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Research Report RR-329

Do Green Buildings Outperform Conventional Buildings?
Indoor Environment and Energy Performance in North American Offices

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Summary

A comprehensive post-occupancy investigation of the performance of "green" and "conventional" office buildings has been completed. The study included occupant surveys and physical building and energy use data collected from 24 buildings (12 green, 12 conventional) across Canada and the northern US. Occupants completed a questionnaire with items related to environmental satisfaction, job satisfaction and organizational commitment, health and well-being, environmental attitudes, and commuting behaviour. In total we recorded valid surveys from 2545 occupants. In addition, we conducted on-site physical measurements at each building. At a sample of workstations we collected data on prevailing thermal conditions, air quality, acoustics, and lighting. In addition, we recorded workstation size, ceiling height, window access and shading, electric lighting system, and surface finishes. In total we recorded valid data from 974 workstations.

In looking at energy performance, we conducted a re-analysis of data gathered by the New Buildings Institute on one year of data from 100 LEED-certified (Leadership in Energy and Environmental Design) commercial buildings in North America[1]. Each green building was "twinned" with a similar conventional building from the US commercial building stock. We also collected monthly utility data from the 24 buildings in our field study sample, where available.

From analysis of our original post-occupancy field study data, and re-analysis of extant datasets on LEED/conventional building energy use, we can conclude the following:

- Green buildings exhibited superior indoor environment performance compared to similar conventional buildings. Outcomes that were better in green buildings included: environmental satisfaction, satisfaction with thermal conditions, satisfaction with view to the outside, aesthetic appearance, disturbance from HVAC (heating, ventilation and air conditioning) 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: lower articulation index (i.e. physical conditions associated with better speech privacy), lower background noise levels, higher light levels, greater access to windows, lower predicted mean vote (i.e. physical conditions associated with better thermal comfort), and lower number of airborne particulates.
- Green building rating systems might benefit from further attention in several areas, including: consideration of a LEED credit related to acoustic performance; a greater focus on reducing airborne particulates; enhanced support for the interdisciplinary design process; development of post-occupancy evaluation protocols, and their integration into on-going certification systems.
- On average, LEED buildings exhibited lower total energy use intensity than similar conventional buildings. A specific case study from our own field study dataset confirmed the potential for

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[1] This was part of our larger research study, but is reported in detail elsewhere. This document focuses on the original field study data we collected, and only reviews the findings of this re-analysis of energy data provided by others.

substantial energy use intensity reductions through a green building renovation. However, many individual LEED buildings did not meet energy performance expectations. Further, there was little correlation between the number of LEED energy credits obtained during design and the resulting energy performance.

Résumé

Une étude exhaustive de la performance des immeubles de bureaux « verts » ou écologiques par rapport aux immeubles dits « conventionnels » a été réalisée, une fois les bâtiments occupés. L'étude en question comprenait des enquêtes auprès des occupants, ainsi que des données sur les caractéristiques physiques des bâtiments et leur consommation d'énergie, recueillies à partir de 24 bâtiments (12 de conception verte, et 12 de conception conventionnelle) répartis dans le Canada et le Nord des États-Unis. Les occupants ont rempli un questionnaire couvrant des points liés au degré de satisfaction vis à vis de l'environnement, à la satisfaction au travail et engagement envers l'organisation, à la santé et au bien-être, aux attitudes face à l'environnement et leurs habitudes en matière de moyens de transport. Au total, nous avons documenté des enquêtes recevables auprès de 2 545 occupants, et nous avons aussi réalisé des mesures physiques in situ à chacun des bâtiments étudiés. Nous avons recueilli sur un certain échantillonnage de postes de travail, des données sur les conditions thermiques, la qualité de l'air, l'acoustique et l'éclairage. En outre, nous avons documenté les dimensions des postes de travail, la hauteur des plafonds, l'accès aux fenêtres et l'occultation, le système d'éclairage électrique et les finitions des surfaces. Nous avons rassemblé au total des données provenant de 974 postes de travail.

Pour ce qui est de la performance énergétique, nous avons analysé de nouveau les données recueillies par le New Buildings Institute pendant un (1) an sur 100 bâtiments commerciaux agréés LEED (programme Leadership in Energy and Environmental Design [États-Unis]) en Amérique du Nord[2]. Chaque bâtiment vert a été jumelé avec un bâtiment conventionnel semblable provenant du parc immobilier commercial des É.-U. Nous avons recueilli également les données mensuelles des services publics pour les 24 bâtiments de notre étude sur le terrain, lorsque disponibles.

L'analyse des données de notre étude initiale sur le terrain et la nouvelle analyse des bases de données existantes sur la consommation d'énergie des bâtiments agréés LEED/conventionnels nous permettent de conclure ce qui suit :

- Les bâtiments verts ont affiché une performance vis à vis de l'environnement intérieur supérieure à celle des bâtiments conventionnels semblables. Les résultats qui se sont révélés meilleurs dans les bâtiments verts comprenaient les points suivants : satisfaction vis à vis de

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[2] Ce volet faisait partie de notre étude de plus grande portée mais n'est pas exposé en détail ici. Le présent document se concentre sur les données de l'étude sur le terrain d'origine que nous avons recueillies et ne fait état que des constatations découlant de cette nouvelle analyse des données liées à la consommation d'énergie qui sont fournies par d'autres sources.

l'environnement; satisfaction face aux conditions thermiques; satisfaction de la vue offerte sur l'extérieur; esthétique; dérangement occasionné par les bruits provenant du système de CVCA (chauffage, ventilation et conditionnement d'air); représentation (image) du lieu de travail; qualité du sommeil nocturne; humeur; symptômes physiques; et diminution de la quantité de particules en suspension dans l'air.

- Diverses caractéristiques physiques ont contribué à améliorer les résultats pour les occupants dans tous les bâtiments étudiés, y compris : indice de netteté plus bas (soit les conditions physiques associées à une meilleure confidentialité des entretiens), des niveaux de bruit de fond plus bas, des niveaux d'éclairement plus élevés, un accès aux fenêtres amélioré, un indice PMV (vote moyen prévisible) plus bas (soit les conditions physiques associées à un meilleur confort thermique), et une moindre quantité de particules en suspension dans l'air.
- Les systèmes de cotation des bâtiments verts pourraient bénéficier d'une plus grande attention consacrée à plusieurs secteurs, notamment : l'examen d'un crédit LEED pour la performance acoustique; une focalisation accrue sur la réduction des particules en suspension dans l'air; la valorisation du soutien au processus de conception interdisciplinaire; le développement de protocoles d'évaluation après emménagement et leur intégration aux systèmes de certification ayant cours.
- En moyenne, les bâtiments agréés LEED ont affiché une intensité de consommation d'énergie totale plus faible que celle des bâtiments conventionnels semblables. Une étude de cas précise issue de l'ensemble de données de notre propre étude sur le terrain a confirmé le potentiel de réduction appréciable de l'intensité de la consommation d'énergie via la rénovation d'un bâtiment vert. Toutefois, plusieurs bâtiments agréés LEED individuels n'ont pas répondu aux attentes en matière de performance énergétique. Par ailleurs, on n'a noté qu'une faible corrélation entre le nombre de crédits d'énergie LEED obtenus durant l'étape de la conception et la performance énergétique résultante.

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1. Introduction

Since its foundation in the late 1990s, the formalized green building movement in North America has grown rapidly. For example, at the time of writing, more than 3,600 projects had been registered for LEED certification in Canada [CaGBC, 2012], and more than 32,000 commercial building projects had been registered for LEED certification by the US Green Building Council [USGBC, 2012]. In addition, more than 1,400 commercial buildings in Canada have been certified under the BOMA BESt program [BOMA, 2012]. An increasing number of jurisdictions now require such certification for their own new buildings [e.g. PWGSC, 2012; Government of Manitoba, 2006], or new buildings in their region [e.g. San Francisco Department of Building Inspection, 2011].

However, in most cases these buildings are being judged on their “greenness” at the time of their design, and there has been little follow-up to determine whether the post-occupancy performance of these projects meets expectations. We review the prior work below in brief, and then describe the new research that we conducted in order to fill this performance evaluation gap.

1.1 Energy Performance

Perhaps the strongest driver for the green building movement is the goal of reducing building energy use. All green building rating systems provide credits for energy-saving design, and in most cases this is the largest single credit category. In the past few years, the LEED system in North America has placed an even greater emphasis on designed energy performance. However, there has been very little formal investigation of whether green buildings, once built and occupied, save energy, and if so, what the magnitude of that saving is.

As part of our research [Newsham et al., 2009a], we reviewed the evidence available at that time, which was consistent in showing that green buildings used less energy than conventional counterparts, but was limited by small sample sizes. We then conducted an analysis based on one year of data from 100 LEED-certified commercial buildings in North America. Each green building was “twinned” with a similar conventional (non-green) building from the US commercial building stock with energy use data from the CBECS (Commercial Buildings Energy Consumption Survey) database. We also examined energy use by LEED certification level, and by energy-related credits achieved in the certification process. On average, LEED buildings used 18–39% less energy per floor area than their conventional counterparts. However, 28–35% of LEED buildings used more energy than their conventional counterparts. Further, the measured energy performance of LEED buildings had little correlation with certification level, or with the number of energy credits achieved by the building at design time. These results suggested that, at a societal level, green buildings can contribute substantial energy savings, but that further work needs to be done to ensure more consistent success at the individual building level. Scofield [2009] conducted his own analyses on the office building subset (N=35) of these data. He noted that it was the largest LEED buildings in this dataset that appeared to perform worst, so that after weighting the analysis by floor area (thus assuming that this dataset was truly representative of the population of all buildings) the overall savings for the green buildings were substantially lower, and not statistically significant.

Subsequently, the Center for Neighbourhood Technology [2009] studied 25 LEED buildings in Illinois, 17 of which provided whole-building energy data for at least a year. They observed a trend for more energy credits correlating with lower energy use, but there was no effect of LEED certification level. However, only 10 of 17 buildings performed better than the regional CBECS average, and most buildings performed worse than their design energy model.

We noted Newsham et al. [2009a] that our findings should be considered as preliminary, and that the analyses should be repeated when longer data histories from a larger sample of green buildings are available. Encouragingly, both the US and Canada Green Building Councils are placing additional emphasis on measured energy performance, and are collecting data in various programs that may be used in the future for a more comprehensive analysis of green building energy performance. In particular, certification under LEED EBOM (Existing Buildings: Operations & Maintenance) requires whole-year measured energy data to be submitted.

1.2 Indoor Environment Quality

Another large credit category in green building rating systems is indoor environment quality (IEQ). Advocates will often suggest that the superior indoor environments offered by green buildings will lead to more satisfied occupants with higher levels of well-being, and thus to better outcomes for the organizations that employ them. There is abundant evidence that better indoor environments do lead to such positive outcomes [e.g. Newsham et al., 2008; Newsham et al, 2009b, Thayer et al., 2010]. And a recent industry survey [PRNewswire, 2010] reported that 10% of building tenants have seen an improvement in worker productivity associated with green buildings, 83% say they have a healthier indoor environment, and 94% say satisfaction levels are higher. However, again, there has been very little formal investigation of whether green buildings specifically, once built and occupied, offer physical environments that are measurably better than those in conventional (non-green) buildings, and in turn if occupant environmental satisfaction, job satisfaction and health are benefitted.

We reviewed much of the evidence available at the time [Birt & Newsham, 2009] and 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 between green and conventional buildings (improvement in daylighting and views might have been offset with overly aggressive electric lighting reductions). Conversely there was a clear 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 of these features have negative effects for acoustics [Bradley & Wang 2001]. This is compounded by the fact that no credits for acoustic performance currently exist, potentially resulting in acoustic quality not being considered at all in the design. Proposals for new acoustics credits in LEED have been made [Jensen et al., 2008; USGBC, 2012b].

Singh et al. [2010] conducted a pre-post study of people moving into two LEED buildings (N=56 and 207, respectively), the study comprised survey data only. There were some methodological problems: in one building the pre-move survey was done retrospectively after the move, and pre-post measurements were done in different seasons. With these limitations, there were statistically-significant improvements in asthma and depression symptoms, and perceived productivity.

1.3 New POE Research

Given the paucity of objective and methodologically-sound data, NRC worked with a consortium of partners to launch a major new research project on the post-occupancy evaluation (POE) of green commercial buildings. Work began in 2008 on the reviews and analysis of extant data described above [Newsham et al., 2009a; Birt & Newsham, 2009]. However, the main aim of the research was to collect and analyze original data, with a sample size and variety of outcomes not previously undertaken. Our particular focus in the field study was office buildings. The remainder of this report describes this field study aspect of the research.

Given the design of green building rating systems, and our review of existing knowledge, we developed the following hypotheses to be tested with the data we collected:

1. Green buildings will produce higher ratings of occupant environmental satisfaction, except for ratings related to acoustics (see hypotheses 8 & 9 below).
2. Green buildings will produce higher ratings of occupant job satisfaction than conventional buildings.
3. Green buildings will produce higher ratings of occupant well-being than conventional buildings.
4. Green buildings will produce higher ratings of organizational commitment among employees than conventional buildings.
5. Green buildings will have lower levels of air pollutants than in conventional buildings.
6. Green buildings will have temperatures closer to thermally neutral than conventional buildings.
7. Green buildings will have lighting conditions closer to recommended practice, and provide more access to daylight, than conventional buildings.
8. Speech privacy will be lower in green buildings than in conventional buildings due to the reduced use of sound absorbing materials.
9. Background noise levels will be higher in green buildings than in conventional buildings.
10. Green buildings will achieve better energy performance than conventional buildings.
11. Green buildings will perform according to building design goals and energy use predictions (e.g. lighting, air quality, temperature, acoustics, and electricity consumption).

We also aimed to use the results of the analyses to suggest modifications to the existing rating systems, and to offer guidance for the development of POE protocols, particularly in the context of on-going green building certification following occupancy.

2. Methods & Procedures

Our POE took a multi-dimensional approach to evaluating indoor environment conditions and energy performance. The various elements of this approach are described below. This approach was reviewed and approved by NRC's Research Ethics Board, under protocol 2009-46.

2.1 Study Buildings

The focus of building selection was to find pairs of buildings that were as similar as practically possible in all respects except that one of them was a green building. This enables us to be more confident that any differences we find in the measured outcomes are due to “greenness” rather than the myriad of other factors that potentially differ between buildings. Ideally, this would mean finding pairs of buildings of the same size and age, in the same climate zone, with the same owner, employer, occupants doing the same kind of work, with measurements made at the same time. Further, the study buildings would be randomly selected from a larger set of eligible buildings. In practical field studies, many factors intervene to prevent access to this perfect sample. Members of our research consortium had the opportunity to propose study buildings, and we supplemented this set of buildings with others that we identified through our network. Nevertheless, the final choice of buildings was always made by the researchers in consideration of the eligibility criteria above. Table 1 shows summary physical characteristics of the buildings (as observed by the research team or reported by the building operator). Appendix A provides a summary of the LEED credits claimed by the green buildings in the sample, where available.

The definition of what classified a building as green in this study was somewhat broad. In most cases, green buildings either had, or were in the process of applying for, LEED certification at some level. However, we did also include a building that had a very high rating on the BOMA Go Green Plus scale, and another two buildings that were considered green by the owner compared to their typical building stock, as a result of specific sustainability measures that had been taken (and before LEED rating existed). On the other hand, we had a study building that had been designed to be unusually energy efficient for its vintage, but with no other features that would be considered green by current standards, and was thus labelled conventional.

Table 2 shows summary demographic characteristics of the occupants (as reported by those who responded to the survey), and the fraction of their work time they reported spending on computer/quiet work. We used Goodman-Kruskal (G-K) Tau tests on the distribution of the former variables between building pairs, and an ANOVA on the work split between building pairs, to test for similarity between building populations; a statistically significant test indicates a lack of similarity. The Goodman-Kruskal Tau test is based on a cross-tabulation analysis, like a Chi-squared test, but gives an indication of the strength of the relationship, and is directional; specifically, we were interested in whether knowledge of building type in a pair influences the categorization of a given demographic variable. The strength of the relationship is expressed as a percentage reduction in the classification error; for example, if one were to guess the job type of an individual, how much better would that guess be knowing which building of the pair the individual was in? There were a number of statistically-significant differences, but where they did occur, the strengths of the differences were small. We conducted 45 G-K tests and 26 were statistically significant. However, of these, 22 had strengths of 3% or less. Evaluating relationship strengths in these terms is somewhat arbitrary, but one source suggests that values of 10% or less are very weak associations [Smith, 2010]. For the work split tests, 4 of 9 were statistically significant, with the largest effect size (partial eta-squared) of 13.4%. More importantly, there was no systematic pattern of difference between building types. Therefore, although not all building pairs were perfectly matched on all criteria, they were closely matched on many criteria, and we observed no obvious biases with respect to green buildings. We posit that this represents a set that meets the requirements of the research design very well given all the practical limitations inherent in field studies.

Note that Table 1 shows that in a few cases we grouped buildings together to form a single datapoint. In one case (Buildings LNP & MOQ), these were relatively small buildings within a single site and employer where we judged that the sample sizes for each individual building alone were too small to be reliable. In a second case (Buildings UV), these were almost identical buildings within a single site and employer, with a single paired building (Building T) for comparison.

Table 1. Summary of features of the study buildings. Buildings are listed in pairs, with pairs separated by background shading. Building E, which had no pair, is listed at the end, with a different background shading.

Building Code Letter	Type	Certif. (target/ obtain.	Dist. apart (km)	Sector	Setting	CBECS Climate Zone*	Age	Size (m^2)	Interior Layout	Measure. Dates	N. survey responses (rate %)	N. Cart Measures	Notes
A	Green	LEED Silver		Provincial Govt.	Urban	1	1965 (LEED reno 2009)	14400	Mostly private	May, 2010	160 (41)	53	
B	Conv.		260	Provincial Govt.	Urban	1	1976	18500	Mostly private	May, 2010	147 (26)	41	
C	Conv.		4	Provincial Govt.	Urban	1	1963	13500	Mostly open	Nov/Dec 2010	112 (33)	45	
D	Green	LEED Platinum		Provincial Govt.	Urban	1	1968 (LEED reno 2009)	3500*	Mostly open	Nov/Dec 2010	35 (29)	25	Two floors in larger building
F	Green	LEED Platinum	1	Private, multi-tenant	Urban	2	2006	17300	2/3 open	Oct/Nov, 2010	94 (49)	46	
G	Conv.			Private, multi-tenant	Urban	2	2000	9900	2/3 open	Oct/Nov, 2010	50 (47)	50	
H	Green	LEED Gold	1	State Govt.	Sub-urban	1	2009	5100	Mix of open & closed	Oct/Nov, 2010	47 (39)	49	
I	Conv.			Federal Govt.	Sub-urban	1	1978	26500	2/3 open	Oct/Nov, 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	Nov, 2010	43 (73)	26	
K	Conv.			University Admin.	Sub-urban	1	1967	7700	Mix of open & closed	Jan, 2011	125 (40)	41	
LNP	Conv.		1	University Depts.	Sub-urban	3	1959, 1997, 1997	1300, 3900, 1300	Mix of open & closed	Mar, 2011	56 (40)	47	Three small buildings on same site
MOQ	Green	Various		University Depts.	Sub-urban	3	1996, 2005, 2000	2400, 6000, 1500	Mix of open & closed	Mar, 2011	80 (20)	74	Three small buildings on same site One LEED Gold, others deemed green w/o certif.
R	Conv.		3	Federal Govt.	Urban	1	1958	10500	Mostly open	Jun, 2011	67 (30)	47	
X	Green	Go Green Plus		Federal Govt.	Urban	1	1956 (reno 1996)	38500	Mix of open & closed	Oct, 2011	242 (36)	69	
S	Green	LEED Platinum	5	Federal Govt.	Urban	1	2009	4700	Open	Jun, 2011	115 (42)	59	Three floors in larger building
W	Conv.			Federal Govt.	Urban	1	2003	20000	Open	Oct, 2011	273 (37)	69	
T	Green	LEED Gold	55	Private	Sub-urban	1	2008	27900	Open	Aug/Sep 2011	211 (31)	70	
UV	Conv.			Private	Sub-urban	1	1994, 1998	7400, 7400	Open	Aug/Sep 2011	250 (38)	70	Two buildings on same campus
E	Conv.			Provincial Govt.	Urban	1	1967	21600	Closed	Oct 2010	187 (35)	58	No pair, expected renovation did not occur as originally scheduled.

*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. A dark outline with dashed grid indicates a statistically-significant distribution between building pairs, using the Goodman-Kruskal (G-K) test.

Building Code Letter	**Type**	**Sex (%)**		**Age (%)**					**Job Type**				**With Current Employer (yrs)**					**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+**	**Sec/High School**	**College/Tech**	**University<Bach.**	**Bach.Degree**	**Grad/ProDegree**	**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

2.2 On-Site Physical Measurements

Physical measurements related to indoor environment conditions were made using two custom-built integrated sensor platforms, referred to colloquially as the “NICE Cart” (National Research Council Indoor Climate Evaluator) and the “Pyramids”. Figures 1 and 2 show photographs of both.

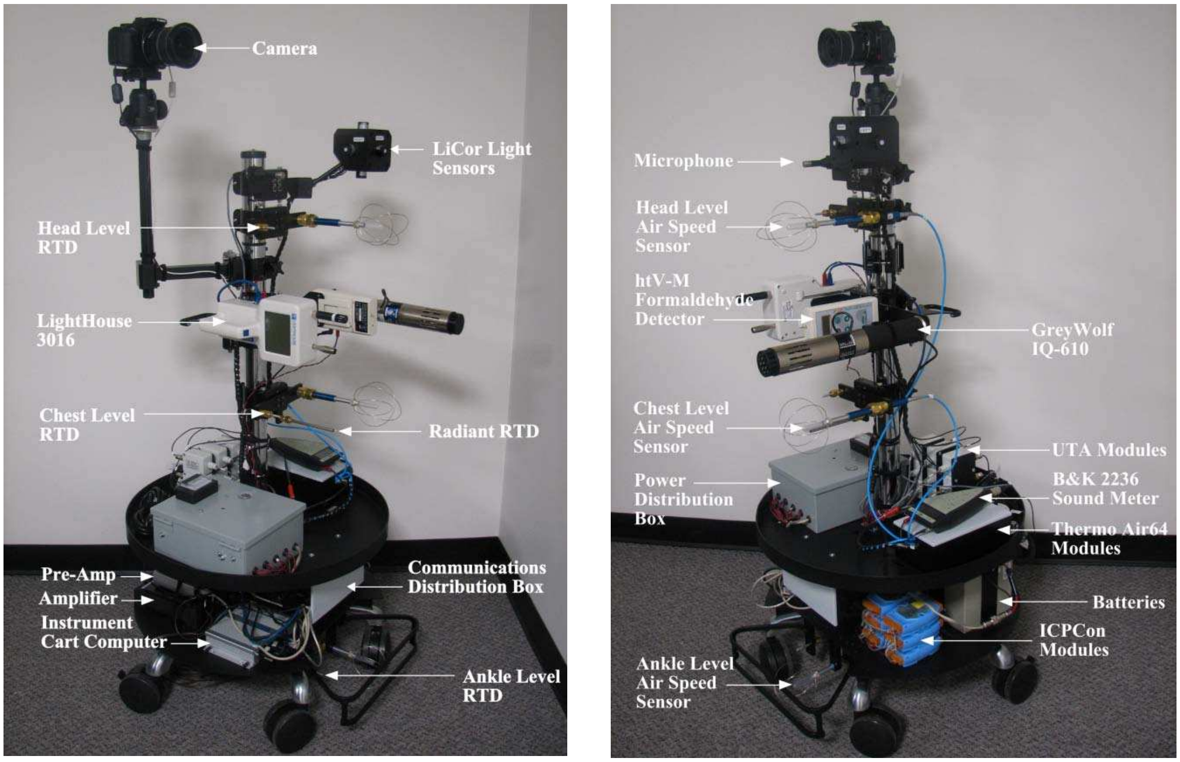

Figure 1. NICE cart (height ~ 1.5m), showing sensors and other system components.

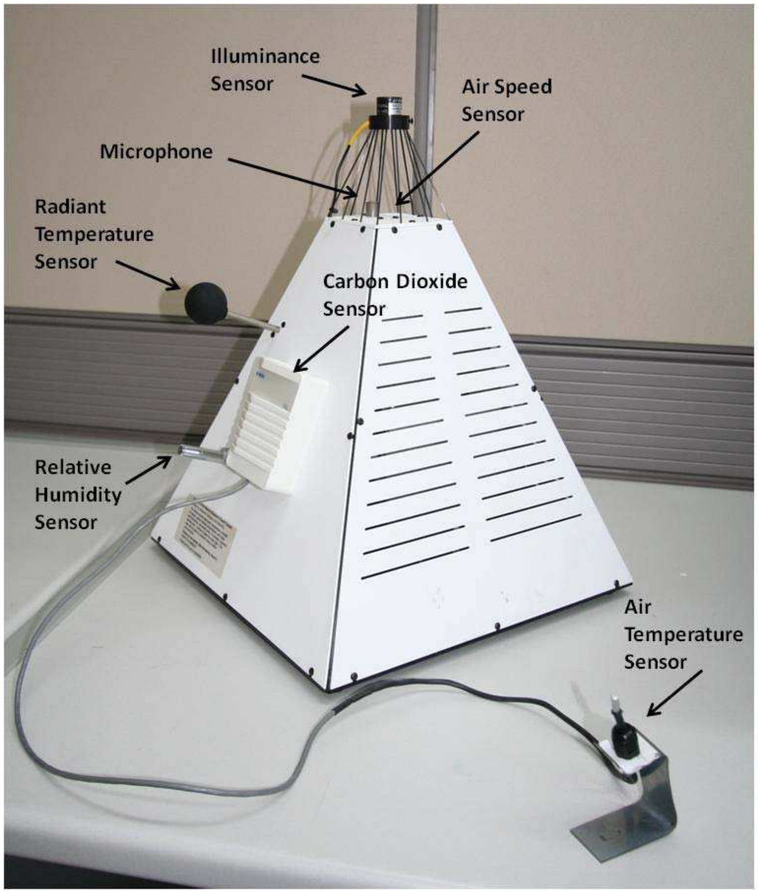

Figure 2. Pyramid (height 0.5m.), showing sensors.

The NICE Cart was designed as a mobile platform to take a detailed snapshot of indoor environment conditions over a 10-15 minute period at multiple representative locations within a building. Table 3 summarizes the instruments/sensors on the NICE Cart.

Table 3. Summary information on NICE Cart instruments/sensors.

Instrument/sensor	**Parameter measured**	**Range**	**Accuracy** (specified by manufacturer)	**Mounting Height**[3]
Htv-M	Formaldehyde	0 to 10 ppm	25%	0.9 m
Htv-M	Temperature	-40° to +128°C	± 0.4°C	0.9 m
Htv-M	Relative humidity	0 to 100% RH	±3% RH	0.9 m
GreyWolf IQ 610	Carbon dioxide	0 to 10000 ppm	±3% reading ±50 ppm	0.9 m
GreyWolf IQ 610	Carbon monoxide	0 to 500 ppm	±2 ppm<50 ppm, ±3 % reading>50 ppm	0.9 m
GreyWolf IQ 610	VOCs	5 to 20000 ppb		0.9 m
GreyWolf IQ 610	Relative humidity	0 to 100% RH	±2% RH <80% RH, (±3% RH >80% RH)	0.9 m
GreyWolf IQ 610	Temperature	-10° to +70°C	±0.3°C	0.9 m
LightHouse 3016	Particle count	0.3 to 10.0 µm	10% (20% for 0.3µm)	0.9 m
LightHouse 3016	Temperature	0° to 50°C	±0.5°C	0.9 m
LightHouse 3016	Relative humidity	15 to 90% RH	±2% RH	0.9 m
ThermoAir 6/64	Air speed	0 to 1 m/s	1.5% + 0.5% of full scale	0.1 m, 0.7 m, 1.1 m
LiCor LI-210	Illuminance	0 to 60000 lux	5%	Desktop (x2), cube @ 1.25 m
RTD	Air temperature	-50 to 250 °C	0.12%	0.1 m, 0.7 m, 1.1 m
RTD	Radiant temp.	-50 to 250 °C	0.12%	0.7 m
B&K 2236	Sound pressure level	18 to 140 dB	Type 1	1.2 m
Camera with wide-angle lens	Luminance	0 – 6000 cd/m^2	~15%	1.5 m

The Pyramids were designed to collect a subset of the parameters collected by the cart, but at a fixed location and in a longitudinal manner, recording each parameter every 15 minutes. The instruments and sensors used on the pyramids are shown in Table 4.

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[3] ASHRAE Standard 55 [2004] specifies that the measurement positions above ground appropriate for the determination of thermal comfort 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 by 0.1 – 0.3 m. We deviated from the ASHRAE specifications due to issues of practicality; we had many other sensors that went beyond thermal conditions, and they could not all be mounted in the same place because of the size of the instruments and the potential for interference with each others' measurements. Thus the final positions were a compromise between ASHRAE's specifications and the physical constraints. However, our previous experience with similar measurements in our Cost-effective Open-Plan Environments (COPE) field study [Veitch et al., 2003] suggested that height variations of this size are unlikely to have a large effect for typical office spaces.

Table 4. Summary information on pyramid instruments/sensors.

Instrument/sensor	**Parameter measured**	**Range**	**Accuracy** **(specified by manufacturer)**
Vaisala GMW20	Carbon dioxide	0 to 2000 ppm	<±30 ppm CO2 +2% of reading]
Vaisala HMP50	Relative humidity	0 to 98 % RH	0 to 90 % RH = ±3 %RH, 90 to 98 % RH = ±5 %RH
TSI 8475	Air speed	0.05 m/s to 0.5, 0.75, 1.00, 1.25, 1.50, 2.0, 2.5 m/s	±3.0% of reading ±1.0 % of range
LiCor LI-210	Illuminance	0 to 60000 Lux	5 %
RTD	Air temperature	-50 to 250 °C	0.12 %
RTD	Radiant temp.	-50 to 250 °C	0.12 %
Norsonic Nor131	Sound pressure level	17 to 140 dB	Class 1

Cart-based measurements were made during normal working hours only, to capture the conditions experienced by occupants.

Practical considerations prevented us from using the cart to collect data at all possible occupant locations in the building. We chose to focus on office spaces, as the single space type to which most occupants are exposed to more than any other. Before visiting each site we reviewed the floor plans and chose a target sampling pattern representative of the balance of space types (open-plan vs. enclosed, perimeter vs. interior) and orientations, and balanced across floors.

We were also committed to causing the least possible disruption to building occupants. Therefore, when on site, we first looked for measurement locations that were temporarily unoccupied (e.g. usual occupant at a meeting, on vacation). Because this unoccupied space was usually surrounded by other occupied spaces, and because these spaces were all served by common building systems, we judged that this would provide us with measurements representative of those experienced by occupants. For acoustics-related measurements we needed to place a loudspeaker in an adjacent space. This loudspeaker briefly generated a standard noise signal (picked up by the microphone on the cart), and thus required that the adjacent space was also unoccupied, or had an occupant who was willing to be disturbed for a few minutes. These considerations meant that some on-site modifications were made to the pre-visit sampling plan.

Photographs for luminance mapping via HDR photography [e.g. Inanici, 2006] were centred on the computer screen in an office, and taken from as far back as possible to include surrounding surfaces. Following this, the remainder of the measurements were made with the cart placed in the location the occupant would be in if they were working on their computer. Figure 3 shows a schematic diagram of the cart location, including locations of illuminance sensors placed on the desktop during the cart visit.

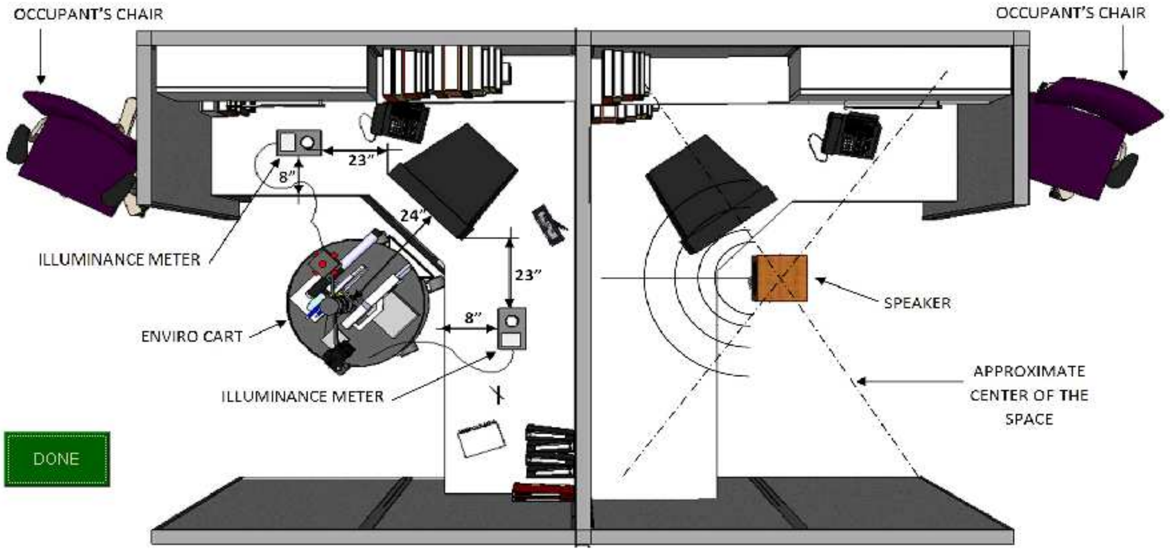


Figure 3. Schematic diagram of cart location during the majority of the measurement procedure.

Data collection from the instruments/sensors was semi-automated via software controlled by the researcher from a laptop computer that communicated wirelessly with the cart. During this process, the researcher also manually recorded several other workstation characteristics, including: relative location of office entrance and occupant's computer; height of walls (and whether workstation was enclosed); length and width of workstation; ceiling height; floor, ceiling and wall finishes; lighting type; distance to a window, window orientation, sky condition, and whether window was open; distance to printer/copier; shade type, opacity, and position.

Pyramid locations (up to six) were also chosen to be representative of the variety of workstation types in the building. Pyramids were placed in a single location for several days, and again, we tried to find locations where the usual occupant would be absent for this period. If positioned in a workstation, they were generally located on a desk, close to the normal seating position of the occupant.

We wanted to collect additional information regarding the office properties. We were conscious that these could vary across the building, and we chose to sample at the same places that the pyramids were located. Sometime during the period that the pyramid was collecting data, a researcher returned to each pyramid to check that it was operating normally and to make supplementary measurements and observations, including: photographs of the general office layout, furniture, floor, and ceiling plan; reflectance measurements (using Konica Minolta CM2500d) of all major surfaces; luminaire and lamp type; furniture manufacturer; air supply/return location; window and shading type.

These data were supplemented by data from a structured interview with the building manager/operator to gather information on the following topics: building size and age; number and type of occupants; HVAC system type and operation; lighting system type and operation; use of sound masking; complaint handling procedure; availability of energy data; occupant transportation options; major retrofits; availability of green building certification documents (if applicable).

2.3 Occupant Questionnaire

In addition to the physical measurements, occupants at the study sites were invited by NRC to complete an on-line questionnaire hosted on our server in Ottawa. Questionnaire items were chosen to address elements that green buildings are said to improve or affect, based on the credits provided by green building rating schemes, and recent research on the built environment and well-being. The relevant literature for each area is cited below in relation to each concept. The large majority of questionnaire items were drawn from prior studies that had shown them to be valid and sensitive measures. The questionnaire was available in both English and French, where appropriate.

The questionnaire was organized into seven modules; Table 5 gives a brief description of each module. All respondents were asked to complete the core module; they were then presented with any two of the six other modules, randomly assigned. We took this approach to keep the time burden reasonable for respondents, while preserving a valid sample size.

Table 5. Summary description of questionnaire modules, and number of responses to each module.

Module	# 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

The individual items in each module are described below.

Core Module

Environmental Features Rating (EFR)

Satisfaction with 18 specific aspects of the work environment, scored on a 7-point scale from 1 (very unsatisfactory) to 7 (very satisfactory). This set of questions was originally developed for a prior NRC study on Cost-effective Open-Plan Environments (COPE) [Veitch et al., 2007], based on the Ratings of Environmental Features developed by Stokols & Scharf [1990]. The COPE research demonstrated that the 18 items formed a stable 3-factor structure to create subscale scores for satisfaction with lighting (Sat_L), with ventilation & temperature (Sat_VT), and with privacy & acoustics (Sat_AP); the physical environment in individual cubicles predicted their occupants' satisfaction on these scales [Veitch et al., 2003]. We followed the same structure, in which subscale scores are the mean of the contributing items, as shown in Table 6.

Table 6. Individual items in environmental features ratings, with associated subscale designation.

Question	Subscale
Amount of lighting on your desktop	Sat_L
Overall air quality in your work area	Sat_VT
Temperature in your work area	Sat_VT
Aesthetic appearance of your office	Sat_AP
Level of privacy for conversations in your office	Sat_AP
Level of visual privacy within your office	Sat_AP
Amount of noise from other people's conversations while you are at your	Sat_AP
Size of your personal workspace to accommodate your work, materials, and visitors	Sat_AP
Amount of background noise (i.e. not speech) you hear at your workstation	Sat_AP
Amount of light for computer work	Sat_L
Amount of reflected light or glare in the computer screen	Sat_L
Air movement in your work area	Sat_VT
Your ability to alter physical conditions in your work area	Sat_AP
Your access to a view of outside from where you sit	Sat_L
Distance between you and other people you work with	Sat_AP
Quality of lighting in your work area	Sat_L
Frequency of distractions from other people	Sat_AP
Degree of enclosure of your work area by walls, screens or furniture	Sat_AP

Overall Environmental Satisfaction (OES)

This measure was also developed under NRC’s COPE project, and has been shown to relate to conditions in the physical environment [Veitch et al., 2003]. Two-items were used, and their average was the OES score. The first asked participants to rate how their personal productivity is affected by the physical environment, on a 7-point scale from -30% to +30%. This was developed by Wilson and Hedge [1987]. The second item used the same scale as the EFR, and asked participants to consider all of the environmental conditions in their workstations, and to rate their degree of satisfaction with the indoor environment in their workstations, as a whole.

Job Satisfaction

A single-item measure of overall job satisfaction was used, based on the question used by Dolbier et al. [2005]. It used the same scale as the EFR, but asked participants “Taking everything into consideration, what is your degree of satisfaction with your job as a whole?” The COPE research found that OES predicted job satisfaction [Veitch et al., 2007], a relationship supported in other NRC research [Veitch et al., 2010].

Demographics

Participants were asked to report their sex, age, job type, type of computer monitor, education, years of work experience (general and with their present employer), and education.

Job Demands

The job demand questions were taken from the organizational psychology literature [Lowe et al., 2003]. Four items were presented (“My job is very stressful”; “My job is hectic”; “I have difficulty keeping up with the workload”; “I often experience conflicting demands from other people”), scored from 1 (strongly disagree) to 7 (strongly agree). This measure was used to establish the comparability of the jobs in pairs of green and conventional buildings.

Window Proximity and Workstation Tenure

Participants were asked to indicate the availability of a window to the outside, with four response categories: "Yes, in my office"; "Yes, in the office next to me"; "No, but there is a window across the corridor"; "No, there is no window visible from my office". Participants were also asked whether or not they had moved to a new workstation during the previous three months. Window access predicts satisfaction with lighting, satisfaction with ventilation and temperature, and OES [Veitch et al., 2005].

Work Time Allocation

Participants were asked to report the percentage of time at work spent doing the following activities (total 100%): Computer and quiet work; Telephone work; Meetings, interactions in one's own workspace; Scheduled meetings outside one's workspace; Informal interactions outside one's workspace; Taking breaks; Doing office chores/lab work [Brill & Weidemann, 2001]. This measure was used to establish the comparability of the jobs in pairs of green and conventional buildings.

Module 1

This module addressed the relationships between the occupant and the organization. Two previous NRC field studies found links between workstation lighting and these outcomes [Veitch et al. 2010b; Veitch et al. 2010].

Organizational commitment

This module included the six-item scale of affective organizational commitment developed by Meyer et al. [1993]. The individual items are shown in Table 7, and were scored from 1 (strongly disagree) to 7 (strongly agree). The composite scale score was the average of six items (after reverse coding).

Table 7. Individual items in organizational commitments ratings, with reverse-coded items indicated.

I would be very happy to spend the rest of my career with <*this organization*>	
I really feel as if <*this organization*'>s problems are my own	
I do not feel a strong sense of "belonging" to <*my organization*>	R
I do not feel "emotionally attached" to <*this organization*>	R
I do not feel like "part of the family" at <*my organization*>	R
<*This organization*> has a great deal of personal meaning for me	

R=Reverse coded

Intent to Turnover

This three-item scale of turnover intention (leave present employer voluntarily) was developed by Colarelli [1984]. The individual items ("I am planning to search for a new job outside of <*organization*> during the next 12 months"; "I often think about quitting this job"; "If I have my own way, I will be working for <*organization*> one year from now") were scored from 1 (strongly disagree) to 7 (strongly agree). The composite scale score was the average of the three items (after reverse coding the final item).

Workplace Image

Three questions were used to assess employee opinions concerning the match between the physical environment in which they work and their understanding of corporate values, based on questions used by workplace design consultants, which they have found to have practical utility [Laing, 2005]. The individual items (“This office environment is a good expression of our corporate values”; “This office environment was designed with us in mind”; “This office environment is consistent with our mission”) were scored from 1 (strongly disagree) to 7 (strongly agree). The composite scale score was the average of the three items.

Internal Communications

Interior design decisions in open-plan offices are often said to have been made in order to foster good internal communication [Heerwagen et al., 2004]. We used the Communication & Social Support scale from Lowe et al. [2003]. The individual items (“Communication is good among the people I work with”; “The people I work with are helpful and friendly”; “I have a good relationship with my supervisor”; “I receive recognition for work well done”) were scored from 1 (strongly disagree) to 7 (strongly agree). The composite scale score was the average of the four items.

Module 2

These questions focused on acoustics issues, and were developed by researchers in NRC’s Acoustics Sub-Program in order to validate and to provide more detail on this aspect of the work environment, which the literature review had revealed as a potential problem in green buildings. The individual items are shown in Table 8. All were rated on a 7-point scale from 1 (very) to 4 (moderately) to 7 (not at all), except for the eighth item, related to privacy, which was rated on a 7-point scale from 1 (not at all private) to 4 (moderately private) to 7 (very private). These items were then reverse-coded, such that high values indicated poor performance. We constructed subscales from multiple items related to speech privacy (Speech, Cronbach’s alpha = .79) and non-speech sounds (Non-Speech, Cronbach’s alpha = .77), and a variation on the speech privacy subscale related only to overheard speech from others (Speech2, Cronbach’s alpha = .79).

Table 8. Individual items in acoustics module, with associated subscale designation.

Question	**Subscale**
How disturbing do you find the noise (from all sources other than speech) that you hear at your workstation?	Non-Speech
Noise from heating, ventilating and cooling systems?	Non-Speech
Noise from office equipment (e.g. printers, copiers, computers, telephones ringing)?	Non-Speech
Noise from washrooms and other plumbing noises?	Non-Speech
Noise from outdoors (e.g. road traffic)?	Non-Speech
Speech sounds from others in your office?	Speech, Speech2
Non-speech sounds generated by others in your office (e.g. footsteps, shuffling papers)?	Non-Speech
Rate the privacy of your workstation (i.e. do you feel you can have a private conversation or phone call at your workstation)?	Speech
At your workstation, how understandable are overheard conversations and phone calls from others in your office?	Speech, Speech2
Noise (from all sources other than speech) that you hear at your workstation?	Non-Speech
Overheard speech from others in your office?	Speech, Speech2

Module 3

This module focused on Thermal Comfort issues, both in the classical sense of thermal sensation [ASHRAE 2004] and adding information about adaptive responses in line with more recent discussions about green buildings [Barlow & Fiala 2007]. The individual thermal sensation items ("Please rate your typical thermal sensation in your workstation in the winter"; "Please rate your typical thermal sensation in your workstation in the summer"; "At the moment I feel…") were scored on a 7-point scale from 1 (cold) to 4 (neutral) to 7 (hot). A single item on current thermal preference had three response options: "cooler"; "no change"; "warmer" [McIntyre, 1980].

Further questions asked about adaptive responses used by occupants [Huizenga et al, 2006; Bordass et al., 1994; Brown and Cole, 2009]. Participants were asked to indicate how often they took various actions to improve their thermal comfort in their office. The individual actions are shown in Table 9; response options (coded from 1-7) were: Never; Once per month; 2-4 times per month; Once per week; 2-4 times per week; At least once per day; Several times per day; Not an option for me. We then created four sub-scales from these items, 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); for the purposes of these scales, we coded "Not an option for me" the same as "Never". Participants were also offered an open text box to describe any other actions they took.

Table 9. Individual items in thermal adaptation section, with associated subscale designation.

Question	Sub-scale
Have a hot or cold drink to improve your thermal comfort in your office	Adap_NoEnergy, Adap_Person
Use a portable heater to improve your thermal comfort in your office	Adap_Energy, Adap_Enviro
Use a portable fan to improve your thermal comfort in your office	Adap_Energy, Adap_Enviro
Change the thermostat to improve your thermal comfort in your office	Adap_Energy, Adap_Enviro
Add or remove a layer of clothing to improve your thermal comfort in your office	Adap_NoEnergy, Adap_Person
Open or close the window to improve your thermal comfort in your office	Adap_NoEnergy, Adap_Enviro
Adjust a window blind or curtain to improve your thermal comfort in your office	Adap_NoEnergy, Adap_Enviro

Participants were also asked a simple Yes/No question on 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 ensemble they typically wore in their office in the current season. We created composite ensembles based on ASHRAE Standard 55 [ASHRAE, 2004]to simplify the question. Response options are shown in Table 10 along with the estimated insulation value of the ensemble, in clo units.

Table 10. Individual items in clothing ensemble options list, with estimated insulation value.

Ensemble	clo
Shorts or knee-length skirt, short-sleeve shirt	0.54
Shorts or knee-length skirt, short-sleeve shirt, sweater or jacket	0.89
Shorts or knee-length skirt, long-sleeve top	0.67
Shorts or knee-length skirt, long-sleeve shirt, long-sleeve sweater or jacket	1.02
Trousers or ankle-length skirt, short-sleeve shirt	0.57
Trousers or ankle-length skirt, short-sleeve shirt, sweater	0.92
Trousers or ankle-length skirt, long-sleeve shirt	0.61
Trousers or ankle-length skirt, long-sleeve shirt, sweater	0.96
Trousers or ankle-length skirt, long-sleeve shirt, suit jacket	0.96
Trousers or ankle-length skirt, long-sleeve shirt, suit jacket, vest or T-shirt	1.14
Trousers or ankle-length skirt, long-sleeve shirt, suit jacket, sweater, vest or T-shirt	1.49

Module 4

This module concerned effects related to the effect of light exposure on individuals. The International Commission on Illumination (CIE) issued a report in 2004 that suggested potential health and well-being benefits of increasing daily light exposure [CIE 2004/2009]. An increase in light exposure might be expected for green building occupants because of the emphasis on daylighting.

Chronotype

This scale, developed by Di Milia et al. [2008], assesses, in layman's terms, whether individuals are "morning people" or "evening people". This individual difference can influence daily light exposure [Goulet et al., 2007]. The individual items are shown in Table 11, and asked participants to indicate when they would prefer to do certain things relative to most people. All were rated on a 5-point scale from 0 (Much earlier than most people) to 2 (About the same as most people) to 4 (Much later than most people). The composite scale score was the sum of the six items.

Table 11. Individual items in chronotype scale.

When would you prefer to take an important three-hour examination?
When would you prefer to get up?
When would you prefer to do some difficult mental work that needed full concentration?
When would you prefer to get up if you had a day off and nothing to do?
When would you prefer to have an important interview at which you needed to be at your best?
When would you prefer to eat breakfast?

Sleep Quality at Night

Daytime light exposure influences the quality of night-time sleep [CIE 2004/2009]. We used the Groningen Sleep Quality Scale [Leppämäki, 2003]. Participants were asked to provide True (0) /False (1) responses to 15 items as shown in Table 12. The composite score was the sum of the individual items (after reverse coding); the first question did not count for the total score.

Table 12. Individual items in sleep quality scale, with reverse-coded items indicated.

I had a deep sleep last night	
I feel that I slept poorly last night	
It took me more than half an hour to fall asleep last night	
I woke up several times last night	
I felt tired after waking up this morning	
I feel that I didn't get enough sleep last night	
I got up in the middle of the night	
I felt rested after waking up this morning	R
I feel that I only had a couple of hours' sleep last night	
I feel that I slept well last night	R
I didn't sleep a wink last night	
I didn't have trouble falling asleep last night	R
After I woke up last night, I had trouble falling asleep again	
I tossed and turned all night last night	
I didn't get more than 5 hours' sleep last night	

R=Reverse coded

Positive and Negative Experiences

To assess overall well-being (which is believed to be influenced by daily light exposure [CIE 2004/2009]), we used a new scale developed by Diener, et al. [2009]. Participants were asked to report how much they experienced each of 12 feelings. The individual items are shown in Table 13. All were rated on a 5-point scale 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.

Table 13. Individual items in positive/negative feelings scale, with associated subscale designation.

Positive	P
Negative	N
Good	P
Bad	N
Pleasant	P
Unpleasant	N
Happy	P
Sad	N
Afraid	N
Joyful	P
Angry	N
Contented	P

P=contributes to positive scale; N=contributes to negative scale

View quality

Participants with access to a view through a window were asked to rate that view on an 11-point scale from 1 (Unattractive) to 11 (Attractive). View quality has been associated with well-being and work and night-time sleep quality [Aries et al., 2010].

Module 5

This module related to health symptoms and their consequences, conditions that green buildings are said to improve relative to conventional buildings. Visual discomfort was measured using a short version of the scale developed by Wibom and Carlsson [1987]. More general physical discomfort measures were adapted from the literature [e.g., Hedge et al., 1992] and placed in the same format as the visual discomfort symptoms. Veitch & Newsham [1998] and Newsham et al. [2004] have found these discomfort measures to be sensitive to changes in lighting conditions. Table 14 shows the individual items. For each symptom, participants were asked to report, on 5-point scales, both the frequency (VCF, PCF) (Never (1); Very rarely; Monthly; Weekly; Daily (5)) and intensity (VCI, PCI) (None (1); A little uncomfortable; Somewhat uncomfortable; Uncomfortable; Very uncomfortable (5)). Composite scales were constructed, including a mean frequency and intensity score for both visual and physical discomfort. An overall visual discomfort score was the mean value of the frequency multiplied by intensity for each item (VCOMF), and an overall physical discomfort score was similarly constructed (PCOMF).

Table 14. Individual items in visual/physical discomfort scales, with associated subscale designation.

Smarting, itchy, or aching eyes	V
Dry, irritated skin	P
Teary eyes	V
Dry eyes	V
Sore back, wrists or arms	P
Stuffy, congested, or runny nose	P
Headache	P
Sore, irritated throat	P
Sensitivity to light	V
Excessive fatigue	P
Wheezing, chest tightness	P

V=contributes to visual discomfort scale; P=contributes to physical discomfort scale

In addition participants were asked to report on the number of work days missed in the past month because they were personally ill, and the number missed for any reason, scored from 0 to 5+.

Module 6

Transport/Commuting

Among the goals of some green building projects is the promotion of sustainable modes of transportation to the workplace. We examined this using questions from the environmental psychology and human geography literature [Gardner & Abraham, 2008; Gardner, 2009; Verplanken, et al., 2008]. Participants were asked to report all modes of transport used to get to work from: Carpool; Taxi; Car (no passengers); Bus/Tram/Subway/LRT; Train; Bicycle; Foot. They were then asked to indicate which was their primary mode, how many days per week they used it, and how long the journey to work took. They were also asked their reason for using this mode: Cost; Travel Time; Parking Availability; Other Responsibilities/Errands; Pleasure; Exercise; Other (please specify). They were then asked the same questions about their secondary mode of transport.

Environmental Attitudes

Environmental attitudes may be an important mediator of responses to other survey questions. We used the New Environmental Paradigm (NEP) Scale [Dunlap et al., 2000] to measure such attitudes. This scale contained 15 items, shown in Table 15, and were scored on a 5-point scale from 1 (strongly disagree) to 5 (strongly agree). The composite NEP score was the average of the 15 items (after reverse coding). Participants can be categorized as low or high in environmental concern according to a median split [Verplanken et al., 2007].

Table 15. Individual items in New Environmental Paradigm scale, with reverse-coded items indicated.

We are approaching the limit of the number of people the earth can support	
Humans have the right to modify the natural environment to suit their needs	R
When humans interfere with nature it often produces disastrous consequences	
Human ingenuity will insure that we do NOT make the earth unliveable	R
Humans are severely abusing the environment	
The earth has plenty of natural resources if we just learn how to develop them	R
Plants and animals have as much right as humans to exist	
The balance of nature is strong enough to cope with the impacts of modern industrial nations	R
Despite our special abilities humans are still subject to the laws of nature	
The so-called 'ecological crisis' facing humankind has been greatly exaggerated	R
The earth is like a spaceship with very limited room and resources	
Humans were meant to rule over the rest of nature	R
The balance of nature is very delicate and easily upset	
Humans will eventually learn enough about how nature works to be able to control it	R
If things continue on their present course, we will soon experience a major ecological catastrophe	

R=Reverse coded

2.4 Energy and Water Data

For energy and water data, we relied primarily on monthly utility bills from the buildings' records. Unfortunately, these were not universally available in a complete time-series over a lengthy period. On the other hand, in some cases, more detailed sub-system data was available.

2.5 Procedure

Data collection at the study buildings was co-ordinated with the site visits. The month during which each building was visited in shown in Table 1. The NICE cart measurements were collected over a period of 2-4 days at each building, with pyramids in place for a similar period. Supplementary physical data and interviews with the building operator were also conducted in this period. Typically, the first invitation to the on-line questionnaire was sent a few days before the site visit. A week later a reminder was sent to those who had not responded, and another reminder followed a week after that. The questionnaire was closed a week after this last reminder.

3. Results

3.1 Statistical Methods

The principal method for exploring our hypotheses regarding the performance of green vs. conventional buildings was the Wilcoxon Signed Ranks Test on data aggregated at the building level. This approach is illustrated by Figure 4. The mean value of an outcome (Figure 4 shows rating of overall environmental satisfaction as an example) was calculated for each building and rank ordered. From Figure 4, it appears that green buildings tended towards the upper end of the scale; the Wilcoxon Signed Ranks Test allows us to test whether this is a statistically-significant phenomenon. The difference between paired buildings is calculated, and the absolute value of these differences are rank-ordered. The null hypothesis is that these ratings will be randomly distributed — that is, there will be as many cases where green buildings are rated more highly than their conventional pair as there are green buildings that are less highly rated, and further that the differences in either direction will be both large and small. This is a non-parametric test, which is favoured over the corresponding parametric test (a paired t-test) when sample normality is either difficult to establish (which is true with small sample sizes) or not expected [Siegel & Castellan, 1988]. Moschandreas & Nuanual [2008] followed this approach for their green building study (although details of method and results in their paper are scant).

Following these analyses we then looked at relationships between physical measurements and survey outcomes, again measured at the building level, regardless of the building type and pairing. This enabled us to draw general conclusions about which physical conditions engendered positive outcomes for occupants. We conducted these analyses using straightforward linear regression.

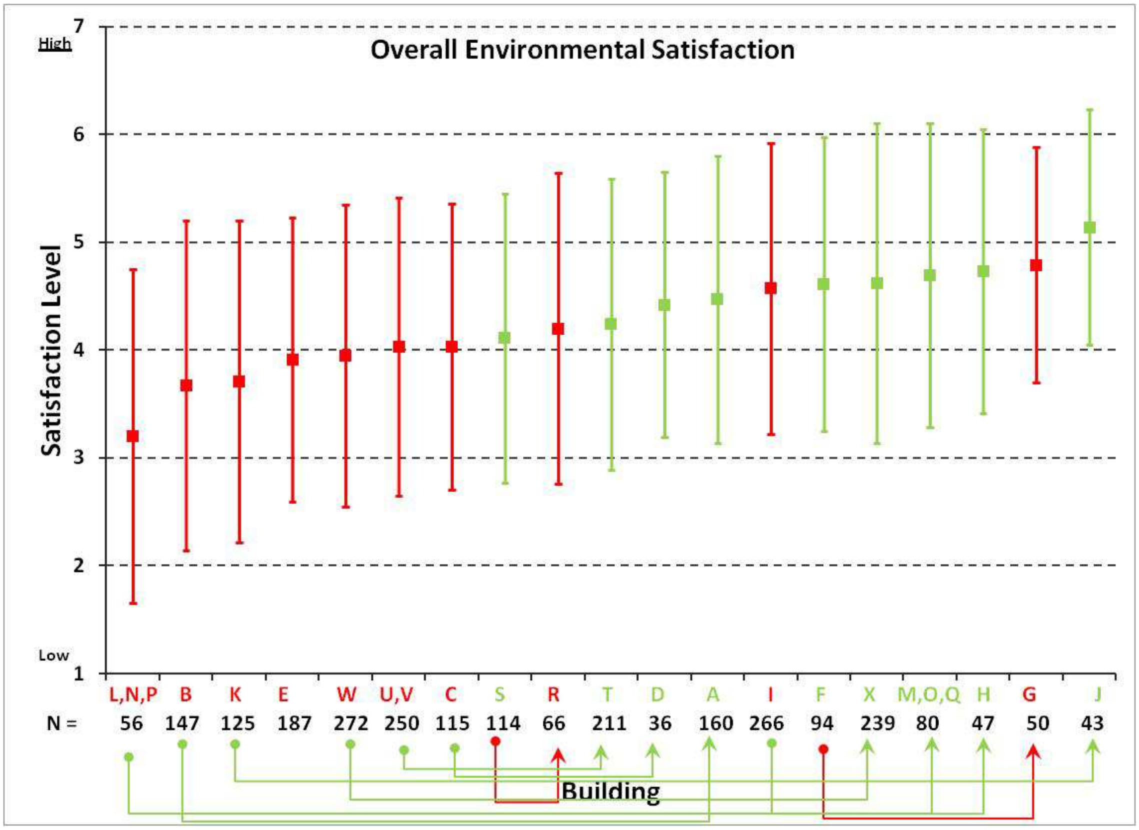


Figure 4. Mean (and s.d.) rating of overall environmental satisfaction for each study building in a pair (N=number of individual ratings comprising the mean). Buildings have been rank-ordered according to this rating, and colour-coded (green = green buildings; red = conventional buildings). Arrows below the x-axis connect paired buildings, and are colour-coded according to which building in the pair had the higher ranking.

We report the results of our analysis below. In general, we only present the results of statistically-significant tests in tables, and it is only these that we consider in interpreting the results of our study. We do report means for green and conventional buildings in the text even when differences were not statistically significant, but we do this only to illustrate the general conditions prevailing in the study buildings independent of building type. Appendix B contains descriptive statistics of the primary variables collected via the questionnaire and NICE cart.

Conventionally, tests would be considered statistically significant if the value *p* is lower than .05 (alpha). However, if one has reason to expect that the effect should be in one direction, one can use the one-tailed *p*-value (half the two-tailed value) to test against alpha [Siegel, 1956]. Our hypotheses provided these expectations – for most outcomes (except those related to acoustics), we expected green buildings to perform better. Thus, outcomes of our Wilcoxon Signed Ranks analyses may be labelled as statistically significant with two-tailed *p*-values of .10, as long as the trend is in the hypothesized direction.

3.2 Green vs. Conventional Buildings

3.2.1 Survey Outcomes

Table 1 reports the number of completed questionnaires received from each site, and the associated response rates. Response rates across sites ranged from 20-70%, with a mean of site-level response rates of 39%. We found this to be a very satisfactory response rate for an on-line, voluntary survey, and response rates for on-line surveys on a similar topic in other recent studies fell within our range of response rates across buildings [Lee, 2011; Monfared & Sharples, 2011].

Core Module

Job Demands

The main purpose of this variable was to ensure a good match between buildings, and indeed, there was no statistically-significant difference between the building types on this scale, suggesting that the jobs conducted by the occupants of the two building types were similar. The building-level means for the green and conventional buildings were 4.28 and 4.47 (scale: 1-7) respectively, suggesting that, overall, jobs were on the demanding side of neutral.

Environmental Satisfaction

In the case of all environmental features ratings, a higher value indicates a better rating. Table 16 shows that building-level ratings of overall environmental satisfaction (OES) were significantly higher for green buildings. Overall, OES was neutral for conventional buildings, but above neutral for green buildings. For the individual EFR sub-scales, green buildings rated significantly higher for satisfaction with ventilation and temperature (Sat_VT). Overall, Sat_VT was neutral for conventional buildings, but above neutral for green buildings. There were no significant differences between building types for satisfaction with lighting (Sat_L) or satisfaction with acoustics and privacy (Sat_AP). Mean values for these scales (Sat_L, green=5.36; conv.=5.05; (scale: 1-7)) (Sat_AP, green=4.43; conv.=4.16 (scale: 1-7)) indicate a high overall level of satisfaction with lighting conditions, and overall impressions of acoustics and privacy on the satisfied side of neutral . However, if we look at tests on the individual EFR items related to these sub-scales, we do see significant effects related to specific environmental features. Table 17 shows these individual item tests. Overall, building occupants were satisfied with the aesthetic appearance of their office and the size of their workspace, but ratings were very high for green buildings. (Note that later analysis of physical measurements shows average office sizes were the same between building types). Similarly, in general, building occupants were satisfied with their access to a view of outside, but ratings were significantly higher for green buildings. As a supplement to this, we used the Goodman-Kruskal Tau test to examine the responses to the question on self-reported proximity of a window to the outside *vis-a-vis* the respondent's office. Table 18 shows that of the nine tests, five were statistically significant, with strengths ranging from 2-11%. Four of the five significant tests suggested that the green buildings offered greater access to a window to the outside, which is not surprising given the design goals in many green buildings.

Table 16. Results of Wilcoxon Signed Ranks Test related to environmental satisfaction composite measures, and related means (scale: 1-7) of building-level means for each building type.

Outcome	**Ranks**		**Sum of Ranks**		**Z**	***p***	**Mean Rating**	
	Pos.	**Neg.**	**Pos.**	**Neg.**			**Green**	**Conv.**
OES	8	1	42	3	-2.31	.021	4.55	4.01
Sat_VT	8	1	44	1	-2.55	.011	4.75	3.95

Using OES as an example, "Pos./Neg." indicates that of the 9 building pairs, in how many cases did the green buildings have higher ratings (which in this case means better performance). "Sum of Ranks" is the total of 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. "Z" is the test statistic calculated from the difference in the sum of ranks. "p" is the probability of seeing an effect this large if there was, in fact, no effect.

Table 17. Results of Wilcoxon Signed Ranks Test related to individual environmental features ratings (not included in composites above), and related means of building-level means (scale: 1-7) for each building type.

Outcome	**Ranks**		**Sum of Ranks**		**Z**	***p***	**Mean Rating**	
	Pos.	**Neg.**	**Pos.**	**Neg.**			**Green**	**Conv.**
Aesthetic appearance … (Sat_AP)	9	0	45	0	-2.67	.008	5.55	4.34
Size of personal workspace … (Sat_AP)	7	2	42	3	-2.31	.021	5.44	4.80
Access to a view of outside … (Sat_L)	8	1	38	7	-1.84	.066	5.18	4.58

Table 18. Information on window location for the occupants of the study buildings who completed the questionnaire. A dark outline with dashed grid indicates a statistically-significant distribution between building pairs, using the Goodman-Kruskal (G-K) test.

Building Code Letter	**Type**	**Window Location**			
		In my office	**In office next to me**	**Across the corridor**	**No window visible**
A	G	71	7	16	6
B	C	34	12	12	42
C	C	80	3	12	5
D	G	74	14	11	0
F	G	63	12	22	3
G	C	57	8	22	12
H	G	38	2	47	13
I	C	34	8	23	35
J	G	55	10	24	12
K	C	65	10	9	16
LNP	C	61	11	23	5
MOQ	G	81	9	10	0
R	C	95	5	0	0
X	G	53	10	12	25
S	G	34	25	26	15
W	C	10	10	50	30
T	G	23	6	51	20
UV	C	26	13	45	15
E	C	57	10	13	19

Job Satisfaction

Job satisfaction was very high for occupants of both building types (green=5.72; conv.=5.57 (scale: 1-7)), and there was no statistically-significant difference between the building types.

Module 1

Items in this module related to the concept of satisfaction with the organization that the respondent worked for. There was no statistically significant effect on the outcomes related to organizational commitment, intent to turnover, or internal communications, but a significant difference for workplace image. Overall means indicated a high level of organizational commitment (green=4.81; conv.=5.00

(scale: 1-7)), low intent to turnover (green=2.77; conv.=2.71 (scale: 1-7)), and a very high level of satisfaction with internal communications (green=5.73; conv.=5.68 (scale: 1-7)). Table 19 shows the significant effect related to workplace image: green buildings had a significantly higher rating of workplace image, suggesting that green buildings were a better expression of corporate values than conventional buildings. Overall, workplace image was neutral for conventional buildings, but above neutral for green buildings.

Table 19. Results of Wilcoxon Signed Ranks Test related to workplace image scale, and related means of building-level means (scale: 1-7) for each building type.

Outcome	**Ranks**		**Sum of Ranks**		**Z**	***p***	**Mean Rating**	
	Pos.	**Neg.**	**Pos.**	**Neg.**			**Green**	**Conv.**
Workplace Image	9	0	45	0	-2.67	.008	4.86	3.96

Module 2

Items in this module related to acoustics. For the individual items there was only one statistically-significant effect, in that noise from HVAC systems was rated as less disturbing in green buildings (Table 20), although in both building types this noise was rated below the mid-point of the disturbance scale. 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 for both building types (green=2.56; conv.=2.68 (scale: 1-7)), and concerns with speech privacy (Speech) above the mid-point of the scale for both building types (green=4.71; conv.=4.62 (scale: 1-7)).

Table 20. Results of Wilcoxon Signed Ranks Test related to individual acoustic items, and related means of building-level means (scale: 1-7) for each building type.

Outcome	**Ranks**		**Sum of Ranks**		**Z**	***p***	**Mean Rating**	
	Pos.	**Neg.**	**Pos.**	**Neg.**			**Green**	**Conv.**
Noise from heating, ventilating and cooling systems?	1	8	5	40	-2.07	.038	2.28	2.96

These analyses included data from occupants of all office types, and we did not know from the survey responses if the occupant was in an open-plan or private office. Our hypothesis (#8) was that green buildings would perform more poorly with respect to speech privacy, due to office designs that would include few sound absorbing materials and lower panel heights. One would expect this effect to be particularly manifest in open-plan settings. Therefore we conducted additional t-tests on building pairs 8 and 9, which featured open-plan offices almost exclusively, with relatively large sample sizes. However, these t-tests showed only two statistically-significant effects, for individual items on building pair 8 (Table 21). Both of these items refer to non-speech sounds, and indicate that although overall disturbance is below the mid-point of the scale, it was worse for the conventional building in the pair; this is consistent with the overall analysis above. 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 for both building pairs and types (Pair 8: green=2.65; conv.=2.91; Pair 9: green=2.63; conv.=2.54 (scale: 1-7)), and concerns with speech privacy (Speech) above the mid-point of the scale for both building types (Pair 8: green=4.92; conv.=5.27; Pair 9: green=5.32; conv.=5.13 (scale: 1-7)).

Table 21. Results of Wilcoxon Signed Ranks Test related to individual acoustic items (Building Pair 8 only), and related means (scale: 1-7).

Outcome	**t**	***p***	**N**		**Mean Rating (s.d.)**	
Building Pair 8			**Green**	**Conv.**	**Green**	**Conv.**
How disturbing do you find the noise (from all sources other than speech) that you hear at your workstation?	2.64	.011	33	90	3.12 (1.45)	3.92 (1.60)
Non-speech sounds generated by others in your office (e.g. footsteps, shuffling papers)?	2.05	.044	36	93	2.58 (1.38)	3.19 (1.83)

Although the analysis does not show any statistically-significant differences between building types on speech sounds, the data do show that speech privacy is unsatisfactory in office buildings generally.

Module 3

This module focused on thermal comfort issues. The three items related to thermal sensation were all bipolar with respect to comfort, so the middle of the scale represented the best possible performance, and either end of the scale represented poor performance. For analysis, we recoded these scales in terms of distance from the middle of the scale, irrespective of whether this represented warm or cool discomfort. There were no statistically-significant differences between building types on these scales. To take immediate thermal sensation (“At the moment I feel…”) as an example, overall means indicated an average distance from thermally-neutral of about one scale unit for both building types (green=0.88; conv.=1.04 (scale: 0-3)).

For the item related to thermal preference we looked at the fraction of respondents per building saying that they would prefer anything other than the current thermal conditions. There was a statistically-significant effect (Table 22), indicating that occupants of green buildings were less likely to prefer a change in thermal conditions: 40% of green building occupants would have preferred conditions to be either warmer or cooler than current, whereas almost 50% of conventional building occupants would have preferred a change.

Table 22. Results of Wilcoxon Signed Ranks Test related to thermal preference, and related means of building-level means (scale: 0-1) for each building type.

Outcome	**Ranks**		**Sum of Ranks**		**Z**	***p***	**Mean Rating**	
	Pos.	**Neg.**	**Pos.**	**Neg.**			**Green**	**Conv.**
Prefer change in thermal conditions	2	7	8	37	-1.72	.086	0.40	0.49

For the sub-scales related to thermal adaptation, there were three statistically-significant affects (Table 23), consistent in showing that the occupants of green buildings took fewer actions to attempt to secure their own thermal comfort. This indicates that green buildings provided a better basic level of thermal comfort. Some have suggested that green buildings should offer more adaptive opportunities in order to save energy in base building conditioning, with the adaptations offering a way to preserve comfort that would be more desirable to occupants than conventional operation [de Dear & Brager, 1998]. We did not record whether there were more adaptive opportunities in green buildings, but these results show that whatever was available was used less frequently than in similar conventional buildings.

Table 23. Results of Wilcoxon Signed Ranks Test related to thermal adaptive behaviours, and related means of building-level means (scale: 1-7) for each building type.

Outcome	**Ranks**		**Sum of Ranks**		**Z**	***p***	**Mean Rating**	
	Pos.	**Neg.**	**Pos.**	**Neg.**			**Green**	**Conv.**
Adap_Energy	2	7	4	41	-2.19	.028	1.47	1.93
Adap_NoEnergy	2	7	3	42	-2.31	.021	2.83	3.12
Adap_Enviro	1	8	1	44	-2.55	.011	1.53	1.95

Module 4

Items in this module addressed aspects of occupant well-being. There were no differences between building types on chronotype (means, green=9.84; conv.=9.72 (scale: 0-24)), this is as expected and is another confirmation that the populations in the building types were similar. For those occupants that had a view to the outside, there was no difference between building types on the rated quality of that view, with the mean rating for both building types on the attractive side of neutral (green=7.22; conv.=7.11 (scale: 1-11)). Overall, occupants of our study buildings indicated modest sleep issues, and an overall positive mood; however, building type moderated their experience: There were statistically significant effects on sleep quality at night and on affect balance (Table 24): occupants of green buildings experienced better sleep quality (lower score is better, indicating fewer problems) and more positive feelings.

Table 24. Results of Wilcoxon Signed Ranks Test related to well-being, and related means of building-level means (sleep scale: 0-14; affect balance scale: -24-24) for each building type.

Outcome	**Ranks**		**Sum of Ranks**		**Z**	**p**	**Mean Rating**	
	Pos.	**Neg.**	**Pos.**	**Neg.**			**Green**	**Conv.**
Sleep Quality at Night	0	9	45	0	-2.67	.008	3.99	4.85
Affect Balance	6	3	39	6	-1.96	.051	8.64	7.49

Module 5

Items in this module addressed aspects of occupant health in terms of symptom frequency and intensity. Both visual and physical symptom frequency were statistically significantly lower in green buildings (Table 25), though still occurring less than weekly for both building types. There was no effect of building type on visual (means, green=1.87; conv.=2.09 (scale: 1-5)) or physical (means, green=2.19; conv.=2.33 (scale: 1-5)) symptom intensity, means suggested relatively low intensity of discomfort when symptoms do occur. There was also no effect of building type on self-reported days away from work per month for personal illness (means, green=0.50; conv.=0.60 (scale: 0-5)), or for any reason (means, green=1.81; conv.=1.86 (scale:0-5)). The personal illness rates compare to the overall Canadian average for full-time workers in 2009 of 0.65 [StatCan, 2011].

Table 25. Results of Wilcoxon Signed Ranks Test related to discomfort symptoms, and related means of building-level means (scale: 1-5) for each building type.

Outcome	**Ranks**		**Sum of Ranks**		**Z**	**p**	**Mean Rating**	
	Pos.	**Neg.**	**Pos.**	**Neg.**			**Green**	**Conv.**
Visual discomfort frequency	2	7	7	38	-1.84	.066	2.13	2.48
Physical discomfort frequency	3	6	6	39	-1.96	.051	2.35	2.60

Module 6

Module 6 related to transportation and environmental attitudes. We found no statistically-significant difference in commuting distance (means, green=18.1 km; conv.=17.8 km), though it is noteworthy that the means for our sample were about double the Canadian median [Vital Signs, 2008]. As a supplement to this, we used the Goodman-Kruskal Tau test to examine the responses to the question on primary commuting mode. Table 26 shows that of the nine tests, two were statistically significant, with strengths of 11 and 3%, respectively. In both cases, one could interpret the effects as indicating that the occupants of the green buildings used more sustainable modes of transport, as might be hoped, but overall the evidence for this in our building sample is not strong.

Table 26. Information on commuting mode for the occupants of the study buildings who completed the questionnaire. A dark outline with dashed grid indicates a statistically-significant distribution between building pairs, using the Goodman-Kruskal (G-K) test.

Building Code Letter	Type	Primary Commuting Mode (%)				
		Carpool	Bus/Tram/Subw/LRT	Bicycle	Foot	Car
A	G	11	4	5	9	71
B	C	22	8	3	3	64
C	C	6	55	9	21	9
D	G	17	58	8	8	8
F	G	7	0	3	7	83
G	C	5	10	5	0	81
H	G	8	0	8	0	85
I	C	4	0	0	1	95
J	G	18	0	0	0	82
K	C	15	18	0	8	59
LNP*	C	11	32	16	11	32
MOQ*	G	18	50	14	0	18
R	C	23	38	23	0	15
X	G	11	59	7	10	13
S	G	17	48	3	21	10
W	C	17	19	1	2	60
T	G	10	0	0	0	90
UV*	C	1	0	1	0	97
E	C	13	7	2	5	73

We also found no statistically-significant difference in environmental attitudes between building types (means, green=3.67; conv.=3.65 (scale: 1-5)). Again, this is further confirmation that the populations in the building types were similar. In particular, the lack of difference in environmental attitudes suggest that the occupants of green buildings in our sample were not unusually motivated or biased [Monfared & Sharples, 2011]. The means on this scale suggested a level of environmental concern above neutral across buildings.

3.2.2 NICE Cart Outcomes

All of our analyses included tests for all workstation types combined, but for some variables we conducted tests for open-plan and private offices separately, or windowed and non-windowed offices separately. For these latter tests, we only included building pairs in which there were at least 10 workstations in each category for both buildings in the pair, we judged that smaller numbers would not provide reliable building-level means. Table 27 shows the numbers of each workstation type in each building.

Table 27. Number of offices sampled with NICE cart with type and window proximity characteristics, by building and building type.

Building Type	Pair Number	Building Code	Workstation Type		Window Proximity	
			Open-plan	Private	In Workstation	Outside Workstation
C	1	B	8	32	16	24
	2	C	32	13	29	16
	3	G	33	17	24	23
	4	I	27	11	15	23
	5	K	20	21	25	16
	6	LNP	28	19	25	22
	7	R	37	10	34	13
	8	W	68	1	2	67
	9	UV	70	0	6	64
G	1	A	16	37	33	20
	2	D	22	3	14	11
	3	F	28	17	23	22
	4	H	27	22	13	36
	5	J	20	5	10	15
	6	MOQ	35	39	57	17
	7	X	37	32	42	27
	8	S	58	1	21	38
	9	T	66	4	0	70

Enclosure

This category of outcomes included variables related to the physical size of the individual workstations where cart measurements were made: average height of walls, minimum height of walls, floor area, and ceiling height. We conducted tests for all workstation types combined, and for open-plan and private offices separately. Note that in a very small number of cases there were multiple workstations in a single enclosed space with a door, for our purposes these were coded as open-plan. Using the Wilcoxon Signed Ranks Test, there were no statistically-significant differences between these variables at the building average level. Using open-plan space as an example (eight building pairs had enough open-plan space for reliable statistics), overall mean values for average height of walls/partitions (green=1.8 m (71.0”); conv.=1.74 m (68.5”)), workstation area (green=6.64 m^2 (71.5 ft^2); conv.=6.83 m^2 (73.5 ft^2)), and ceiling height (green=3.07 m (121”); conv.=2.95 m (116”)) were typical of office space in general.

Sound

The cart-based physical measurements included metrics of speech intelligibility (STI, AI, SII, S/N ratio), and A-weighted background noise (AW). Of the several speech intelligibility indices we focussed on AI (Articulation Index) as it is defined in an ASTM standard for evaluating speech privacy [ASTM, 2008]. As with enclosure, we conducted tests for all workstation types combined, and for open-plan and private offices separately. We found statistically-significant effects related to speech intelligibility in private offices (Table 28), in which green buildings performed slightly worse, although both building types, on average, were at or close to the level for open plan workstations (0.15). It is worth noting that in private offices, occupants’ expectations for speech privacy are usually higher than in the open plan. However, only five building pairs had enough private offices for reliable statistics. Note that the speech privacy indicator in open-plan offices in both building types was poor (AI mean, green=0.42; conv.=0.38), and background noise, which may help to mask speech sounds, was relatively low in both building types (AW mean, green=42.6 dBA; conv.=43.1 dBA).

Table 28. Results of Wilcoxon Signed Ranks Test related to articulation index in private offices, and related means of building-level means for each building type.

Outcome	**Ranks**		**Sum of Ranks**		**Z**	**p**	**Mean Rating**	
	Pos.	**Neg.**	**Pos.**	**Neg.**			**Green**	**Conv.**
AI (Private Offices)	4	1	14	1	-1.75	.080	0.17	0.15

Lighting

For illuminance, we focussed our analysis on desktop illuminance (the mean of the two measurements per desk), which unlike cubic illuminance has well-established targets. We tested how far conditions were from typical recommended practice: in general, lower levels may be perceived as gloomy and inadequate for visual tasks, and high levels may lead to uncomfortably high contrast ratios and glare. We derived the fraction of measurements per building below 300 lux and the fraction above 500 lux, and the fraction that met either condition. These levels were chosen as representative of typical recommendations in North America that prevailed during the past two decades or so [ANSI/IESNA 2004]. We conducted tests for all measured workstations, and for those that contained windows and those that did not separately. There were no statistically-significant effects for any tests. For offices without windows, there were substantial numbers of workstations with illuminances outside of recommended practice in both building types (Below: green=0.37; conv.=0.46; Above: green=0.24; conv.=0.21). Although the conditions below recommended practice represent a potential cause of dissatisfaction, recall that survey responses indicated a relatively high level of satisfaction with lighting overall. Illuminances above recommended practice might represent the potential for energy savings, depending on the lighting design and available control options. As expected, for offices with windows, there were fewer instances of illuminances below recommended practice (green=0.15; conv.=0.26), and more instances of illuminances above recommended practice (green=0.61; conv.=0.53).

Thermal Conditions & Air Quality

As an additional metric of high relevance to thermal comfort, we calculated Fanger's thermal comfort indices, PMV and PPD [ASHRAE, 2004] for each cart measurement location. For the environmental variables in the calculation we used air temperature and air velocity measured at chest level, measured relative humidity, and measured radiant temperature. For the personal variables, we assumed the typical office activity level of 1.2 met, and the building-level mean clothing insulation level as reported from the survey data (0.71-0.98 clo). We also conducted separate tests on air speed as a standalone outcome variable. For the air quality metrics, we conducted tests on particulates, TVOC and CO_2. Values of CO and ozone were very low in both building types (a good thing), and thus did not lend themselves to meaningful statistical tests. Unfortunately, we suspected our formaldehyde meter of multiple malfunctions, and thus these data were not included in our analysis.

As shown in Table 29, there was a statistically-significant difference in the building-level means of air speed at both the head and chest level. In both cases the air velocity in green buildings tended to be lower, which for air speeds in the range we observed can be interpreted as favouring green buildings as the risk of draught was lower. Nevertheless, ASHRAE Standard 55 [2004] suggests that there is little risk of local draughts below (approx.) 0.16 ms^{-1}, and in this regard both sets of buildings performed well, on average. Note that overall thermal comfort indices suggested that, on average, thermal conditions in both sets of buildings was good (PPD mean, green=6.1 %; conv.=6.7 %, standards are typically based on achieving average values below 10% [ASHRAE, 2004]).

Table 29. Results of Wilcoxon Signed Ranks Test related to air speed, and related means of building-level means for each building type.

Outcome	**Ranks**		**Sum of Ranks**		**Z**	**p**	**Mean Rating**	
	Pos.	**Neg.**	**Pos.**	**Neg.**			**Green**	**Conv.**
Air speed (m/s) at head level	1	8	7	38	-1.84	.066	0.106	0.122
Air speed (m/s) at chest level	2	7	6	39	-1.96	.051	0.112	0.129

As shown in Table 30, there were statistically-significant differences for several metrics related to particulates. Standards and recommendations typically apply to the mass of particulates ≤ 2.5 microns in diameter (PM2.5) and ≤ 10 microns in diameter (PM10); respirable par ticles in this size range have been associated with negative health outcomes [Health Canada, 1989]. The instrument we used provided cumulative particle counts ≥ 0.3, 0.5, 1.0, 2.5, 5, 10 microns. To convert these counts into mass we calculated the number of counts in each size bin, assumed the particles were spherical, assumed the diameter to be that of the mid-point of the bin, and assumed a particle specific gravity (density) of 2800 kg/m^3, following the method of Levy et al. [2000], which is a simplified approach to a complex process [Binnig et al, 2007]. Note, that others have suggested lower specific gravities; for example, Tittarelli et al [2008] used 1650 kg/m^3 for outdoor air measurements. If we used this value our mass values would be reduced by 40%. In all cases, the particulate metric was lower for green buildings, suggesting better air quality. In the US the most stringent regulations require PM_{10} to be less than 50 µg/m^3 for 1 yr and less than 150 µg/m^3 for 24 hr (NAAQS/EPA), and in this regard both sets of buildings performed well, on average. Further, on average, the CO_2 concentrations in both building sets were well below the value (1075 ppm) used by ASHRAE [2007] to determine recommended ventilation rates (CO_2 mean, green=628 ppm; conv.=651 ppm).

Table 30. Results of Wilcoxon Signed Ranks Test related to airborne particulates, and related means of building-level means for each building type.

Outcome	**Ranks**		**Sum of Ranks**		**Z**	**p**	**Mean Rating**	
	Pos.	**Neg.**	**Pos.**	**Neg.**			**Green**	**Conv.**
Number of particles >=0.5 microns	2	7	8	37	-1.72	.086	1782	6298
Number of particles >=5 microns	3	6	8	37	-1.72	.086	92	117
PM10 (µg/m^3)	2	7	7	38	-1.84	.066	21	29

3.3 Regressions across all Buildings

The next stage of our analysis at the building level was to use regression analysis to explore relationships between mean survey outcomes (dependent variables) and mean physical measures (independent variables). We chose variable pairs based on theoretical expectations of a relationship; for example, satisfaction with acoustics and privacy vs. articulation index. For these regressions we did not distinguish between green and conventional buildings, and could thus expand the sample size by including Building E. For this exploration, we focussed on univariate regression; i.e. looking at how one variable is predicted by one other variable, and not considering predictions from multiple variables or variable transformations.

Sound

As dependent variables we chose the building means for Sat_AP, Non-Speech, Speech, Speech2, PCI, PCF, PCOMF, and Absence from work; independent variables were the building means for AI, AW, fraction of open-plan offices, and proportion of window access. We conducted analyses for all workstations, and for private and open-plan workstations separately; in the latter case we did this only for buildings that had at least ten workstations in the private/open category from which to construct a reliable mean at the building level. We did not test all pairs of DVs and IVs, but chose only those we judged to have the strongest theoretical interest.

Table 31 shows the statistically-significant relationships (regressions with overall $p \leq 0.05$). Satisfaction with acoustics and privacy declined as mean articulation index increased. AI had a stronger negative effect on disturbance from speech sounds, as might have been expected; this relationship is illustrated in Figure 5. It is possible that mean AI at the building level is simply coding for the prevalence of open-plan accommodation in each building. Indeed, there was a statistically significant relationship between disturbance from speech sounds and fraction of offices in the building that were open plan. Countering this simple interpretation is the observation that AI is also negatively related to disturbance from speech sounds in private offices only.

However, the effects of the acoustic environment extended beyond outcomes related directly to satisfaction with noise. Absence was also associated with background noise level, in that higher A-weighted noise was associated with more frequent absence from work. This is consistent with research by others on office noise and stress [e.g. Evans & Johnson, 2000].

Table 31. Results of linear regression analysis related to acoustics.

DV	**IV**	**R^2_{adj}**	**F**	**Constant**	**B**
Sat_AP	AI	.26	7.16*	5.04	-2.36
Speech (disturbance)	AI	.48	17.83*	3.30	4.26
Speech (disturbance)	AI (private offices only)	.38	8.33*	3.58	5.20
Speech2 (disturbance)	AI	.45	15.76*	3.27	3.84
Speech2 (disturbance)	AI (private offices only)	.48	12.22*	3.35	5.94
Speech (disturbance)	Fraction Open	.26	7.18*	3.92	1.10
PCF	Fraction Open	.28	7.81*	2.83	-0.534
Absence (any reason)	AW	.20	5.39*	-2.65	0.050
Absence (any reason)	AW (open-plan offices only)	.18	4.53*	-.509	0.055

* indicates statistically significant

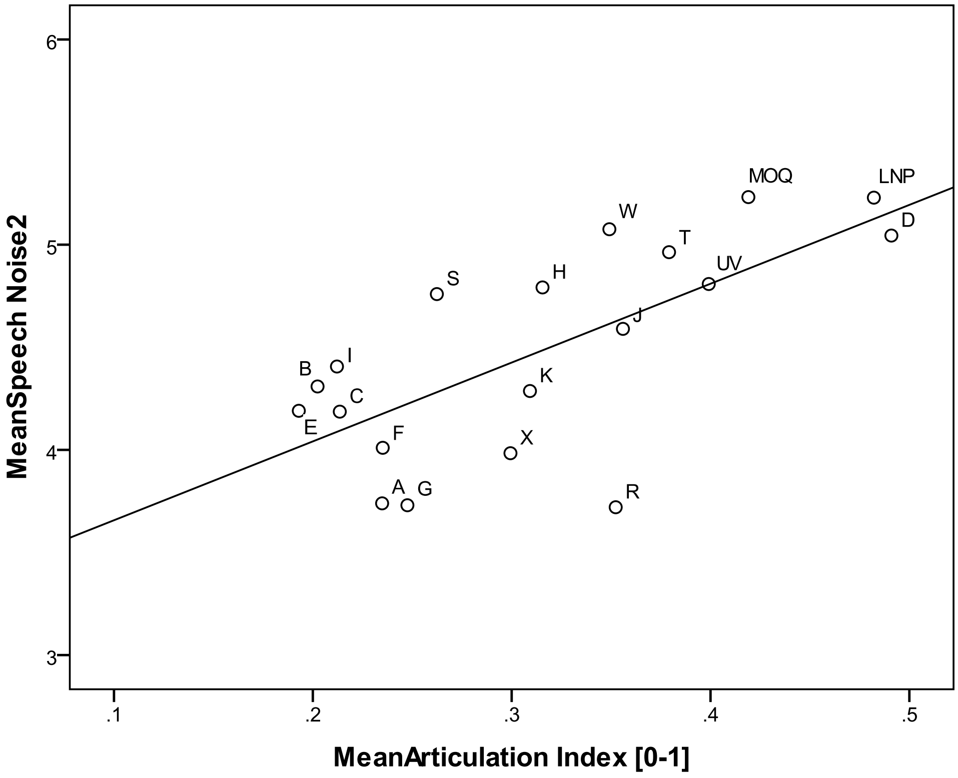


Figure 5. Rated disturbance from speech sounds vs. measured articulation index (building-level means). The best-fit linear regression line is shown.

Lighting

As dependent variables we chose Sat_L, OES, VCI, VCF, PCI, PCF, VCOMF, PCOMF, and Absence from work; independent variables were illuminance (as variously measured), luminance above the monitor, and window access. For outcomes related to illuminance we repeated tests both with and without Building H, which had substantially higher mean illuminances compared to other buildings, and might be considered an outlier. We did not test all pairs of DVs and IVs, but chose only those we judged to have the strongest theoretical interest.

Table 32 shows the statistically-significant relationships ($p \leq 0.05$). Note that for cubic illuminance variables we also tested mean illuminance on all six faces as a predictor; similarly, for desktop illuminance variables we also tested mean desktop illuminance as a predictor. These composite variables may be more reliable and generalizable, but did not prove to be significant predictors. Nevertheless, the pattern of relationships using the individual metrics is consistent and suggests robust conclusions, and therefore we present these in Table 32. We observed a variety of positive outcomes with higher light levels, for example, satisfaction with lighting increased with higher illuminance as measured on multiple cube faces.

However, the effects of the lighted environment extended beyond outcomes related directly to satisfaction with lighting. OES also increased with higher illuminance as measured on multiple cube faces. Physical comfort also improved with higher light levels, measured both by illuminance on multiple cube faces and by luminance above the computer monitor. It is interesting that we observed lighting effects on physical comfort, but not on visual comfort. Prior studies have shown that poor lighting may lead to the adoption of compensatory, but unergonomic, postures [Rea et al., 1985; Heerwagen & Diamond, 1992]. In what may be a related effect, absence from work (for any reason) 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; evidence suggests that higher light levels are desirable for better well-being [CIE 2004/2009]. Absence was also associated with the fraction of workstations with illuminance outside of recommended levels (<300 lx or >500 lx). The effect seems contradictory, because a higher fraction outside recommended levels was associated with lower absence. But note that cases with levels above recommended levels occurred most frequently due to daylight in offices with windows.

Table 32. Results of linear regression analysis related to lighting.

DV	IV	R^2_{adj}	F	Constant	B
Sat_L	IllumCubeFront (H removed)	.19	4.89*	4.65	0.002
Sat_L	IllumCubeLeft (H rem.)	.28	7.55*	4.73	0.001
Sat_L	IllumCubeBottom (H rem.)	.18	4.73*	4.75	0.004
OES	IllumCubeLeft	.21	5.88*	3.80	0.001
OES	IllumDeskRight	.17	4.68*	3.83	0.001
PCI	IllumCubeFront	.16	4.44*	2.51	-0.001
PCI	IllumCubeLeft	.26	7.18*	2.52	-0.001
PCI	IllumCubeLeft (H rem.)	.20	5.30*	2.53	-0.001
PCI	Luminance above Monitor	.22	6.00*	2.45	-0.002
PCOMF	IllumCubeLeft	.21	5.85*	7.97	-0.003
PCOMF	IllumCubeLeft (H rem.)	.24	6.31*	8.24	-0.004
Absence (any reason)	IllumOutsideRecommend	.18	5.00*	2.72	-1.29
Absence (any reason)	Fraction Windows in WS	.16	4.43*	2.16	-0.605
Absence (any reason)	Fract. Windows in WS/Next	.19	5.34*	2.27	-0.674

* indicates statistically significant

Thermal Conditions & Air Quality

As dependent variables we chose Sat_VT, Thermal Sensation, Thermal Preference, Adap_Energy, Adap_NoEnergy, Adap_Person, Adap_Enviro, OES, VCI, VCF, PCI, PCF, VCOMF, PCOMF, and Absence from work; independent variables were PM2.5, PM10, TVOC, CO_2, PMV (absolute distance from neutral), PPD (which is a polynomial and exponential transformation of PMV), and air speed. We did not test all pairs of DVs and IVs, but chose only those we judged to have the strongest theoretical interest.

Table 33 shows the statistically-significant relationships ($p \leq 0.05$). Satisfaction with ventilation and temperature increased the closer PMV was to neutral (or PPD was to zero). PMV is a composite metric comprising physical variables expected to relate to thermal comfort (confirmed through numerous laboratory and other field studies), so this relationship is both expected and provides a useful validity check. It is also not surprising that the further physical thermal conditions were from predicted neutrality the more frequently building occupants took actions to improve their own thermal comfort.

However, the effects of the thermal environment (PMV and PPD) extended beyond outcomes related directly to thermal comfort. We also found that the closer PMV was to neutral (or PPD was to zero) the higher was OES and the lower were physical symptoms. Visual comfort metrics were not related to PMV (and PPD), but VCI was related to air speed. Higher air speed on the upper body was associated with higher intensity of visual comfort symptoms, this might be expected as higher air speed would cause more rapid drying of eyes, for example.

There was also a consistent pattern of relatively strong relationships related to the mass of various particle sizes in the air, and in particular the PM10 composite metric. Sat_VP was related to PM10 in the expected direction – fewer particles was associated with higher satisfaction – but it is interesting that it was particle mass, and not any of the other physical IAQ measures, that was a significant predictor. But again, the relationships extended beyond the direct satisfaction outcome to other outcomes with, arguably, more importance to organizations and their employees. Higher particle mass was also associated with higher levels of visual and physical discomfort, and with higher absence from work due to illness (see Figure 6).

Table 33. Results of linear regression analysis related to thermal conditions and air quality.

DV	IV	R^2_{adj}	F	Constant	B
Sat_VT	PMV (abs. from neutral)	.21	5.79*	5.28	-0.504
Sat_VT	PPD	.22	6.16*	6.20	-0.301
Adap_Energy	PMV (abs. from neutral)	.18	4.82*	1.11	3.24
Adap_NoEnergy	PMV (abs. from neutral)	.17	4.60*	2.36	3.19
Adap_Enviro	PMV (abs. from neutral)	.22	5.95*	1.09	3.48
OES	PMV (abs. from neutral)	.19	5.16*	4.89	-3.22
OES	PPD	.23	6.36*	5.53	-0.198
PCI	PMV (abs. from neutral)	.24	6.67*	1.19	1.798
PCI	PPD	.21	5.73*	1.64	0.096
PCF	PMV (abs. from neutral)	.16	4.49*	2.16	1.67
PCF	PPD	.18	5.03*	1.85	0.099
PCOMF	PMV (abs. from neutral)	.19	5.21*	5.15	8.35
PCOMF	PPD	.20	5.39*	3.69	0.480
VCI	Air speed (head)	.20	5.39*	1.41	5.04
VCI	Air speed (chest)	.21	5.74*	1.18	6.63
Sat_VT	PM10	.42	14.20*	5.06	-0.031
VCI	PM10	.38	12.19*	1.71	0.010
PCI	PM10	.32	9.30*	2.03	0.009
VCF	PM10	.52	20.63*	1.91	0.016
PCF	PM10	.49	18.15*	2.19	0.012
VCOMF	PM10	.45	15.85*	3.95	0.072
PCOMF	PM10	.25	6.99*	5.70	0.041
Absence (illness)	PM10	.40	12.81*	0.283	0.011

* indicates statistically significant

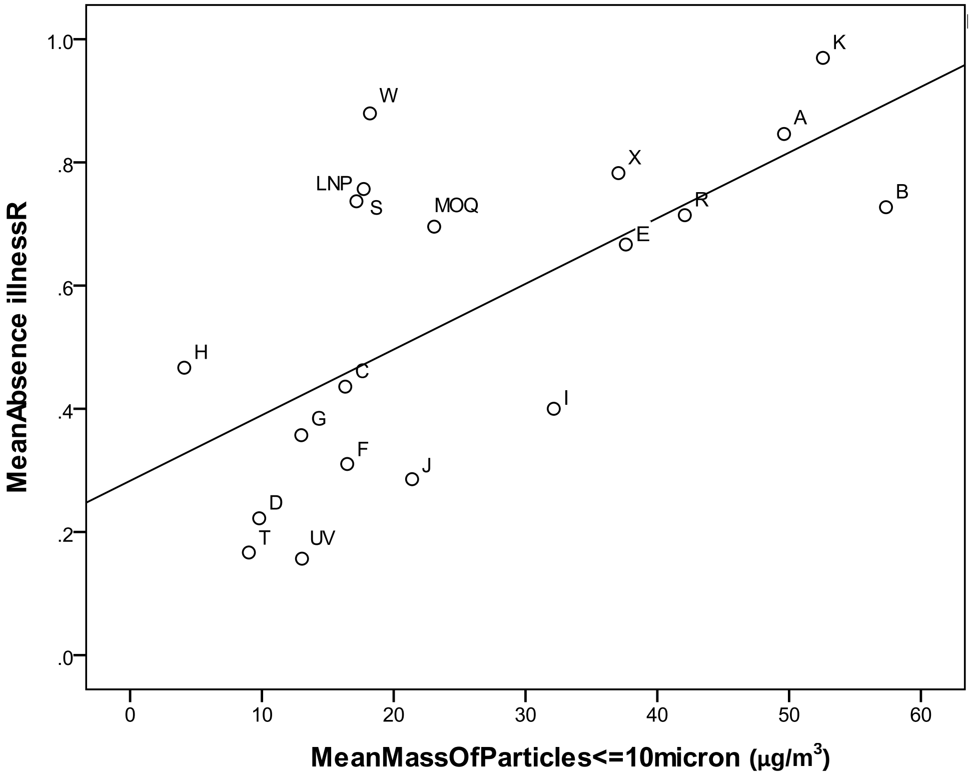


Figure 6. Days/month absent from work due to illness vs. measured airborne particle mass (PM10). The best-fit linear regression line is shown.

3.4 Energy Use

For each of the buildings in our study, we sought energy performance data, at least at the level of monthly utility bills. Unfortunately, the data we were able to obtain was inconsistent across the sample. Some buildings made monthly utility data available for many years, some for only one or two years, some buildings had much higher time resolution data, and some were not able to make any data available to us at all. This inconsistency, combined with the relatively small sample size, made drawing statistically-valid conclusions about the energy performance of green buildings from our field study sample impossible.

For descriptive information only, Table 34 shows total energy use intensity (kWh/m^2) for the five green-conventional pairs for which both buildings had available utility data. In some cases, multiple years of data were available, and for this summary we show the most recent year only. Of the five pairs, the green building had substantially lower energy intensity in three, it was about even in one, and the conventional building had substantially lower energy intensity in one. In the latter case, it was Building I with lower energy intensity than Building H. Although considered as a conventional building from the perspective of indoor environment quality, the main perspective of the field study, Building I was designed to be a very energy-efficient building at the time of its construction.

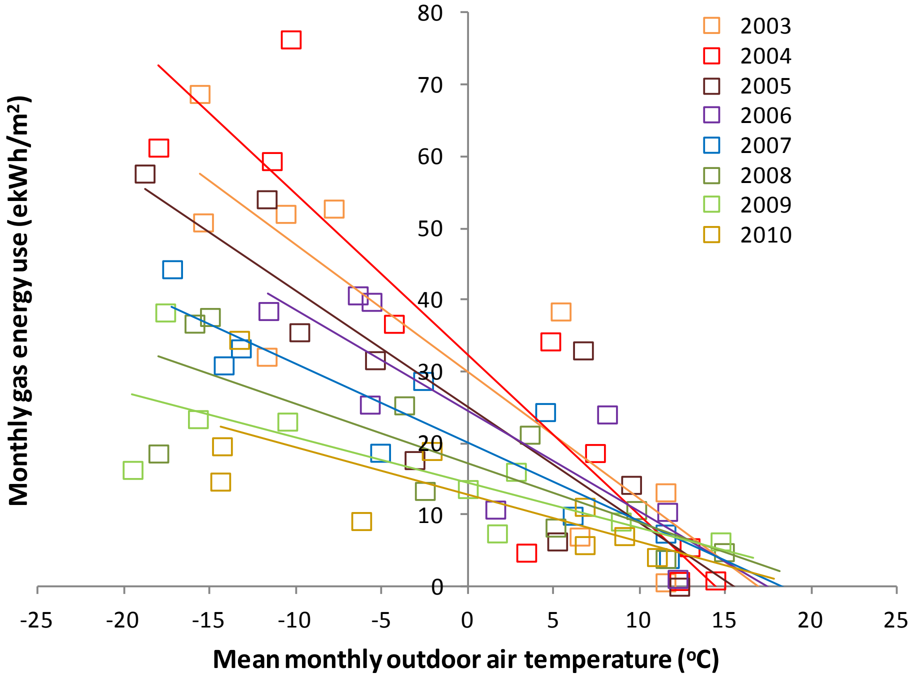
Table 34. Total Energy Use Intensity for building pairs where both buildings had valid data, for the most recent year with complete data.

Building	**A**	**B**	**F**	**G**	**H**	**I**	**J**	**K**	**R**	**X**
kwh/m^2	317	371	217	205	567	217	157	530	699	261
Year	2010		2009		2010		2010		2010	

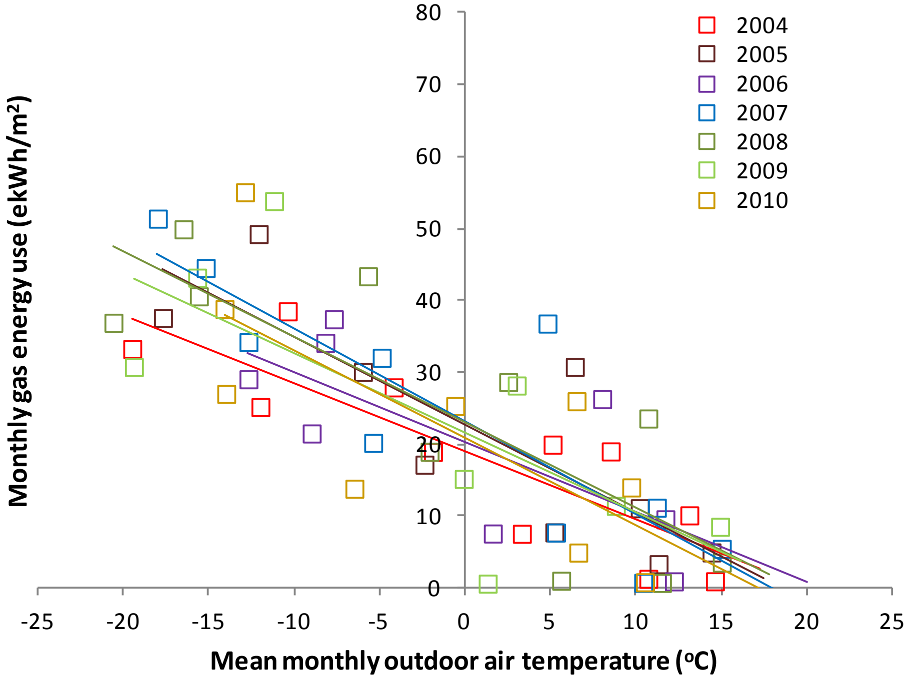
For a more reliable estimate of the energy performance of green buildings more generally, relative to conventional buildings, we direct the reader to our analysis of data from 100 other LEED-certified buildings summarized in the Introduction [Newsham et al., 2009a].

Nevertheless, the data from our field study sample did provide an interesting case study. For one matched building pair (A and B) we were provided with monthly utility data dating back eight and seven years respectively. Here we focus on natural gas data, which was the space heating fuel for both buildings in this cold climate location (HDD18 5200-6200). Figure 7 shows monthly natural gas energy use intensity (ekWh/m^2) for the heating season (monthly mean outdoor temperature <15 ^{o}C) vs. monthly mean outdoor temperature. The symbols for each year are colour-coded, and the best-fit linear regression line for each year is also shown with the same colour code. This regression line represents an overall estimate of the heating energy efficiency of the building. The slopes are negative: as the outdoor temperature drops the heating energy goes up, of course. A steeper negative gradient indicates that energy use goes up more rapidly for a given drop in outdoor temperature, and thus that the building is less efficient in heating mode. Many factors may contribute to a building's overall heating efficiency, including: insulation levels of walls and windows, ventilation rates and infiltration, and efficiency of heating equipment.

For Building B, the conventional building of the pair, which did not undergo any substantial renovation or change in operation during the period for which we had energy data, the gradient of the graph stayed relatively constant from year-to-year, and there was no obvious trend in the small between-year variations that did occur. For Building A, the data presented a very different picture. In 2003/4 Building A was a conventional building, with heating energy performance substantially worse than Building B. At that time a series of renovations was begun that spanned multiple years and systematically improved heating energy performance, and which supported the application for LEED Silver certification at the end of the decade (thus making it the green building of the pair by the time of our on-site measurements and survey data collection). The graph clearly shows that by 2009/10 the heating energy performance of Building A was substantially better than that of Building B.



Building A



Building B

Figure 7. Monthly natural gas energy use intensity (ekWh/m^2) for the heating season, for one pair of study buildings.

Historical information on the specific renovations and their sequence was not readily available, but we were given general information. The energy objective was to improve the overall building energy performance from the prevailing 90% above the existing Model National Energy Code prescription to 25% below [CCBFC, 1997]. Improving heating energy performance was the major part of this objective. The 16-foot high single pane windows on the main floor were replaced with considerably smaller sealed units at the beginning of the project. New condensing boilers were then installed along with HVAC heat recovery on the exhaust air, at the same time as the 11th and 10th floors were gutted to the interior face of the masonry, and reroofing was undertaken. Once those floors were completed subsequent floors were completely redone with overlapping work floor-to-floor, all work was complete by 2009. Staff on floors undergoing renovation were temporarily relocated elsewhere in the building. The work on each floor included: replacing the standard double-glazed windows with triple-pane argon-filled sealed glazing units, a new envelope membrane to provide a better air and vapour barrier, additional envelope insulation, and perimeter induction units replaced with radiant heating (and cooling) hydronic ceiling radiant panels. A new DDC/BEM system for HVAC control was also installed and commissioned.

4. Discussion

We return to the hypotheses laid out in the Introduction, and use the statistically-significant results of our analyses (original field study, and reanalysis of US data on LEED building energy performance) to indicate whether or not each was supported:

1. Green buildings will produce higher ratings of occupant environmental satisfaction, except for ratings related to acoustics (see Hypotheses 8 & 9 below).
   This hypothesis was supported. Compared to similar conventional buildings, green buildings exhibited higher levels of overall environmental satisfaction, as well as higher levels of satisfaction with: ventilation and temperature, aesthetic appearance, size of workspace, and access to a view of outside. In addition, occupants of green buildings indicated that they were less likely to prefer a change in thermal conditions, and reported taking fewer adaptation actions to improve their thermal comfort.
2. Green buildings will produce higher ratings of occupant job satisfaction than conventional buildings.
   This hypothesis was not supported. We observed no statistically-significant difference between green and conventional buildings on our specific job satisfaction measure.
3. Green buildings will produce higher ratings of occupant well-being than conventional buildings.
   This hypothesis was supported. Occupants of green buildings reported visual and physical discomfort symptoms occurred less frequently. In addition they reported being in a better overall mood, and experiencing better sleep quality at night.
4. Green buildings will produce higher ratings of organizational commitment among employees than conventional buildings.
   This hypothesis was partially supported. We observed no statistically-significant difference between green and conventional buildings on our specific organizational commitment measure.

However, occupants of green buildings indicated that their facilities offered a better workplace image.

5. Green buildings will have lower levels of air pollutants than conventional buildings.
   This hypothesis was supported. Specifically, green buildings exhibited lower levels of airborne particulates. Further, as described in Hypothesis 1 above, green building occupants had higher ratings of satisfaction with ventilation and temperature.
6. Green buildings will have temperatures closer to thermally neutral than conventional buildings.
   This hypothesis was partially supported. We observed no statistically-significant difference between green and conventional buildings on measured temperatures, or the composite thermal comfort index predicted mean vote (PMV). However, our data did show that, regardless of building type, lower air velocities were preferred, and green buildings did exhibit lower air velocities. Further, as described in Hypothesis 1 above, 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.
7. Green buildings will have lighting conditions closer to recommended practice, and provide more access to daylight, than conventional buildings.
   This hypothesis was partially supported. We observed no statistically-significant difference between green and conventional buildings on any physical measure of the luminous environment. However, as described in Hypothesis 1 above, green building occupants had higher ratings of satisfaction with access to a view of outside.
8. Speech privacy will be lower in green buildings than in conventional buildings due to the reduced use of sound absorbing materials.
   This hypothesis was partially supported. We observed no statistically-significant difference between green and conventional buildings on subjective measures of speech privacy (it was poor in both building types). However, articulation index in private offices was higher (indicating less speech privacy) in green buildings; there was no statistically-significant difference in articulation index measured in open-plan spaces in the two building types. AI was poor in both building types.
9. Background noise levels will be higher in green buildings than in conventional buildings.
   This hypothesis was not supported. We observed no statistically-significant difference between green and conventional buildings on physical measures of background noise. However, ratings of disturbance from HVAC systems noise were lower in green buildings.
10. Green buildings will achieve better energy performance than conventional buildings.
   This hypothesis was supported. Our reanalysis of data on 100 LEED-certified buildings indicated that they used, on average, 18-39% less energy than otherwise similar conventional buildings.
11. Green buildings will perform according to building design goals and energy use predictions (lighting, air quality, temperature, acoustics, electricity consumption).
   This hypothesis was partially supported. The results pertaining to Hypotheses 1-10 above suggest superior performance by green buildings. In areas related to indoor environment quality, occupant well-being, and organizational satisfaction, our results indicate that whenever there was a statistically-significant difference it favoured green buildings. However, there were

> *several outcomes for which there was no measured overall benefit associated with green buildings (e.g. job satisfaction, illuminance). Further, even on measures for which there was an overall positive effect for green buildings, it was rare for all green buildings to perform better than their paired conventional building, as might have been expected at design time. Similarly, although energy performance for LEED-certified buildings was better on average, many individual LEED buildings performed worse than their conventional counterparts. Further, there was little relationship between the number of LEED energy performance credits achieved at design time and resulting post-occupancy energy performance.*

A review of the summary of hypotheses above suggests that, on the whole, green buildings did deliver higher quality indoor environments and lower energy use. However, note that these effects, although statistically significant, were on the average. These results were obtained through paired comparisons of green buildings with otherwise similar conventional buildings, and there were few measures in which all green buildings outperformed their conventional partners. Similarly, in no building pair did the green building outperform their conventional counterpart on every measure. Also, our study employed many measures, and although there might have been a green building benefit for one measure in a class, that might not have been true for all measures. For example, on air quality, we found lower levels of particulates in green buildings, but no differences in CO_2 or TVOC levels. It is worth noting that, although we choose not to provide detail on trends that were not statistically significant, on the whole these trends also favoured green buildings, and may prove to be statistically significant in a future study with a larger sample size.

To our knowledge, this study represents the most comprehensive post-occupancy evaluation of green buildings conducted to date, and, overall, green building advocates will be encouraged by the results. On average, green buildings appear to offer superior performance, which is good news for a society that is increasingly facilitating the development of green buildings. This does not mean there is no room for improvement; moreover, as we have observed, not all individual green buildings may be delivering the performance expected by their owners, which may hamper green building uptake. Our data did not allow us to provide a comprehensive analysis of the reasons for underperformance where it was observed, but we can offer a few observations from the literature, and from anecdotes from our own field studies.

An earlier literature review [Birt & Newsham, 2009] indicated a trend for acoustics to be rated more poorly in green buildings. We did not see this effect in our sample, but a potential mechanism is straightforward to construct. For example, the LEED rating system offers credits for improved indoor air quality, and practitioners might seek to achieve this through the use of hard flooring rather than carpets, and by providing gaps in systems furniture to facilitate air flow. Further there are credits for daylight penetration and access to a view of outside, and practitioners might seek to achieve this via low partitions between workstations, and exposed, and thus higher, ceilings. However, these air quality and daylighting design features also facilitate the propagation of sounds, particularly speech sounds, which are the main source of acoustic dissatisfaction in workplaces [Bradley & Wang, 2001]. As an example, in Building Q in our field study, a building with a specific green intent, the designers had left large horizontal gaps above the doors of otherwise “private” offices to facilitate airflow. We were told that this led to serious complaints related to acoustics, and remedial measures were taken to block the gaps (Figure 8).

Figure 8. Gaps above doors in Building Q (left), and remedial measure for acoustic concerns (right).

Poor energy performance in green buildings relative to expectations may occur for a variety of operational and technological reasons. The building’s actual operational requirements may be different from those assumed at design time; the advanced energy-efficient technology often deployed in green buildings can have “teething problems” particularly in the early years of operation; and the building operators might not engage the building systems according to the design intent. Anecdotally, there is industry concern regarding the availability of operators with the knowledge and experience to successfully manage sophisticated, modern buildings. It is also possible that overly-optimistic assumptions are made at design time that lead to overestimates of realistic energy savings. An example was in Building J in our sample, a LEED-certified building. The inputs to the energy simulations included very aggressive night-time setbacks for thermostats. The building operator informed us that after a short period of occupancy, building occupants complained about morning thermal comfort conditions; evidently the building systems were not able to bring indoor conditions back to comfortable levels following the aggressive setbacks. As a result, setbacks were removed altogether. (Despite this loss of anticipated energy savings, Building J’s overall energy performance was still very good.)

In Newsham et al. [2009a] we observed that, on average, green buildings had better energy performance than conventional buildings, despite the fact that there was little relationship between the number of energy performance credits obtained at design time and post-occupancy energy performance. We suggested that one explanation for this might be that it is the process of designing green that is more important than the specific energy measures taken. In other words, a greater focus on energy use to begin with, and a more holistic outlook, means that many actions are taken to improve energy performance, not all of which may be documentable or recorded for credits in a rating system, but that can nevertheless lead to energy savings, either immediately or over the longer term. Even if some specific measures do not work, the more measures that are considered the greater the likelihood of overall energy savings.

The results of our field study suggest that a similar mechanism might prevail with regard to indoor environment quality. In terms of physical measures, we observed few substantial differences between green and conventional buildings, and the differences we did observe were not necessarily in the more commonly considered variables (e.g. illuminance, CO_2) that one might expect to respond to the credits in, for example, the LEED system (e.g. daylight, enhanced ventilation, CO_2 monitoring). 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 and direct cause-and-effect relationship between individual design credits and the resulting post-occupancy performance. Rather, it may be that the green building process leads to a greater focus on indoor environment quality in general. This might spawn specific technologies and actions, some of which are documentable, and some of which work. 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. Further, the occupants themselves might develop a greater sense of well-being by being in a building in which they know that indoor environment has a higher priority. The finding that workplace image scores are greater in green than conventional buildings supports this notion.

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

- Although acoustic performance in our buildings was not different in green versus conventional buildings, it was not good in either type. Therefore, we suggest an acoustics credit should be created that might counterbalance some of the design choices engendered by other credits that are detrimental for acoustics. There are acoustics credits in some international green rating systems [e.g. BRE Global, 2012; Green Building Council of Australia, 2012], and a suggestion for a LEED credit has been made [Jensen et al., 2008]. However, these existing/proposed credits do not place particular emphasis on reducing the propagation of speech sounds, which is the most problematic acoustics issue in offices.
- Our field study suggested that airborne particulates were particularly important for predicting satisfaction with ventilation, visual and physical comfort, and even absence due to illness. The composite measure PM10 appeared to be the most reliable predictor. We also observed that green buildings tend to have lower levels of PM10. There is a LEED credit that potentially addresses particulates. Under LEED-CI (for example), Construction IAQ Management Plan, Option B 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 goals, among other IAQ outcomes. Our results suggest that a modification to these credits that elevated the importance of particulate reduction might be valuable. Methods to reduce the number of airborne particulates can include filters in the HVAC

system, materials that are less likely to generate particulates, and facilitation of cleaning and operational practices that capture rather than disperse particulates.
- The argument we have made above, that process is at least as important as specific, creditable, actions, suggests that a credit be developed that enhances this process. Perhaps this credit could reward documented interdisciplinary design team meetings, or documentation of all implemented measures intended to improve building performance, whether eligible for credit or not, or a specific mechanism to facilitate on-going performance review and continuous improvement (beyond the energy realm).

This study emphasizes the importance of post-occupancy evaluation to ensure the achievement of the ultimate goal of the green building movement: enhanced building *performance* (leading to enhanced sustainability), and not just enhanced building *designs*. Mechanisms are already in place, or are being instigated, to require on-going quantitative energy performance criteria to be met to maintain green certification e.g. LEED EBOM [USGBC, 2011]. We suggest that this quantitative approach be extended to other aspects of green building performance – our particular interest is in indoor environment quality, but it could also include water use, and even the performance of recycling systems or use of alternative transit. With respect to IEQ, we suggest resources be devoted to the development of an objective and subjective measurement kit and protocol. The details, and what constitutes adequate performance, should be developed by expert consensus, but our research findings suggest the following:

- To be valid, physical measurements should be taken at a large number of representative locations, and over several days and in more than one season. Snapshot measurements should be supplemented by longitudinal measurements, which may highlight performance issues that snapshots miss. Similarly, subjective measurements should involve a survey of the entire building population. Again, surveys should be conducted in more than one season, as building operations, and the effect of outside climate on the building interior, may vary dramatically.
- A database of identical measurements in otherwise similar “non-green” (conventional) buildings should be maintained. If the goal of green buildings is to offer superior performance then it is necessary to know “superior to what?”
- The basic set of physical measurements is obvious: temperature, humidity, air speed, illuminance, CO_2. Additional air quality measures are (currently) expensive to obtain, and the limited set that we used showed them to be of marginal value. The one exception to this was airborne particulates. If the importance of PM10, for example, is confirmed in future research, we suggest resources should be devoted to developing methods to measure particulates in a cost-effective manner. Good acoustics data is also expensive to obtain. Though our work showed this to be of limited value in differentiating between green and conventional buildings, it is an important predictor of acoustic satisfaction overall. Therefore, again, resources should be devoted to more cost-effective gathering of acoustic information.
- Green building advocates claim that the benefits extend beyond more satisfactory indoor environments to improved occupant well-being and health, and better organizational outcomes. Therefore, measures for on-going performance evaluation should address all of these aspects. Survey questions to address indoor environment satisfaction (the bulk of the Core Module in

our field study survey, and elements of Modules 2 and 3) are well-established, and variations on a similar set of questions have been deployed successfully by various international research groups [e.g. Abbaszadeh et al, 2006; Leaman & Bordass, 2007]. There may be an advantage to further standardization of these questions going forward. Objective measures for well-being, health and organizational outcomes are notoriously difficult to obtain, but our results suggest that subjective measures are valuable in differentiating green building performance from that of conventional buildings. In our current study, questions related to discomfort symptoms, mood, and absence (leave) from work proved to be particularly useful, as well as the less obvious, but important, sleep quality at night. Although job satisfaction and organizational commitment measures did not prove to be valuable in differentiating green buildings in this study, they have been associated with other aspects of building performance in previous research [Veitch et al., 2010; Veitch et al., 2010b], and we would advocate maintaining them alongside the measure of workplace image, that was useful in this study.

Conducting our field study required a great deal of specialist scientific knowledge and equipment, and was very expensive. Widespread deployment will require that the data can be collected by either a well-qualified and committed building operator or consultant, using a kit costing no more than several thousand dollars. Careful consideration should be given to the tradeoffs in data quality required to meet this goal. It is common practice among building owners to survey their tenants on a regular basis to identify areas for performance improvement, so if such a kit can be developed, incorporating its use might be relatively straightforward.

Having said this, the short-term focus will be on the collection of on-going energy performance data. Our experience in this field study suggests that putting mechanisms in place to collect data at the monthly, whole-building level may be more challenging than one might expect. We found, to our surprise, that several buildings in our sample had not retained utility bills over several years without gaps, or could not readily find such data. This reinforces the importance of a standardized and well-observed mechanism to archive data at least at the utility bill level, and to consider such data as valuable even after the utility account has been settled. Increased penetration of BEMS (Building Energy Management Systems) should allow for much higher resolution data to be generated in the future. However, at present, the default is to use these data for alarms and short-term troubleshooting and trending, and not to archive these data over long periods. Electronic storage is now inexpensive, and getting more so; we suggest that the industry develop protocols for the routine archiving of these data.

5. Conclusions

By analysis of original post-occupancy field study data, and re-analysis of an extant datasets on LEED/conventional building energy use, we can conclude the following:

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

- Analysis of data from across all buildings, regardless of green status, showed a variety of physical features that led to improved occupant outcomes, including: lower articulation index (i.e. physical conditions associated with better speech privacy), lower background noise levels, higher light levels, greater access to windows, lower predicted mean vote (i.e. physical conditions associated with better thermal comfort), and lower number of airborne particulates.
- Our results suggest several areas in which further attention might benefit green building rating systems, including: consideration of a LEED credit related to acoustic performance; a greater focus on reducing airborne particulates; enhanced support for the interdisciplinary design process; development of post-occupancy evaluation protocols addressing a broad set of outcomes (including energy, water, indoor environment metrics, and occupant surveys), and their integration into on-going certification systems.
- On average, LEED buildings exhibited lower total energy use intensity than similar conventional buildings. A specific case study from our own field study dataset confirmed the potential for substantial energy use intensity reductions through a green building renovation. However, many individual LEED buildings did not meet energy performance expectations. Further, there was little correlation between the number of LEED energy credits obtained during design and the resulting energy performance.

References

Abbaszadeh, S.; Zagreus, L.; Lehrer, D.; Huizenga, C. 2006. Occupant satisfaction with indoor environmental quality in green buildings. Proceedings of Healthy Buildings (Lisbon), 3, 365-370.

ANSI/IESNA. Various years. American National Standard Practice for Office Lighting, RP-1.

Ariës, M.B.C.; Veitch, J.A.; Newsham, G.R. 2010. Windows, view, and office characteristics predict physical and psychological discomfort. Journal of Environmental Psychology, 30(4), 533-541.

ASHRAE. 2004. Thermal environmental conditions for human occupancy (ANSI/ASHRAE Standard 55). American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.

ASHRAE. 2007. Standard 62.1 Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, USA.

ASTM. 2008. Standard Test Method for Objective Measurement of Speech Privacy in Open Plan Spaces Using Articulation Index, Standard E1130. ASTM International, West Conshohocken, USA.

Barlow, S.; Fiala, D. 2007. Occupant comfort in UK offices--How adaptive comfort theories might influence future low energy office refurbishment strategies: Comfort and Energy Use in Buildings - Getting Them Right. Energy and Buildings, 39(7), 837-846.

Binnig, J.; Meyer, J.; Kasper, G. 2007. Calibration of an optical particle counter to provide $PM_{2.5}$ mass for well-defined particle materials. Aerosol Science, 38, 325-332.

Birt, B.; Newsham, G.R. 2009. Post-occupancy evaluation of energy and indoor environment quality in green buildings: a review. Proceedings of 3rd International Conference on Smart and Sustainable Built Environments (Delft, the Netherlands), 7 pages.

BOMA. 2012. BOMA BESt (Building Environmental Standards) Certified Buildings. URL: http://www.bomabest.com/certified-buildings/ (last visited 2012-03-20).

Bordass, B.; Leaman, A.; Willis, S. 1994. Control Strategies for Building Services: The role of the user. Proceedings of Building and the Environment conference (BRE, UK), 16-20 May.

Bradley, J. S.; Wang, C. 2001. Measurements of sound propagation between mock-up workstations, National Research Council.

BRE Global. 2012. BREAM Europe Commercial. URL: http://www.breeam.org/filelibrary/Presentations/BREEAM_Europe_Presentation.pdf (last accessed 2012-03-20).

Brill, M.; Weidemann, S.; BOSTI Associates. 2001. Disproving widespread myths about workplace design. Jasper, IN: Kimball International.

Brown, Z.; Cole, R. J. 2009. Influence of occupants' knowledge on comfort expectations and behaviour. Building Research & Informatics, 37, (3), 27-245.

CaGBC. 2012. LEED Projects in Canada (spreadsheet). URL: http://www.cagbc.org/Content/NavigationMenu/Programs/LEED/ProjectProfilesandStats/default.htm (last visited 2012-03-20).

Canadian Commission on Building and Fire Codes (CCBFC). 1997. Model National Energy Code for Buildings. National Research Council Canada.

Center for Neighborhood Technology. 2009. Regional Green Building Case Study Project: A post-occupancy study of LEED projects in Illinois.

Charles, K.E.; Veitch, J.A.; Farley, K. M. J., Newsham, G. R. 2003. Environmental Satisfaction in Open-Plan Environments: 3. Further Scale Validation. NRC Institute for Research in Construction, IRC-RR-152. URL: http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr152/rr152.pdf (last accessed 2012-03-20).

Commission Internationale de l'Eclairage (CIE). 2004/2009. Ocular lighting effects on human physiology and behaviour (No. CIE 158:2009). Vienna, Austria: CIE.

Colarelli, S. M. 1984. Methods of communication and mediating processes in realistic job previews. Journal of Applied Psychology, 69, 633-642.

de Dear, R. J.; Schiller Brager, G. 1998. Developing an adaptive model of thermal comfort and preference. ASHRAE Transactions, 104 (Pt. 1A), 145-167.

Diener, E.; Wirtz, D.; Tov, W.; Kim-Prieto, C.; Choi, D. W.; Oishi, S., et al. 2009. New well-being measures: Short scales to assess flourishing and positive and negative feelings. Social Indicators Research, 1-14.

Di Milia, L.; Wikman, R.; Smith, P. 2008. Additional psychometric evidence and construct validity for a revised Preferences Scale of morningness. Chronobiology International, 25(5), 776-787.

Dolbier, C. L.; Webster, J. A.; McCalister, K. T.; Mallon, M. W.; Steinhardt, M. A. 2005. Reliability and validity of a single-item measure of job satisfaction. American Journal of Health Promotion, 19, (3), 194-198.

Dunlap, R. E.; Van Liere, K. D.; Mertig, A. G.; Emmet-Jones, R. 2000. Measuring endorsement of the new ecological paradigm: A revised NEP scale. Journal of Social Issues, 56, 425–442.

Evans, G.W.; Johnson, D. 2000. Stress and open-office noise. Journal of Applied Psychology, 85 (5), 779-783.

Farley, K.M.J.; Veitch, J.A. 2001. A Room with a View: A Review of the Effects of Windows on Work and Well-Being. NRC Institute for Research in Construction, IRC-RR-136. URL: http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr136/rr136.pdf (last accessed 2012-03-20).

Gardner B. 2009. Modelling motivation and habit in stable travel mode contexts. Transportation Research Part F: Traffic Psychology and Behaviour, 12, (1), 68-76.

Gardner, B.; Abraham, C.. 2008. Psychological correlates of car use: A meta-analysis. Transportation Research Part F: Traffic Psychology and Behaviour, 11, (4), 300-311.

Goulet, G.; Mongrain, V.; Desrosiers, C.; Paquet, J.; Dumont, M. 2007. Daily light exposure in morning-type and evening-type individuals. Journal of Biological Rhythms, 22(2), 151-158.

Government of Manitoba. 2006. News Release - All New Provincially-funded Buildings To Meet International Environmental Standards. URL: http://www.gov.mb.ca/chc/press/top/2006/06/2006-06-15-01.html (last visited 2012-03-20).

Green Building Council of Australia. 2012. Green Star - Office v3. URL: http://www.gbca.org.au/green-star/rating-tools/green-star-office-design-v3-green-star-office-as-built-v3/1710.htm (last accessed 2012-03-20)

Health Canada. 1989. Exposure guidelines for residential indoor air quality.

Hedge, A.; Erickson, W.A.; Rubin, G. 1992. Effects of personal and occupational factors on sick building syndrome reports in air-conditioned offices. In J. C. Quick, L. R. Murphy & J. J. Hurrell (Eds.), Work and Well Being: Assessment and Interventions for Occupational Mental Health. Washington, D.C.: American Psychological Association, 286-298.

Heerwagen, J.; Diamond, R.C. 1992. Adaptations and coping: occupant response to discomfort in energy efficient buildings. Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings (Pacific Grove, USA), 10.83-10.90.

Heerwagen, J.H.; Kampschroer, K.; Powell, K.M.; Loftness, V. 2004. Collaborative knowledge work environments. Building Research & Information, 32(6), 510-528.

Huizenga, C.; Abbaszadeh, S.; Zagreus, L.; Arens, E. 2006. Air quality and thermal comfort in office buildings: results of a large indoor environmental quality survey, Proceedings of the Healthy Buildings, vol. 3: Design and Operation of Healthy Buildings Portugal, June, 393–397.

Inanici, M. 2006. Evaluation of high dynamic range photography as a luminance data acquisition system. Lighting Research & Technology, 38(2), 123-136.

Jensen, W., Fischer, B., Wentz, T.; Camara, G. 2008. A proposed LEED standard for indoor acoustical quality. Journal of Green Building 3(1), 93-101.

Laing, A. 2005. DEGW approaches to workplace performance measurement. Presentation to Work Environments Network at EDRA 35 (Environmental Design Research Association), Vancouver, B.C.

Leaman, A.; Bordass, B. 2007. Are users more tolerant of 'green' buildings? Building Research & Information, 35 (6), 662-673.

Lee, Y.S. 2011. Comparisons of indoor air quality and thermal comfort quality between certification levels of LEED-certified buildings in USA. Indoor and Built Environment, 20(5), 564-576.

Leppämäki, S.; Meesters, Y.; Haukka, J.; Lönnqvist, J.; Partonen, T. 2003. Effect of simulated dawn on quality of sleep – a community-based trial. BMC Psychiatry, 3(1), 14.

Levy, J.I.; Houseman, E.A.; Ryan, L.; Richardson, D.; Spengler, J.D. 2000. Particle concentrations in urban microenvironments. Environmental Health Perspectives, 108(11), 1051-1057.

Lowe, G. S.; Schellenberg, G.; Shannon, H. S. 2003. Correlates of employees' perceptions of a healthy work environment. American Journal of Health Promotion, 17(6), 390-399.

McIntyre, D. A. 1980. Indoor Climate. London: Applied Science.

Meyer, J. P.; Allen, N. J.; Smith, C. A. 1993. Commitment to organizations and occupations: Extension and test of a three-component conceptualization. Journal of Applied Psychology, 78(4), 538-551.

Monfared, I.G.; Sharples, S. 2011. Occupants' perceptions and expectations of a green office building: a longitudinal case study. Architectural Science Review, 54, 344-355.

Moschandreas, D.J.; Nuanual. R.M. 2008. Do certified sustainable buildings perform better than similar conventional buildings? International Journal of Environment and Sustainable Development, 7(3), 276-292.

Newsham, G. R.; Veitch, J. A.; Arsenault, C. D.; Duval, C. L. 2004. Effect of dimming control on office worker satisfaction and performance. IESNA Annual Conference (Tampa, USA), 19-41.

Newsham, G.R.; Veitch, J.A.; Charles, K.E. 2008. Risk factors for dissatisfaction with the indoor environment in open-plan offices: an analysis of COPE field study data. Indoor Air, 18, (4), 271-282.

Newsham, G.R.; Mancini, S.; Birt, B.J. 2009a. Do LEED-certified buildings save energy? Yes, but … Energy and Buildings, 41, 897-905.

Newsham, G.R.; Brand, J.; Donnelly, C.L.; Veitch, J.A.; Aries, M.; Charles, K.E. 2009b. Linking indoor environment conditions to organizational productivity: a field study. Building Research & Information, 37, (2), 129-147.

PRNewswire. 2010. Building performance and occupant satisfaction tied to green investment in new report. URL: http://www.prnewswire.com/news-releases/building-performance-and-occupant-satisfaction-tied-to-green-investment-in-new-report-108745204.html (last accessed 2012-03-20).

PWGSC. 2012. Office of Greening Government Operations, Sustainable Office Buildings. URL: http://www.tpsgc-pwgsc.gc.ca/ecologisation-greening/immeubles-buildings-eng.html (last visited 2012-03-20).

Rea, M. S.; Ouellette, M. J.; Kennedy, M. E. 1985. Lighting and task parameters affecting posture, performance and subjective ratings. Journal of the Illuminating Engineering Society, 15 (1), 231-238.

San Francisco Department of Building Inspection. 2011. Green Building Ordinance. URL: http://www.sfdbi.org/index.aspx?page=268 (last visited 2012-04-11).

Scofield, J.H. 2009. Do LEED-certified buildings save energy? Not really… Energy and Buildings, 41, 1386–1390.

Siegel, S. 1956. Nonparametric Statistics for the Behavioral Sciences. McGraw-Hill Book Company.

Siegel, S.; Castellan, N.J. 1988. Nonparametric statistics for the behavioral sciences (2 ed.). New York: McGraw-Hill.

Singh, A.; Syal, M.; Grady, C.; Korkmaz, S. 2010. Effects of green buildings on employee health and productivity. American Journal of Public Health, 100(9), 1665-1667.

Smith, B.W. 2010. Cross-Tabs and Chi Square. URL: http://myweb.stedwards.edu/brianws/3328fa10/sec2/lecture17.htm (last visited 2012-03-20).

Statistics Canada (StatCan). 2011. Work absences in 2009. URL: http://www.statcan.gc.ca/pub/75-001-x/2010106/article/11282-eng.htm#a5 (last visited 2012-04-11)

Stokols, D.; Scharf, F. 1990. Developing standardised tools for assessing employees' ratings of facility performance. In G. Davis, & F. T. Ventre (Eds.), Performance of Buildings and Serviceability of Facilities (pp. 55-68). Philadelphia, PA: American Society for Testing and Materials.

Thayer, J.F.; Verkuil, B.; Brosschot, J.F.; Kampschroer, K.; West, A.; Sterling, C.; Christie, I.C.; Abernethy, D.R.; Sollers, J.J.; Cizza, G.; Marques, A.H.; Sternberg, E.M. 2010. Effects of the physical work environment on physiological measures of stress. European Journal of Cardiovascular Prevention and Rehabilitation, 17, 431-439.

Tittarelli, A.; Borgini, A.; Bertoldi, M.; De Saeger, E.; Ruprecht, A.; Stefanoni, R.; Tagliabue, G.; Contiero, P.; Crosignani, P. 2008. Estimation of particle mass concentration in ambient air using a particle counter. Atmospheric Environment, 42, 8543-8548.

USGBC. 2011. Existing Buildings: Operations & Maintenance. URL: http://www.usgbc.org/DisplayPage.aspx?CMSPageID=221 (last visited 2012-03-20).

USGBC. 2012. About LEED (presentation). URL: http://www.usgbc.org/DisplayPage.aspx?CMSPageID=1720 (last visited 2012-03-20).

USGBC. 2012b. LEED Pilot Credit Library. URL: http://www.usgbc.org/DisplayPage.aspx?CMSPageID=2104 (last visited 2012-04-12).

Veitch, J. A.; Newsham, G. R. 1998. Lighting quality and energy-efficiency effects on task performance, mood, health, satisfaction and comfort. Journal of the Illuminating Engineering Society, 27(1), 107-129.

Veitch, J. A.; Charles, K. E.; Newsham, G. R.; Marquardt, C. J. G.; Geerts, J. 2003. Environmental satisfaction in open-plan environments: 5. Workstation and physical condition effects (IRC-RR-154). Ottawa, ON: National Research Council Canada, Institute for Research in Construction.

Veitch, J.A.; Geerts, J.; Charles, K.E.; Newsham, G.R.; Marquardt, C.J.G. 2005. Satisfaction with lighting in open-plan offices: COPE field findings. Proceedings of Lux Europa 2005 (Berlin, Germany): Deutsche Lichttechnische Gesellschaft e. V. (LiTG), 414-417.

Veitch, J.A.; Charles, K.E.; Farley, K.M.J.; Newsham, G.R. 2007. A Model of satisfaction with open-plan office conditions: COPE field findings. Journal of Environmental Psychology, 27 (3), 177-189.

Veitch, J.A.; Newsham, G.R.; Mancini, S.; Arsenault, C.D. 2010. Lighting and office renovation effects on employee and organizational well-being (No. NRC-IRC RR-306). Ottawa, ON: NRC Institute for Research in Construction. URL: http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr306.pdf (last visited 2012-04-11).

Veitch, J.A.; Donnelly, C.L.; Galasiu, A.D.; Newsham, G.R.; Sander, D.M.; Arsenault, C.D. 2010b. Office occupants' evaluations of an individually-controllable lighting system (No. IRC-RR-299). Ottawa, ON: NRC Institute for Research in Construction.

Verplanken, B.; Walker, I.; Davis, A.; Jurasek, M. 2008. Context change and travel mode choice: Combining the habit discontinuity and self-activation hypotheses. Journal of Environmental Psychology, 28 (2), 121-127.

Vital Signs, 2008. Table XII-1: Average Commuting Time and Median Commuting Distance for a Round Trip Between Work and Home for Individuals. URL: http://www.vitalsignscanada.ca/rpt2008/table-XII-1.pdf (last visited 2012-03-20).

Wibom, R. I.; Carlsson, L. W. 1987. Work at video display terminals among office workers. In B. Knave & P. G. Wideback (Eds.), Work with Video Display Units 86 (Amsterdam, the Netherlands), 357-367.

Wilson, S.; Hedge, A. 1987. The office environment survey: a study of building sickness. Building Use Studies, London.

Glossary of Abbreviations

ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
B	Coefficient in regression equation
BEMS	Building energy management system
BOMA	Building Owners and Managers Association
CaGBC	Canada Green Buildings Council
CBECS	Commercial Buildings Energy Consumption Survey
CDD	Cooling degree days
CICES	Commercial and Institutional Consumption of Energy Survey
CIE	Commission Internationale de l´Eclairage (Int'l Commission on Illumination)
COPE	Cost-effective Open-Plan Environments (prior research conducted by NRC-IRC)
CRT	Cathode ray tube (TV-like computer screen)
DDC	Direct Digital Control
DV	Dependent Variable (outcome)
EUI	Energy Use Intensity
HDD	Heating degree days
HVAC	Heating, ventilating, and air conditioning
IE	Indoor Environment
IV	Independent Variable (predictor)
IESNA	Illuminating Engineering Society of North America
LCD	Liquid crystal display (flat computer screen)
LEED	Leadership in Energy and Environmental Design
N	Sample size (when referring to numerical data in charts and tables)
NAAQS/EPA	National Ambient Air Quality Standards/Environmental Protection Agency
NICE Cart	National Research Council Indoor Climate Evaluator Cart
NRCan	Natural Resources Canada
NRC-IRC	National Research Council Canada – Institute for Research in Construction
PERD	Program of Energy Research and Development
POE	Post-occupancy evaluation
p	In statistical tables, probability of an effect this large if there was, in fact, no effect
ppb	Parts per billion
ppm	Parts per million
R^2_{adj}	In statistical tables, variance in DV explained by IV
RTD	Resistance temperature detector
SBS	Sick Building Syndrome
s.d.	Standard deviation
t	A test statistic
TVOC	Total volatile organic compounds
USGBC	U.S. Green Building Council
VAV	Variable air volume
VDT	Video display terminal (computer screen)
VOC	Volatile organic compounds
WHO	World Health Organization
WS	workstation
Z	A test statistic

Glossary of Variable Names

Adap_Energy	Thermal adaptation sub-scale related to actions using additional energy
Adap_Enviro	Thermal adaptation sub-scale related to actions affecting the IE generally
Adap_NoEnergy	Thermal adaptation sub-scale related to actions using no additional energy
Adap_Person	Thermal adaptation sub-scale related to actions affecting the person only
AI	Articulation Index (a measure of speech privacy)
AW	A-weighted sound level
clo	A measure of clothing insulation value
EFR	Environmental Features Rating
met	A measure of metabolic rate
NEP	New Environmental Paradigm
Non-Speech	Acoustics satisfaction sub-scale related to non-speech sounds
OES	Overall Environmental Satisfaction
PCF	Physical Comfort Frequency
PCI	Physical Comfort Intensity
PCOMF	Physical Comfort composite scale
PM2.5	Mass of particulates ≤ 2.5 microns in diameter
PM10	Mass of particulates ≤ 10 microns in diameter
PMV	Predicted Mean Vote (a measure of thermal comfort)
PPD	Predicted Percentage Dissatisfied (a measure of thermal comfort)
RH	Relative humidity
Sat_AP	Satisfaction with privacy & acoustics
Sat_L	Satisfaction with lighting
Sat_VT	Satisfaction ventilation & temperature
SII	Speech intelligibility index
Speech	Acoustics satisfaction sub-scale related to speech privacy
Speech2	Acoustics satisfaction sub-scale related to overheard speech from others
VCF	Visual Comfort Frequency
VCI	Visual Comfort Intensity
VCOMF	Visual Comfort composite scale

Appendix A. Green Building Credit Summary

Table A1 lists the credits claimed/achieved by the green buildings in our field study sample. Note that different buildings may have used different LEED systems or versions. Thus, the list of credits is a composite from several LEED systems. Many credits are common between versions, but might have entailed different criteria. For energy credits, in most cases we know only the total number of credits, and not the mechanisms by which energy savings were achieved. Finally, some buildings had achieved certification, while others were still in the final application phase.

Table A1. Summary of LEED credits received by our study buildings. Shading indicates areas where credits were received, but where the exact credit was not available to us; n/a indicates buildings for which data were not available.

		A	D	F	H	J	M	O	Q	S	T	X
							n/a		n/a	n/a		Go Green
	Sustainable Sites											
Prereq	Erosion & Sedimentation Control (Required)	✓		✓	✓	✓		✓			✓	
Prereq	Wetland Protection (Required)							✓				
Credit	Site Selection (1)	✓		✓	✓	✓		✓				
Credit	Development Density (1)	✓	✓	✓				✓				
Credit	Redevelopment of Contaminated Site (1)											
Credit	Brownfield Development			✓								
Credit	Alternative Transportation, Public Transportation Access (1)	✓	✓	✓				✓				
Credit	Alternative Transportation, Bicycle Storage & Changing Rooms (1)	✓	✓	✓	✓	✓		✓			✓	
Credit	Alternative Transportation, Alternative Fuel Vehicles (1)			✓							✓	
Credit	Alternative Transportation, Parking Capacity (1)		✓	✓		✓					✓	
Credit	Reduced Site Disturbance, Protect or Restore Open Space (1)					✓		✓			✓	
Credit	Reduced Site Disturbance, Development Footprint (1)				✓	✓						
Credit	Stormwater Management, Rate and Quantity (1)			✓	▨ ✓	✓					✓	
Credit	Stormwater Management, Treatment (1)			✓	▨	✓					✓	
Credit	Heat Island Effect, Non-Roof (1)		✓	✓	▨ ✓			✓				
Credit	Heat Island Effect, Roof (1)			✓	▨	✓					✓	
Credit	Light Pollution Reduction (1)	✓		✓	✓	✓		✓			✓	
Credit	Tenant Design and Construction Guidelines (1)			✓	✓							
	Water Efficiency											
Credit	Water Efficient Landscaping, Reduce by 50% (1)	✓		✓	▨ ✓	✓		✓			✓	
Credit	Water Efficient Landscaping, No Potable Use or No Irrigation (1)	✓		✓	▨	✓		✓			✓	
Credit	Innovative Wastewater Technologies (1)			✓		✓						
Credit	Water Use Reduction, 20% Reduction (1)	✓	✓	✓	▨ ✓	✓		✓			✓	

Credit	Water Use Reduction, 30% Reduction (1)	✓	✓	✓		✓		✓			✓	
	Energy & Atmosphere											
Prereq	Fundamental Building Systems Commissioning (Required)	✓	✓	✓	✓	✓		✓			✓	
Prereq	Minimum Energy Performance (Required)	✓	✓	✓	✓	✓		✓			✓	
Prereq	CFC Reduction in HVAC&R Equipment (Required)	✓	✓	✓	✓	✓		✓			✓	
Credit	Optimize Energy Performance (1 to 10)	5		8	✓	3		4			4	
	Lighting Power		3									
	Lighting Controls		1									
	HVAC		1									
	Equipment & Appliances		2									
Credit	Renewable Energy, 5% (1)											
Credit	Renewable Energy, 10% (1)											
Credit	Renewable Energy, 20% (1)											
Credit	Best Practice Commissioning (1)	✓	✓	✓		✓					✓	
Credit	Ozone Protection (1)	✓		✓	✓	✓		✓			✓	
Credit	Measurement & Verification (1)		✓	✓							✓	
Credit	Green Power (1)	✓	✓	✓				✓			✓	
	Materials & Resources											
Prereq	Storage & Collection of Recyclables (Required)	✓	✓	✓	✓	✓		✓				
Credit	Building Reuse: Maintain 75% of Existing Walls, Floors, and Roof (1)	✓									✓	
Credit	Building Reuse: Maintain 95% of Existing Walls, Floors, and Roof (1)	✓										
Credit	Building Reuse: Maintain 50% of Interior Non-Structural Elements (1)											
Credit	Construction Waste Management: Divert 50% from Landfill (1)	✓	✓	✓		✓		✓			✓	
Credit	Construction Waste Management: Divert 75% from Landfill (1)		✓	✓		✓		✓			✓	
Credit	Resource Reuse: 5% (1)		✓									
Credit	Resource Reuse: 10% (1)											
Credit	Recycled Content: 7.5% (or 10%) (1)	✓	✓	✓	✓	✓		✓			✓	
Credit	Recycled Content: 15% (or 20%) (1)		✓	✓		✓		✓			✓	
Credit	Regional Materials: 10% Extracted and Manufactured Regionally (1)		✓	✓	✓	✓		✓			✓	
Credit	Regional Materials: 20% Extracted and Manufactured Regionally (1)		✓	✓		✓		✓			✓	
Credit	Rapidly Renewable Materials (1)											
Credit	Certified Wood (1)		✓			✓						
Credit	Durable Building (1)					✓						
	Indoor Environmental Quality											
Prereq	Minimum IAQ Performance (Required)	✓	✓	✓	✓	✓		✓			✓	
Prereq	Environmental Tobacco Smoke (ETS) Control (Required)	✓	✓	✓	✓	✓		✓			✓	
Credit	Carbon Dioxide (CO2) Monitoring (1)	✓	✓	✓	✓			✓			✓	
Credit	Ventilation Effectiveness / Increased Ventilation (1)	✓		✓	✓			✓			✓	

Credit	Construction IAQ Management Plan: During Construction (1)	✓	✓	✓	✓	✓		✓			✓	
Credit	Construction IAQ Management Plan: Testing Before Occupancy (1)		✓			✓		✓			✓	
Credit	Low-Emitting Materials: Adhesives & Sealants (1)	✓	✓	✓	✓			✓			✓	
Credit	Low-Emitting Materials: Paints and Coating (1)	✓	✓	✓		✓		✓			✓	
Credit	Low-Emitting Materials: Carpet (1)	✓	✓	✓		✓		✓			✓	
Credit	Low-Emitting Materials: Composite Wood and Laminate Adhesives (1)		✓					✓			✓	
Credit	Low-Emitting Materials: Systems Furniture and Seating (1)		✓									
Credit	Indoor Chemical & Pollutant Source Control (1)	✓		✓	✓						✓	
Credit	Controllability of Systems: Perimeter Spaces (1)			✓	✓							
Credit	Controllability of Systems: Non-Perimeter Spaces (1)			✓								
Credit	Controllability of Systems: Lighting (1)		✓								✓	
Credit	Controllability of Systems: HVAC (1)										✓	
Credit	Thermal Comfort: Compliance ASHRAE 55 (1)	✓	✓	✓	✓	✓		✓			✓	
Credit	Thermal Comfort: Monitoring (1)	✓	✓	✓		✓					✓	
Credit	Daylight & Views: Daylight 75% of Spaces (1)		✓		✓	✓		✓				
Credit	Daylight & Views: Daylight 90% of Spaces (1)		✓									
Credit	Daylight & Views: Views 90% of Spaces (1)		✓			✓		✓				
	Innovation & Design Process											
Credit	Exceptional Performance in Green Power (1)	✓	✓					✓			✓	
Credit	Exceptional Performance in Recycled Content (1)			✓	✓			✓			✓	
Credit	Exceptional Performance in Water Reclamation (1)			✓								
Credit	Water Re-use System (1)			✓								
Credit	Exceptional Performance in Water Use Reduction (1)				✓	✓		✓			✓	
Credit	Innovative Wastewater Technologies (1)					✓						
Credit	Exceptional Performance in Low-emitting Systems (1)				✓							
Credit	Exceptional Performance in Regionally Manufactured Materials (1)							✓				
Credit	Exemplary Open Space (1)				✓							
Credit	Building Remediation (1)	✓										
Credit	Green Education (1)	✓	✓									
Credit	Green Housekeeping (1)	✓	✓								✓	
Credit	Low Mercury Lights		✓									
Credit	Education Outreach					✓						
Credit	Embodied Effects					✓						
Credit	LEED® Accredited Professional (1)	✓	✓	✓	✓	✓		✓			✓	

Building X was accredited under the BOMA Go Green program. Its performance ratings were: Energy 77%; Water 83%; Resources 81%; Emissions 98%; Indoor Environment 100%; EMS Documentation 88%.

Appendix B. Overall Descriptive Statistics

Table B1. Summary descriptive statistics for the primary questionnaire and cart variables collected at the study buildings.

	Total						Green						Conventional					
	N	Mean	SD	Min	Max	Med	N	Mean	SD	Min	Max	Med	N	Mean	SD	Min	Max	Med
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	.99	1	6	2.57	346	2.55	.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	.83	.24	.54	1.49	.92	329	.82	.25	.54	1.49	.89	525	.83	.24	.54	1.49	.92
Adap_Energy	861	1.78	1.06	1	7	1.00	331	1.56	.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	.84	1	6	1.40	331	1.56	.76	1	5	1.20	531	1.81	.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	.82	1	5	1.75	290	1.90	.78	1	5	1.75	442	2.02	.84	1	5	1.88
PCF	798	2.49	.80	1	5	2.43	316	2.40	.75	1	5	2.29	482	2.55	.83	1	5	2.57
PCI	736	2.23	.74	1	5	2.14	291	2.19	.70	1	5	2.14	445	2.26	.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 (kms)	758	19.2	19.3	.00	140	14.5	314	19.5	18.6	.00	110	14.7	444	18.9	19.8	1.00	140	14.5
NEP	788	3.57	.65	1	5	3.60	334	3.59	.63	2	5	3.60	454	3.55	.67	1	5	3.55
NICE Cart																		
Air Speed Head (m/s)	972	.11	.06	.01	.68	.10	467	.11	.06	.01	.68	.10	505	.12	.06	.01	.37	.11
Air Speed Chest (m/s)	972	.12	.06	.01	.50	.12	467	.11	.06	.01	.50	.11	505	.13	.05	.01	.36	.13
Air Speed Feet (m/s)	972	.09	.05	.01	.56	.08	467	.09	.05	.02	.56	.08	505	.09	.04	.01	.34	.09
Radiant Temp. (^{o}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 Temp. Head (^{o}C)	972	23.1	1.09	17.8	27.4	23.2	467	23.0	.90	19.5	25.2	23.1	505	23.2	1.23	17.8	27.4	23.3
Air Temp. Chest (^{o}C)	972	23.5	1.13	18.3	28.1	23.5	467	23.4	.96	19.5	27.0	23.5	505	23.6	1.26	18.3	28.1	23.6
Air Temp. Feet (^{o}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 (µg/m^3)	972	2.38	4.15	.01	36.4	1.47	467	1.39	.87	.17	3.94	1.16	505	3.30	5.55	.01	36.4	1.69
PM10 (µg/m^3)	972	25.1	24.8	.89	388	17.6	467	21.9	19.2	.89	107	15.3	505	28.1	28.7	2.51	388	19.9
TVOC (ppb)	972	93.8	94.0	.00	1122	80.0	467	83.2	67.5	.00	767	76.0	505	104	112	.00	1122	86.0
CO2 (ppm)	972	630	128	383	1133	609	467	618	121	400	995	591	505	642	132	383	1133	624
Ozone (ppm)	972	.00	.01	.00	.06	.00	467	.00	.01	.00	.04	.00	505	.00	.01	.00	.06	.00
CO (ppm)	972	.06	.18	.00	2.50	.00	467	.06	.23	.00	2.50	.00	505	.05	.12	.00	.70	.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	.19	.17	.00	1.22	.16	467	.18	.14	.00	.96	.16	505	.20	.19	.00	1.22	.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 (inch)	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 (x1000 inch^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	117
Ceiling Height (inch)	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	10206	587	467	764	858	53.0	9525	606	505	676	665	45.4	10206	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	17238	228	467	408	591	36.8	5753	243	505	350	878	36.8	17238	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	22214	239	467	444	784	29.0	9974	261	505	411	1356	29.0	22214	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	47021	414	467	643	941	27.6	12435	442	505	671	2564	34.5	47021	380
IllumRightDesk (lux)	972	630	1282	26.9	18820	396	467	674	1327	26.9	18001	430	505	590	1238	26.9	18820	369
IllumMeanDesk (lux)	972	644	1273	27.2	24864	406	467	659	959	27.2	9574	437	505	630	1508	34.1	24864	377
Luminance Above Monitor (cd/m^2)	965	102	236	.00	3130	41.9	463	122	273	.00	3130	50.3	502	83.1	194	1.62	2180	35.1
AI	974	.31	.20	.00	.97	.30	469	.33	.21	.00	.88	.30	505	.30	.19	.00	.97	.29
SNA (dB)	974	.43	6.12	-21.0	22.2	.66	469	.72	6.47	-21.0	17.1	.71	505	.15	5.76	-17.8	22.2	.59
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