Non-speech noise	878	2.61	0.99	1	6	2.57	346	2.55	0.96	1	6	2.43	532	2.65	1.01	1	6	2.57
Speech noise	878	4.60	1.49	1	7	4.75	346	4.55	1.51	1	7	4.50	532	4.64	1.48	1	7	4.75
Speech noise2	878	4.46	1.50	1	7	4.33	346	4.42	1.51	1	7	4.33	532	4.48	1.49	1	7	4.67
Clothing insulation (clo)	854	0.83	0.24	0.54	1.49	0.92	329	0.82	0.25	0.54	1.49	0.89	525	0.83	0.24	0.54	1.49	0.92
Adap_Energy	861	1.78	1.06	1	7	1.00	331	1.56	0.92	1	7	1.00	530	1.92	1.12	1	7	1.33
Adap_NoEnergy	863	2.87	1.13	1	6	3.00	332	2.75	1.16	1	6	2.75	531	2.94	1.11	1	6	3.00
Adap_Enviro	862	1.71	0.84	1	6	1.40	331	1.56	0.76	1	5	1.20	531	1.81	0.87	1	6	1.60
Adap_Personal	862	4.12	1.83	1	7	4.00	332	3.93	1.85	1	7	4.00	530	4.24	1.80	1	7	4.50
Chronotype	868	9.72	4.95	0	24	9.00	349	10.03	5.03	0	24	9.00	519	9.51	4.89	0	24	9.00
Sleep quality	870	4.52	3.68	0	14	4.00	350	4.09	3.60	0	14	3.00	520	4.81	3.71	0	14	4.00
Positive feelings	865	22.2	3.99	4	30	23.0	347	22.6	3.86	4	30	23.0	518	22.0	4.06	8	30	23.0
Negative feelings	866	14.2	3.87	2	28	14.0	348	14.0	3.79	4	25	14.0	518	14.3	3.92	2	28	14.0
Affect balance	865	8.05	6.95	−19	24	9.00	347	8.56	6.62	−12	24	9.00	518	7.72	7.14	−19	24	8.00
VCF	798	2.37	1.08	1	5	2.25	315	2.27	1.07	1	5	2.00	483	2.43	1.08	1	5	2.25
VCI	732	1.97	0.82	1	5	1.75	290	1.90	0.78	1	5	1.75	442	2.02	0.84	1	5	1.88
PCF	798	2.49	0.80	1	5	2.43	316	2.40	0.75	1	5	2.29	482	2.55	0.83	1	5	2.57
PCI	736	2.23	0.74	1	5	2.14	291	2.19	0.70	1	5	2.14	445	2.26	0.76	1	5	2.14
VCOMF	603	5.86	4.57	1	25	4.50	233	5.46	4.41	1	25	4.00	370	6.11	4.65	1	25	5.00
PCOMF	609	6.73	3.61	1	21	6.14	241	6.37	3.33	1	19	6.00	368	6.97	3.76	1	21	6.29
Commuting distance (km)	758	19.2	19.3	0.00	140	14.5	314	19.5	18.6	0.00	110	14.7	444	18.9	19.8	1.00	140	14.5
NEP	788	3.57	0.65	1	5	3.60	334	3.59	0.63	2	5	3.60	454	3.55	0.67	1	5	3.55

(*Continued*)

Table A1 Continued

	Total						Green						Conventional					
	N	Mean	SD	Minimum	Maximum	Medium	*N*	Mean	SD	Minimum	Maximum	Medium	*N*	Mean	SD	Minimum	Maximum	Medium
NICE Cart																		
Air speed head (m/s)	972	0.11	0.06	0.01	0.68	0.10	467	0.11	0.06	0.01	0.68	0.10	505	0.12	0.06	0.01	0.37	0.11
Air speed chest (m/s)	972	0.12	0.06	0.01	0.50	0.12	467	0.11	0.06	0.01	0.50	0.11	505	0.13	0.05	0.01	0.36	0.13
Air speed feet (m/s)	972	0.09	0.05	0.01	0.56	0.08	467	0.09	0.05	0.02	0.56	0.08	505	0.09	0.04	0.01	0.34	0.09
Radiant temperature (°C)	972	23.1	1.21	17.0	28.2	23.2	467	23.0	1.01	18.2	27.9	23.1	505	23.1	1.37	17.0	28.2	23.2
Air temperature head (°C)	972	23.1	1.09	17.8	27.4	23.2	467	23.0	0.90	19.5	25.2	23.1	505	23.2	1.23	17.8	27.4	23.3
Air temperature chest (°C)	972	23.5	1.13	18.3	28.1	23.5	467	23.4	0.96	19.5	27.0	23.5	505	23.6	1.26	18.3	28.1	23.6
Air temperature feet (°C)	972	23.7	1.30	18.3	28.2	23.8	467	23.6	1.14	19.1	25.8	23.8	505	23.9	1.42	18.3	28.2	23.9
PM2.5 ($\mu g/m^3$)	972	2.38	4.15	0.01	36.4	1.47	467	1.39	0.87	0.17	3.94	1.16	505	3.30	5.55	0.01	36.4	1.69
PM10 ($\mu g/m^3$)	972	25.1	24.8	0.89	388	17.6	467	21.9	19.2	0.89	107	15.3	505	28.1	28.7	2.51	388	19.9
TVOC (ppb)	972	93.8	94.0	0.00	1122	80.0	467	83.2	67.5	0.00	767	76.0	505	104	112	0.00	1122	86.0
CO_2 (ppm)	972	630	128	383	1133	609	467	618	121	400	995	591	505	642	132	383	1133	624
Ozone (ppm)	972	0.00	0.01	0.00	0.06	0.00	467	0.00	0.01	0.00	0.04	0.00	505	0.00	0.01	0.00	0.06	0.00
CO (ppm)	972	0.06	0.18	0.00	2.50	0.00	467	0.06	0.23	0.00	2.50	0.00	505	0.05	0.12	0.00	0.70	0.00
Relative humidity IAQ meter (%)	972	32.2	11.3	15.3	62.7	30.2	467	33.5	11.8	15.8	56.1	33.6	505	31.0	10.6	15.3	62.7	28.4
PMV (from neutral)	972	0.19	0.17	0.00	1.22	0.16	467	0.18	0.14	0.00	0.96	0.16	505	0.20	0.19	0.00	1.22	0.16
PPD (%)	972	6.35	2.75	5.00	36.2	5.50	467	6.07	1.81	5.00	24.5	5.50	505	6.61	3.38	5.00	36.2	5.50
Mean height of walls (inches)	974	83.7	35.5	26.8	868	78.4	469	84.8	44.8	26.8	868	80.6	505	82.5	23.8	29.0	131	76.8
Workstation area ($\times$1000 inches^2)	971	13.6	11.9	1.80	210	11.5	466	13.4	12.6	2.16	210	10.8	505	13.8	11.2	1.80	190	11.7
Ceiling height (inches)	973	115	15.5	94.0	250	108	468	117	13.3	94.0	250	115	505	112	17.0	94.0	213	108
IllumCubeTop (lux)	972	718	765	45.4	10 206	587	467	764	858	53.0	9525	606	505	676	665	45.4	10 206	545
IllumCubeFront (lux)	972	344	454	29.8	6245	216	467	396	523	44.7	6245	246	505	296	375	29.8	3689	201
IllumCubeLeft (lux)	972	378	754	36.8	17 238	228	467	408	591	36.8	5753	243	505	350	878	36.8	17 238	213
IllumCubeRight (lux)	972	417	694	29.2	7872	234	467	466	738	36.6	5935	249	505	371	649	29.2	7872	212
IllumCubeBack (lux)	972	427	1118	29.0	22 214	239	467	444	784	29.0	9974	261	505	411	1356	29.0	22 214	224
IllumCubeBottom (lux)	972	126	200	28.4	2285	78.1	467	148	226	28.4	1859	92.2	505	107	170	28.4	2285	71.0
IllumLeftDesk (lux)	972	658	1959	27.6	47 021	414	467	643	941	27.6	12 435	442	505	671	2564	34.5	47 021	380
IllumRightDesk (lux)	972	630	1282	26.9	18 820	396	467	674	1327	26.9	18 001	430	505	590	1238	26.9	18 820	369
IllumMeanDesk (lux)	972	644	1273	27.2	24 864	406	467	659	959	27.2	9574	437	505	630	1508	34.1	24 864	377
Luminance above monitor (cd/m^2)	965	102	236	0.00	3130	41.9	463	122	273	0.00	3130	50.3	502	83.1	194	1.62	2180	35.1
AI	974	0.31	0.20	0.00	0.97	0.30	469	0.33	0.21	0.00	0.88	0.30	505	0.30	0.19	0.00	0.97	0.29
AW (dB)	974	42.0	5.22	30.7	65.1	42.1	469	41.9	5.81	30.7	65.1	41.3	505	42.2	4.60	32.0	56.3	42.5