ACOUSTICAL EVALUATION OF SIX 'GREEN' OFFICE BUILDINGS

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ABSTRACT

To explain the reactions of the building occupants to their acoustical environments, meetings with the designers, walk-through surveys, and detailed acoustical measurements were done. The objective was to determine how design decisions affect office acoustical environments, and how to improve the acoustical design of 'green' office buildings. Design-performance criteria were established. Measurements were made of noise level, reverberation time, speech-intelligibility index (SII), and noise isolation. Noise levels were atypically low in unoccupied buildings with no mechanical ventilation, but excessive in areas near external walls next to noisy external noise sources—especially with windows open for ventilation—and in occupied buildings. Reverberation times were excessive in areas with large volumes and insufficient sound absorption. Speech intelligibility was generally adequate, but speech privacy was inadequate in shared and open-office areas, and into private offices with the doors open for ventilation. Improvement of the acoustical design of 'green' buildings must include increasing the external-internal noise isolation and that between workplaces, and the use of adequate sound absorption to control reverberation and noise.

KEY WORDS

'green' building, offices, acoustical environment, occupant satisfaction, noise levels, reverberation, speech intelligibility, speech privacy, noise isolation

1. INTRODUCTION

The aim of sustainable ('green') building is to create buildings that preserve the environment and conserve natural resources, as well as to provide a 'healthy' environment for its occupants. A healthy environment is one that does not cause disease, promotes well-being and, in the case of places for work and learning (i.e. schools), promotes productivity. An important aspect of the built environment—often overlooked or undervalued in design—is the acoustical environment. Recent papers [Abbaszadeh et al. 2006; Braithwaite and Cowell 2007; Chilton and Skelly 2007; Cowell 2005; Field 2008; Hyde 2005; Jenson et al. 2005; Khaleghi et al. 2007; Noble 2005; Pettyjohn (2006); Richter et al. 2006; Roy and Snader 2007], presented mainly at acoustical conferences with special sessions on 'green' building, have pointed out that 'green' buildings are often less than satisfactory acoustically, and reported the small amount of work that has been devoted to the design, control and/or optimization of their acoustical environments [Connelly et al. 2007; Cowell 2005; Field 2008; Hodgson and Khaleghi 2007; Kang et al. 2005; Noble 2005; Oldham et al. 2005; Richter et al. 2007; Roy and Snader 2007; Salter et al. 2006; Siebein et al. 2005]. The work discussed here was an attempt to further investigate this issue, with a particular focus on office buildings, and to increase awareness of 'green'-building acoustical issues in the non-acoustical design community.

The work formed the acoustical part of a larger study aimed at evaluating six 'green' office buildings from a wide range of aspects, in order to learn design lessons and provide feedback to the design community on how to design better 'green' buildings. The methodology followed for each of the buildings used a previously developed protocol to evaluate energy and water consumption, operating experiences (including commissioning), occupant satisfaction (overall, social-capital development, thermal comfort, indoor-air quality, lighting, acoustics, washrooms), and success in meeting the design intentions. The evaluation protocol and full study reports are presented elsewhere [EcoSmart 2008].

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2. OBJECTIVES AND METHODOLOGY

The acoustical work involved the following steps: meeting with designers; performing an occupant-satisfaction survey (using a web-based survey developed by the Center for the Built Environment at the University of California at Berkeley: CBE 2008); analyzing the responses—in particular, to identify situations corresponding to high and low satisfaction; walking through the building for familiarization purposes; planning the acoustical measurements (i.e. choosing measurement locations and test conditions); performing and analyzing the acoustical measurements; considering the design implications of the results; holding designer meetings and public forums to provide feedback to the design community.

The work was limited by time and access/confidentiality constraints, as well as by small sample sizes and, therefore, low statistical power.

3. BUILDING DESCRIPTIONS

The study involved six very different nominally-'green' office buildings, all designed to the sustainable-development principles—in particular, to be highly energy and water efficient—prevailing at the time of design. The buildings housed 50 to 500 workers and were evaluated one to five years after occupancy. Following are brief, anonymous and general descriptions of the buildings; further details cannot be provided for reasons of confidentiality. All buildings had mainly glass façades for maximum day-lighting, with sun shades and operable windows (except Building E), and contained a mix of private and shared offices, and open-office cubicles.

3.1 Building A

Building A comprised three floors of a high-rise office building, renovated to obtain LEED®-CI Silver rating [USGBC 2005a]. A highly reverberant reception area is coupled to a café and meeting rooms. Remaining work areas are mainly open-office cubicles, arranged in pods, and private offices.

Some energy savings were achieved by dedicating air-handling units to individual floors. These units are able to operate on 100% outdoor air for cooling-energy savings when outdoor-climate conditions permit. The resulting energy use was lower than the average for existing office buildings in the region. The

lighting design involved maximizing day-lighting, with 90% of spaces intended to be day-lit. Floor-to-ceiling glazing, with internal blinds for glare control, were installed on the whole building. In addition to the internal blinds, roller shades were added to the south glass after occupancy, to control glare. The thermal design included fan-powered boxes for increased air circulation. After occupancy, tinted film was placed on the south windows to limit solar gain. The building has night-time lighting 'sweeps' to turn off lights, and occupancy sensors for lighting control in many spaces. The acoustical design involved acoustical isolation of the fan rooms to control HVAC noise, and carpets and partitions to absorb sound in open-office areas. To achieve high air quality, the air-handling system is capable of running on 100% outdoor air. Increased air mixing is obtained through the use of fan-powered boxes. The building has low-VOC finishes.

3.2 Building B

Building B is a large, five-storey building, with an external noise source. The goal of reduced energy consumption was pursued using under-floor air-distribution systems and a high-performance envelope for day-lighting, which resulted in reduced electric-lighting energy. Additional energy-conservation measures included exposed concrete mass for thermal storage, and use of 'hotelling stations' or shared workstations to reduce the total building area and, thus, the energy consumed. Actual energy consumption exceeded predicted values, due primarily to operational differences involving extended hours of occupancy, and also due to conditioning of excess outdoor air. However, the average energy consumption during the years assessed was 8% less than the average energy consumption of existing office buildings in the region. The goal of maximizing day-lighting in Building B was pursued using a long-perimeter design with large areas of glazing, solar shading, light shelves, and high ceilings. In operation, glare concerns led to the addition of blinds both above and below light shelves, hindering the day-lighting strategy. Acoustical ceiling panels added after occupancy reduced the effectiveness of the electrical up-lighting strategy, requiring the addition of task lighting. Optimal thermal comfort was sought in the building using under-floor air-distribution systems.

Occupant control over thermal comfort was pursued in the design by specifying adjustable diffusers for airflow control. 'Snapshot' thermal measurements in the building suggest that temperature conditions were within benchmarks; thermal comfort was rated highly by respondents in an occupant-satisfaction survey. The exposed concrete ceilings in the building led to a more reflective acoustical environment than anticipated, and acoustical ceiling panels were added after occupancy. The goal of optimized indoor-air quality was pursued in the building using the designed under-floor air systems. Evidence suggests that excessive outdoor air is likely being conditioned, leading to excellent indoor-air quality, but also to increased energy consumption. Building B is exposed to a large, powerful, non-continuous external transportation-noise source. Open-office areas are carpeted, and separated by variable-height partitions; some are separated by glass ceiling baffles or sound-absorbent ceiling patches.

3.3 Building C
Building C is a two-storey building with an entrance atrium. It has large air-transfer openings between floors, a displacement ventilation system with low-velocity, ground-level air diffusers and floor diffusers on the second floor, and hydronic radiant ceiling panels for heating and cooling. It is devoid of sound-absorbing materials; some planned interior finishes were ultimately not installed to cut costs. There is a strong, intermittent external noise source. Building C obtained LEED-Canada® Gold rating [CaGBC 2007].

The goal of energy reduction was pursued in the building design using a high-performance envelope, solar shading, displacement ventilation systems, and radiant heating and cooling served by a geo-exchange system. Day-lighting and occupancy sensors were installed for reduced lighting-energy consumption, and carbon-dioxide monitoring was used to control ventilation. The building systems were not designed for full cooling, and operable windows were designed to supplement occupant control over ventilation and cooling in their workspaces. A photovoltaic system was also designed for the building. The goal of water conservation in the building was pursued using low-flow fixtures, waterless urinals and dual-flush toilets, and using rainwater captured in an existing cistern on-site for toilet flushing. The day-lighting objective drove much of the architectural design of the building, with large windows and solar shading contributing to this goal. Internal blinds were intended to be used by occupants to control glare.

3.4 Building D
Building D is a small building with two wings of one or two stories, designed to be highly energy and water efficient. It has radiant floors, under-floor air distribution, and a partial 'green' (vegetative) roof. It used low-VOC materials and paints, and obtained LEED® Gold rating [USGBC 2005b].

The goal of energy reduction was pursued in the building design using a high-performance envelope and solar shading. The mechanical systems used were under-floor air-ventilation and radiant-heating systems served by a combination of heat pumps and solar-heat collectors, with a backup boiler. A natural-ventilation strategy using operable windows was designed for use throughout summer months, with some radiant cooling capacity in case of extreme cooling requirements. Daylight sensors were installed for reduced lighting-energy consumption. A photovoltaic system was also designed for the building. The goal of water conservation was pursued using low-flow fixtures, waterless urinals and dual-flush toilets, and by making use of captured storm water for toilet flushing. Water consumption in the building was very close to the targets set during design. The day-lighting objective drove much of the architectural design of the building, with large windows and solar shading contributing to this goal.

3.5 Building E
Building E is a four-storey university building with lecture halls, computer labs and common areas. It has a 'green' (vegetative) roof, and contains two full-height atria, and a natural-ventilation system with air inlet under the building, many air-transfer ducts/openings (some acoustically lined), and high-level exhaust. The building contains little sound absorption.

In the building design, the goal of energy and load reduction was pursued using strategies of solar shading, relaxed temperature ranges in transition areas, and natural ventilation in shoulder seasons.

Additional energy-saving strategies included pre-heating and pre-cooling of air through underground passages, use of thermal mass, and under-floor air-displacement ventilation in lecture theatres. Actual energy consumption in the building exceeded predicted values, in part because of operational differences involving hours of occupancy, computer loads and temperature set-points, as well as operational problems with the automatically opening windows. Despite these issues, the building still consumes 39% less energy than typical buildings of its type. The goal of maximizing day-lighting in Building E was pursued using two central atria which bring natural light into the building, as well as using large glazed areas. Day-lighting in the large lecture theatre was to be controlled by large, vertical shading louvers. In operation, the day-lighting strategy was effective, but glare problems exist when occupants choose not to make use of blinds. In the lecture theatre, problems with the louver motors resulted in these louvers being closed and disabled. The design strategy to allow wider temperature ranges in the building's transition spaces was agreed to by the owner and a prospective occupant group, in order to reduce energy consumption. However, in actual operation of the building, occupant complaints led the operator to change these set-points to a narrower range. The goal of optimized acoustical quality in Building E was pursued in the use of acoustical treatments in the building, particularly in air-transfer openings. The strategies of natural ventilation in spring and fall, and mechanical ventilation via the atrium the rest of the year, were effective in optimizing indoor-air quality in the building.

3.6 Building F

Building F is a six-story, multi-tenancy, 'shell' building, designed for any occupant, with internal 'fit-up' for tenants. It houses university departments and laboratories, and an elementary school. The building has a forced-air ventilation system, and extensive sound absorption. It obtained a LEED® Silver rating [USGBC 2005b].

The goal of energy savings in the building was pursued using simple and efficient systems in accordance with a 'less-is-more' strategy. Low-flow fume hoods in laboratory areas allowed for significantly lower air-change rates and, thus, less energy for conditioning of outdoor air. Actual energy consumption exceeded predicted values, in part because of operational differences involving schedules of operation. However, in comparison to a building across the street that is owned by the same company and has similar use and operational parameters, Building F consumes 25% less energy per unit of floor area. The goal of reduced water consumption was targeted in the building using low-flow fixtures, dual-flush toilets, and waterless urinals. The actual water consumption in the building, was lower than predicted, and much lower than benchmarks. However, maintenance concerns with dual-flush toilets and waterless urinals indicate that a new design standard must be developed for plumbing systems when these low-flow fixtures are employed. The goal of maximizing day-lighting in the building was pursued by designing glazing areas and floor-plan depths so as to provide as much natural light as possible. In operation, the day-lighting and electric-lighting strategies were effective at producing adequate light levels, but some spaces were over-illuminated. Of course, tenant-fit-out lighting-design decisions also influenced building performance. The goal of optimized acoustical quality in Building F was pursued in the design of acoustical treatments, including carpets, acoustical ceiling tiles, and workspace partitions. The mechanical systems in Building F were effective in optimizing indoor-air quality in most areas, with the exception of a few locations on the ground floor where ultrafine particulate concentrations were higher than benchmarks.

4. DESIGNER MEETINGS

Meetings were held with the building designers (usually an architect and a mechanical engineer) to understand their design objectives, approaches and constraints. Following are the main points relevant to acoustics learned from the designers at the meetings with them:

- obtaining LEED® certification was often a goal that strongly influenced design;
- design usually did not involve specialized acoustical expertise; acoustical consultants were retained to deal with 'special cases';
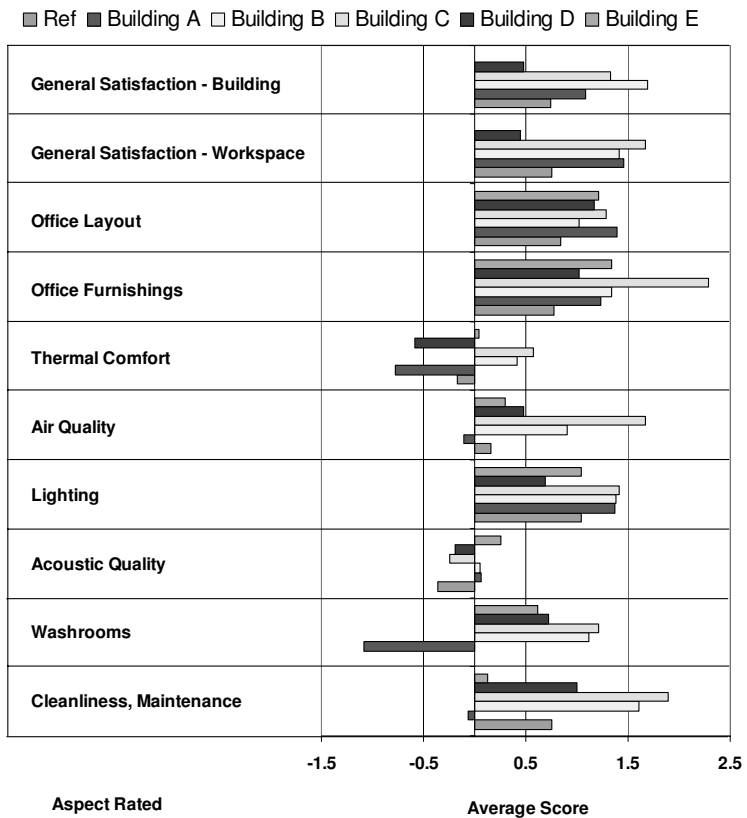- quantitative acoustical design targets were never set;

- designers were aware of acoustical issues such as outside noise, speech privacy, noise isolation, reverberation and HVAC noise;
- external-noise (and air-pollution) concerns may rule out employing a fully-natural ventilation design concept;
- 'green' buildings often have operable windows, which causes noise concerns if there is a strong external noise source;
- low noise levels resulting from absence of a forced-air system can result in low speech privacy;
- client's wishes (e.g. for open-office design) may affect design;
- budget short-falls at the end of the project may affect whether planned acoustical treatments are installed and, therefore, acoustical quality;
- obtaining good noise isolation between workspaces involves lined return-air ducts, upholstered furniture, acoustical ceilings, carpet, open-office partitions, etc.;

- some buildings were designed for any occupant; the internal 'fit-up' (including acoustical treatment) was done later by contractors for tenants (often on limited budgets);
- designers often believe that their buildings are well designed, and successful with the occupants.

5. OCCUPANT-SATISFACTION SURVEYS

The Berkeley survey asks occupants of a building to rate their general satisfaction with the building and with their workspace, with the office layout and furnishings, with thermal comfort, air quality, lighting, acoustical quality, and with the washrooms. In this study, they were also asked to rate cleanliness and maintenance. Respondents rate quality on a scale from -3 (maximum dissatisfaction) to +3 (maximum satisfaction). Figure 1 shows the results of the occupant-satisfaction surveys done in five of the six buildings (one had previously been evaluated by a different survey tool—the results are not directly

FIGURE 1. Occupant-satisfaction survey results for five 'green' office buildings A to E, and (Ref) the average responses for a large number of other office buildings.

comparable). Also shown (Ref case) are the average scores from a large number of buildings ('green' and non-'green') surveyed using the CBE survey. Note that small differences in responses are not likely to be statistically significant.

In general, satisfaction ratings were positive—often in the range +1 to +2—indicating general satisfaction with many aspects of the building design. Occupants were very satisfied with the overall buildings and workspaces, with the office layouts and furnishings, with cleanliness and maintenance and, with one exception (Building D), with the washrooms. With respect to the quality of the work environment, they were generally very satisfied with the lighting, and somewhat satisfied with air quality. Satisfaction with thermal comfort varied from somewhat satisfied to somewhat dissatisfied. Occupants were generally somewhat dissatisfied with the acoustical environment, which often received the lowest rating in the surveys. Note that this is also true of many conventional, non-'green' buildings.

Occupants were asked to rate three aspects of the acoustical environment: noise levels, privacy, and how well the acoustical environment enhances their ability to work ('productivity'). The ranges and average ratings for each aspect are shown in Table 1. Clearly, speech privacy is perceived to be the biggest acoustical issue. Occupants who were dissatisfied with the acoustical environment were asked to state the sources of their dissatisfaction. The sources most frequently cited were lack of privacy, HVAC noise, phone ringing, external noise, people moving and talking, office equipment, and reverberation. Filtering the survey results according to workplace type and location revealed that acoustical concerns were least in private offices and greatest in open-plan and shared offices; they were greatest near external walls and least away from walls.

TABLE 1. Ranges and averages of occupant ratings of three aspects of the acoustical environment.

Aspect	Range (min, max)	Average
Noise level	–0.03, 0.7	0.44
Speech privacy	–1.0, –0.17	–0.47
Productivity	0.08, 0.33	0.19

6. ACOUSTICAL MEASUREMENTS

6.1 Quantities Measured and Acceptability Criteria

The objective here was to use physical-acoustical measurements to evaluate the acoustical environment and help explain the survey results, which identified situations (workplaces and building conditions) of high and low occupant satisfaction. Workplaces at which measurements were performed were chosen to correspond to high and low occupant satisfaction. Following the established protocol, between 20 and 25 locations were measured in each building. These included desks in open-plan, shared and private offices, located in quiet and noisy areas, near and far from operable windows, and in communal areas such as lobbies, atriums, lunchrooms and corridors. Furthermore, measurements were made under building conditions expected to correspond to high and low satisfaction (unoccupied or occupied, windows or doors closed or open, quiet or noisy external environment). Four acoustical parameters were measured, as follows:

- Noise Criterion (NC) noise level. Typical 30-s equivalent-continuous noise levels in octave bands from 63 to 8000 Hz were measured using a Rion NA29E Sound Level Meter, and corresponding NC levels determined;
- Mid-frequency reverberation time (RT_{mid}). Reverberation times in third-octave bands from 100 to 2500 Hz were determined from the corresponding sound-decay curves using a Norsonics NE830 Real-Time Analyzer, and averaged;
- Speech Intelligibility Index (SII). SII is a measure of the quality of verbal communication (speech intelligibility or speech privacy). It is calculated at a receiver position, from octave-band values of speech level, noise level and RT_{mid} [ANSI 1997]. Actual speech levels were not measured. Instead, a 'speech-source' loudspeaker with human-like directional radiation characteristics, radiating continuous white noise, was located at each 'talker' position of interest. Its 250- to 8000-Hz octave-band output sound-power levels had been previously calibrated. At each receiver location of interest, 250- to 8000-Hz octave-band sound-pressure levels were measured. Then,

TABLE 2. Acoustical measurement parameters and acceptability criteria used in the study.

Measurement parameter	Acceptability criteria
background-noise level, NC in dB	NC 30-35 in meeting and conference rooms NC 35-40 in workspaces
Reverberation Time (mid-frequency), RT_{mid} in s	< 0.75 s for comfort, easy verbal communication
Speech Intelligibility Index, SII	> 0.5 (0.75) for acceptable (high) speech intelligibility < 0.2 (0.1) for acceptable (high) speech privacy
Noise Isolation, NIC in dB	NIC 35-40 for executive offices, conference rooms NIC 30-35 for general offices, meeting rooms

sound-pressure levels corresponding to an average adult talking in a given (casual, normal or raised) voice level were calculated from the differences between the corresponding sound-power levels [ANSI 1997] and those of the speech source, and the measured sound-pressure levels;

- Noise Isolation Class (NIC). Noise levels in octave bands from 63 to 8000 Hz were measured at relevant source and receiver positions using the Rion meter. From these, octave-band noise-isolation values were calculated by subtraction, and corresponding NIC values determined.

The first three of these parameters (NC, RT_{mid} and SII) quantify different aspects of the acoustical environment at the receiver position; the fourth (NIC) is useful to help explain the results. Shown in Table 2 are the acceptability criteria used to evaluate each aspect of the acoustical environments in these office buildings, chosen on the basis of information in various sources [ANSI 1995; ANSI 2002; ANSI 2006]; these should be considered as indicative, not definitive.

6.2 Results

Table 3 summarizes the main results of the acoustical measurements.

In the unoccupied buildings, background-noise levels were typically a quiet NC 26-34 with natural ventilation, an acceptable NC 35-42 with forced-air ventilation, and an excessive NC 45-60 with the windows open to an external noise source. Levels in the occupied buildings were typically an excessive NC 40-60.

Reverberation times were typically an acceptable 0.6 to 1.0 s in open-office areas with low absorption, and a low 0.2 to 0.4 s with high absorption. In private offices, they ranged from an acceptable 0.4 to 0.7 s with low absorption, to a low 0.2 to 0.4 s with high absorption. Reverberation times in hallways and atriums were often excessive, in the range 0.9 to 2.4 s.

In private offices, across the desk, with a talker speaking in a casual voice, SII was typically 0.3 to 0.6 (acceptable speech intelligibility) with forced-air ventilation and low sound absorption, and 0.7 to 0.8 (high speech intelligibility) with natural ventilation and high absorption.

Regarding speech privacy, SII between open-office cubicles with a talker speaking in a casual voice was 0.3 to 0.6 (low speech privacy) with forced-air ventilation and low sound absorption (high reverberation), and 0.7 to 0.8 (no speech privacy) with natural ventilation and high sound absorption (low reverberation). From outside to inside private offices, with the door open and a talker speaking in a casual voice, SII was typically 0.7 (no speech privacy).

Noise isolation from outside to inside enclosed offices was typically NIC 25 to 30 (acceptable noise isolation) with the door closed, but only NIC 9 to 15 (unacceptable isolation) with the door open. Between open work areas, noise isolation was typically an inadequate NIC 7 to 20.

7. DESIGN IMPLICATIONS

The main acoustical-design implications of the results related to low and high background-noise levels, inadequate speech privacy, excessive reverberation, inadequate noise isolation between workplaces in open and shared work areas, and inadequate internal and

TABLE 3. Summary of main results of acoustical measurements in six 'green' office buildings.

Quantity	Location	Test conditions	Value
background-noise level (NC)	Work areas	Unoccupied building, natural ventilation	NC 26-34
		Unoccupied building, forced-air ventilation	NC 35-42
		Occupied building	NC 40-60
		External noise, windows open	NC 45-60
Reverberation Time (RTmid, s)	Open-office areas	Low sound absorption	0.6–1.0 s
		High sound absorption	0.2–0.4 s
	Closed-office areas	Low sound absorption	0.4–0.7 s
		High sound absorption	0.2–0.4 s
	Hallways, atriums	Low sound absorption	0.9–2.4 s
Speech Intelligibility (SII)	Private office, across desk (casual voice)	Forced-air ventilation, low absorption	0.3 to 0.6
		Natural ventilation, high absorption	0.7 to 0.8
Speech Privacy (SII)	Between open-office cubicles (casual voice)	Forced-air ventilation, low absorption	0.3 to 0.6
		Natural ventilation, high absorption	0.7 to 0.8
	Outside to inside private office (door open, casual voice)		0.7
Noise Isolation (NIC)	Into enclosed office	Door closed	NIC 25-30
		Door open	NIC 9-15
	Between open-office work areas		NIC 7-20

external wall isolation. Following are further details; since many of the implications pertain to buildings in general, and are not particularly associated with 'green' buildings, these are divided into 'universal' and particularly 'green'-building issues.

7.1 Universal Issues
- a design approach that assumes that acoustical issues are minimal and can be dealt with using the non-specialist knowledge of the design team, and which does not involve setting quantitative acoustical design targets, may not result in occupant satisfaction with the acoustical environment;
- locating an office building next to an external noise source makes noise complaints likely, especially with windows open;
- operable windows significantly reduce the sound isolation provided by the building envelope, resulting in noise complaints, especially if there is a strong external noise source (e.g. a transportation corridor or an industrial site);
- adequate sound isolation from outside to inside offices requires appropriate acoustical design of the external façade, openings and penetrations. This is particularly important when the design involves glass curtain walls or operable windows;
- shared offices inevitably lead to speech-privacy concerns; private offices can provide adequate speech privacy if designed appropriately;
- open-plan office areas are compromises between acoustical and non-acoustical design requirements. They are acoustical challenges that

require appropriate acoustical design, but will never be as satisfactory acoustically as enclosed offices. Appropriate design involves adequate inter-cubicle partition heights, substantial sound absorption on the surfaces of the inter-cubicle partitions and nearby room surfaces (especially the ceiling), as well as the careful location of cubicle entrance openings;

- the amount of speech privacy required in an office setting depends in part on the expectations and activities of the occupants. In one building, two areas, occupied by designers from two different professional groups, were physically and, according to acoustical-measurement results, acoustically very similar. However, one received a low-satisfaction acoustical rating, the other a high-satisfaction rating;

- buildings with insufficient sound-absorbing materials have excessive reverberation, resulting in an acoustical environment which feels 'noisy', in which intermittent sounds (e.g. voices, telephone ringing, door slams) are distracting, and which impairs verbal communication; it also results in low noise isolation between different work areas, allowing sound to propagate with insufficient attenuation between them, causing noise problems;

- school classrooms are acoustically critical spaces that require careful attention to the acoustical design – in particular, with respect to building, school and classroom layout, HVAC and equipment noise levels, noise isolation to adjacent spaces, and reverberation times (consult reference [ANSI 2002] for more details).

7.2 'Green'-Building Issues

- since LEED® virtually ignores the acoustical environment (LEED® for Schools [USGBC 2007] is an exception), a building designed to obtain LEED® certification is unlikely to have adequate attention paid to the acoustical environment;

- 'green' buildings often are designed to have natural or displacement ventilation systems; these can affect the acoustical environment beneficially or detrimentally, resulting in low background-noise levels and low noise isolation; however, forced-air ventilation systems can figure successfully in 'green'-building design (two of the six study buildings had them);

- many 'green' buildings have few sound-absorbing materials (because conventional sound-absorbing materials are not perceived to be 'green', because of budget cuts and/or because of the architectural visual design and glazing); this affects the acoustical environment detrimentally, resulting in excessive reverberation, low acoustical privacy and inadequate attenuation of sound propagating through the building; however, beneficial sound-absorbing materials can figure successfully in 'green'-building design (e.g. in Building F, which rated LEED® Silver);

- if a 'green' building, designed with a ventilation system relying on operable windows, is located next to a significant noise source, noise problems are likely, especially if the windows open on the source side;

- a 'green' building designed to rely on a natural/displacement ventilation system, and with transparent envelope for day-lighting, may overheat on hot, sunny days, forcing occupants to open windows and office doors, reducing noise isolation and resulting in excessive noise and low speech privacy;

- background-noise levels in a 'green' building with a full or partial natural-ventilation system may be lower than in a conventional building with a forced-air system. These low levels may make it more difficult to achieve adequate speech privacy. While speech privacy also depends on limiting voice levels and reverberation, in some cases it may be of interest to also consider introducing masking noise into the building to increase speech privacy;

- a 'green' building designed to rely on a natural or displacement ventilation system usually involves air-transfer openings and/or ducts in partitions. These significantly reduce noise isolation between areas, even when treated acoustically.

8. DISCUSSION AND CONCLUSION

The acoustical environment is often judged the least satisfactory aspect of 'green' office buildings by the occupants. Occupants are dissatisfied with excessive noise and poor speech privacy, and consider that the acoustical environment does not enhance their ability to work. Speech privacy is often the biggest concern. The results of the acoustical measurements help explain the occupant-satisfaction results:

- Noise levels—excessive noise levels are annoying, tiring, stressful and inhibit verbal communication and working efficiency. In the study buildings, dissatisfaction resulted from excessive noise from external noise sources, especially with windows open. Noise levels were generally acceptable, except at workplaces near external walls facing strong external noise sources, especially with windows open for ventilation, where they were unacceptably high. Noise levels due to occupant activity can be high when the acoustical conditions are poor (e.g. when there is excessive reverberation). Excessive noise can also result from excessively noisy forced-air HVAC systems and other noise sources, including occupant activity;

- Speech privacy—poor speech privacy leads to building occupants overhearing other conversations, and feeling that their conversations are overheard. Low noise levels associated with natural ventilation, and excessive reverberation times (resulting from large volumes and insufficient sound-absorbing materials), contribute to low speech privacy, as does inadequate sound isolation between workspaces (due to insufficiently high sound absorption and open-office-cubicle partitions). Speech privacy is also poor between the insides and outsides of closed offices when the doors are open for ventilation;

- Productivity—the acoustical environment enhances a person's ability to work when it is comfortable, free of distractions and supports easy verbal communication (i.e. speech is easy to understand using a comfortable voice level). Excessive reverberation makes a workplace feel 'noisy' and uncomfortable, and contributes to inadequate speech intelligibility. Excessive reverberation and inadequate noise isolation between workspaces (caused by inadequate partition design or the inadequate attenuation of propagating sounds due to insufficient sound absorption), result in sounds (in particular, intermittent sounds) generated in one workplace being heard, causing distraction and breaking concentration, in other workplaces.

Many of the acoustical issues identified in the 'green' office buildings studied are also issues in conventional office buildings, since insufficient attention is often paid to their acoustical design. 'Green' buildings may be different from conventional buildings in having lower noise levels due to a natural-ventilation system, or having higher noise levels due to external-to-internal sound transmission through extensive glass facades and open windows. They may have fewer sound-absorbing materials, and lower noise isolation between internal areas for that reason, and because of air-transfer openings.

It is interesting to note that a number of the issues identified as sources of dissatisfaction in the study buildings were recognized by designers in the meetings with them. Clearly, knowledge of potential acoustical problems by designers is far from a guarantee that buildings realized by these designers will be devoid of acoustical problems. Apparently other priorities can take precedence.

'Green'-building design is crucial to the future of a sustainable world. However, in solving important problems, 'green'-building design must not create new problems, such as buildings that the occupants do not want to use because of unacceptable acoustical environments. The results of this study confirm that improving acoustical environments in 'green' (and conventional) buildings fundamentally requires good acoustical design—that is, the application in design of existing knowledge, with input from an acoustical specialist integrated into the design team from the beginning of the design process. This knowledge relates to site selection and building orientation, to the design of the external envelope and penetrations in it, to the building layout and internal partitions, to the design of the HVAC system, to the appropriate dimensioning of spaces, and to the amount and location of sound-absorbing treatments. For a satisfactory acoustical environment, the advice of the acoustical specialist must be followed, and the budgetary resources made available for it to be implemented.

The results also suggest a need for further research—for example, to address conflicts between acoustics and mechanical/ventilation design, such as how to attenuate sound in air-transfer openings without detrimentally reducing air-flow rates, into 'green' sound-absorbing materials, and on the optimal acoustical design of 'green'-building external envelopes. Failure to resolve the problems and create satisfactory acoustical environments may limit the

evolution of 'green' building and compromise sustainable development.

ACKNOWLEDGMENTS

REFERENCES

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

ANSI S12.2-1995. American National Standard Criteria for Evaluating Room Noise. Acoustical Society of America, New York, 1995.

ANSI S3.5-1997. American National Standard Methods for Calculation of the Speech Intelligibility Index, Acoustical Society of America, New York, 1997.

ANSI S12.60-2002. American National Standard Acoustical Performance Criteria, Design Requirements and Guidelines for Schools. Acoustical Society of America, New York, 2002.

ANSI (2006). Interim Sound and Vibration Design Guidelines for Hospital and Healthcare Facilities, American National Standards Institute WG44 Joint Subcommittee on Speech Privacy, 2006; available from www.speechprivacy.org, last accessed 6 November 2008.

Asdrubali, F. (2007). "Green and sustainable materials for noise control", Proc. 19th International Congress on Acoustics, Madrid.

Beranek, L. (2005). "Acoustical Criteria for Communities and Buildings", Noise and Vibration Control Engineering—2nd edition, Beranek, L. and Ver, I. eds. John Wiley & Sons, New York, Ch. 20.

Braithwaite, P.A. and Cowell, J.R. (2007). "Acoustics and sustainability", Proc. Institute of Acoustics, Vol. 29, Pt. 2.

CaGBC (2007). "LEED Canada for New Construction and Major Renovations Version 1.0", Canada Green Building Council, Ottawa, ON; available at http://www.cagbc.org/leed/systems/index.htm, last accessed 6 November 2008.

CBE (2008). Center for the Built Environment at the University of California, Berkeley, CA. http://www.cbe.berkeley.edu/research/survey.htm, last accessed 6 November 2008.

Connelly, M., Khaleghi, A. and Hodgson, M. (2007). "Field measurement of the acoustical performance of green roofs", Proc. 19th International Congress on Acoustics, Madrid.

Chilton, A. and Skelly, M. (2007). "Conflicts between acoustics and sustainability in schools", Proc. Institute of Acoustics, Vol. 29, Pt. 2.

Cowell, J.R. (2005). "Sustainable Design in Acoustics", Proc. Institute of Acoustics, Vol. 27, Pt. 2.

EcoSmart (2008). http://www.ecosmart.ca/index.cfm?pk=3, last accessed 31 October 2008.

Field, C. (2008). "Acoustical design in green buildings", ASHRAE Journal 50(9) 60-70.

Hodgson, M. and Khaleghi, A. "Design of Noise-Isolation Systems for the Natural-Ventilation System of the UBC Liu Institute for Global Issues", University of British Columbia (2007)

Huston, R. and Duarte, S. (2007). "Sustainability, acoustics and facades", Proc. Institute of Acoustics, Vol. 29, Pt. 2.

Hyde, R. (2005). "Post-occupancy evaluation and acoustics in green buildings", Journal of the Acoustical Society of America 117(4) 2378 (abstract).

Jensen, K., Arens, E. and Zagreus, L. (2005). "Acoustical quality in office workstations, as assessed by occupant surveys", Proc. Indoor Air Conference 2401-2405.

Kang, J., Brocklesby, M., Li, Z. and Oldham, D. (2005). "An acoustic window for sustainable buildings", Journal of the Acoustical Society of America 117(4) 2379 (abstract).

Khaleghi, A., Bartlett, K., and Hodgson, M. "Relationship between ventilation, air quality and acoustics in 'green' and 'brown' buildings", Proc. 19th International Congress on Acoustics, Madrid.

Pettyjohn, S.D. (2006). "Acoustic qualities of three LEED certified buildings and why some disappoint", Journal of the Acoustical Society of America 120(5, Pt. 2) 3184 (abstract).

Richter, M., Hyde, R. and Hodgson, M. (2006). "Acoustical lessons from four green buildings", Journal of the Acoustical Society of America 120(5, Pt. 2) 3184 (abstract).

Richter, M., Razavi, Z., Taylor-Hell, C., Hodgson, M. and Khaleghi, A. (2007). "Improving the acoustical performance of a green office building", Proc. 19th International Congress on Acoustics, Madrid.

Roy, K. and Snader, A. (2007). "Acoustic design for green buildings", Proc. 19th International Congress on Acoustics, Madrid.

Salter, E., Salter, C.M., Davis, C. and Shell, S. (2006). "Achieving acoustical satisfaction in a green building", Journal of the Acoustical Society of America 120(5, Pt. 2) 3185 (abstract).

Siebein, G., Lilkendey, R. and Skorski, S. (2005). "Acoustical studies of three green buildings", Journal of the Acoustical Society of America 117(4) 2378 (abstract).

USGBC (2005a). "LEED for Commercial Interiors", U.S. Green Building Council, Washington, DC; available at http://www.usgbc.org/ShowFile.aspx?DocumentID=684, last accessed 6 November 2008.

USGBC (2005b). "LEED for New Construction and Major Renovations", U.S. Green Building Council, Washington, DC; available at http://www.usgbc.org/ShowFile.aspx?DocumentID=1095, last accessed 6 November 2008.

USGBC (2007). "LEED for Schools for New Construction and Major Renovations", U.S. Green Building Council, Washington, DC; available at http://www.usgbc.org/ShowFile.aspx?DocumentID=2593, last accessed 6 November 2008.