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Executive Summary

As part of a larger project concerning the design and operation of open plan offices, a field study was conducted to determine the effects of open-plan office design on the indoor environment and on occupant satisfaction with that environment. Measurements were made in nine buildings in six cities; six buildings were in Canada, and three in the US; three were federal buildings, two were provincial buildings, and four were private-sector (high-tech) buildings. A total of 779 employees and their workstations were included in the data set. During a workstation visit, research staff conducted detailed measurements of ventilation, temperature, noise, lighting, and descriptive characteristics of the workstation during a 10-minute period. At the same time, the occupant completed a 27-item questionnaire on a handheld computer concerning their satisfaction with the workplace. The satisfaction data are analysed in other project reports, this report is concerned only with relationships between the physical variables.

The physical data from the field study were analysed to check that relationships supported those derived from laboratory and simulation ("non-field") studies in other parts of the project. Where there was a theoretical reason to do so, we also explored the field study data for additional relationships that were not explored in the non-field studies.

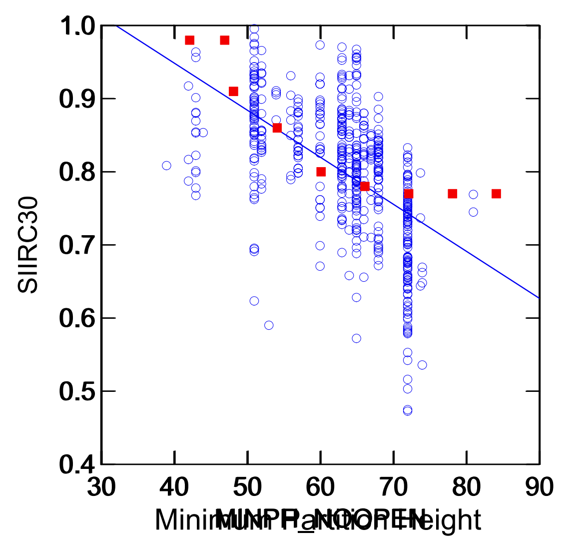

Figure A. A comparison between field measured Speech Intelligibility Index, SII (with assumed constant background noise) and results from an analytical model, for variation with partition height. Individual field measurements are blue open circles, and the best linear fit line to these data is also shown. Analytical model output is shown by red solid squares.

Overall, the field data showed patterns consistent with the findings of the non-field studies. Therefore, we will continue to use these findings in the development of design software and other guidance for designers. Analyses of acoustics and lighting data supported the relationships and expectations from other work (e.g., Figure A). In ventilation, the analyses generally showed only small effects, which were sometimes contradictory and not easy to interpret. However, this was also in line with expectations. Other studies have indicated that office design parameters have little effect on ventilation efficiency and thermal comfort when minimal standards for outside air delivery are met.

The analyses did reveal some interesting, additional relationships. We found that background noise tended to increase with decreasing workstation size (increasing occupant density), and decreasing partition height. We also observed that background noise tended to be higher with higher air velocity and lower carbon-dioxide concentrations, perhaps indicating how the operation of the HVAC system might generate noise. Finally, we were able to confirm that temperatures near to windows are generally a little cooler than temperatures in non-windowed workstations, during the winter and spring months.

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1.0 Introduction

As part of a larger project (COPE) concerning the design and operation of open plan offices, a field study was conducted to determine the effects of open-plan office design on the indoor environment and on occupant satisfaction with that environment.

Measurements were made in nine buildings in six cities; six buildings were in Canada, and three in the US; three were federal buildings, two were provincial buildings, and four were private-sector (high tech) buildings. A total of 779 employees and their workstations were included in the data set. During a workstation visit, research staff conducted detailed measurements of ventilation, temperature, noise, lighting, and descriptive characteristics of the workstation during a 10-minute period. At the same time, the occupant completed a 27-item questionnaire on a handheld computer concerning their satisfaction with the workplace. The satisfaction data are analysed in other project reports; this report is concerned only with relationships between the physical variables. The methodology of these studies and descriptive data from the various study sites has been detailed elsewhere [Veitch et al, 2002a].

In addition, the COPE project has conducted a number of literature reviews, studies in mock-up office laboratories, and simulation studies (collectively referred to in this report as “non-field” studies) exploring the relationships between office design variables (e.g. workstation size, partition height) and indoor environment conditions (e.g. illuminance, ventilation efficiency, speech intelligibility index). In this report we explore similar relationships in the field study data with two goals:

1. To check the findings against those of the “non-field” studies to ensure there were no important conflicts.
2. To explore relationships that were not, or could not, be addressed in the “non-field” studies.

2.0 Method

The methodology of these field studies and descriptive data from the various study sites has been detailed elsewhere [Veitch et al, 2002a], and only the directly relevant information will be summarized here.

2.1 Sites

Data were collected in nine office buildings, located in large Canadian and American cities. The first three buildings were occupied by government organisations in large Canadian cities, and were visited in 2000. The dataset was expanded in 2002, by including data from four private-sector office buildings (one organisation), and two more government office buildings (one organisation). Three of the buildings were in large Canadian cities, and the remaining buildings were located in two US cities. All buildings, and the specific locations within them, were selected because they contained open-plan offices occupied by white-collar workers, and because their management was willing to host the visit. During the 2002 data collection, we also intentionally chose buildings that contained smaller workstations and lower partitions, to increase the presence of these workstation characteristics in the overall dataset. A summary of the building characteristics at each site is shown below, in Table 1.

Table 1. Summary of site characteristics.

Bldg.	Year Built	City	Sector	Visited	# Floors	Floor plate (sq.ft.)	Lighting	HVAC	Windows	Sound Masking
1	1977	Ottawa	public	spring 2000	11 (4 visited)	39,000 (x 2 towers)	4' coffered prismatic fluorescent	ducted air VAV cooling / perimeter hot-water heating	non-openable	no sound masking
2	1975	Toronto	public	summer 2000	12 (3 visited)	40,000	4' recessed parabolic cube	ducted air VAV cooling / perimeter convention heating	non-openable	no sound masking
3	1975	Ottawa	public	spring 2000 & winter 2000	22 (4 visited)	18,000	4' recessed prismatic (some parabolic)	ducted air VAV cooling / perimeter hot and chilled water heating & cooling	non-openable	sound masking in use
4	1976	Ottawa	private	winter 2002	15 (1 visited)	16,000	2' x 4' prismatic	ducted air VAV cooling / perimeter hot-water heating	non-operable	no sound masking
5	1994	San Rafael	private	spring 2002	3 (3 visited)	40,000	2' x 4' recessed parabolic	ducted air VAV cooling / hot-water reheat	non-operable	sound masking in use
6	1984	San Rafael	private	spring 2002	5 (1 visited)	35,000	2' x 4' recessed parabolic	ducted air VAV cooling, perimeter hot-water heating	non-operable	no sound masking
7	1916 (reno-vated 2000)	San Francisco	private	spring 2002	8 (1 visited)	41,000	8' direct/ indirect	ducted air VAV	operable windows	sound masking in specific locations
8	1954	Montreal	public	spring 2002	4 (2 visited)	6,700	50% indirect / 50% 2'x 4' parabolic	ducted air VAV Perimeter heating	non-operable	no sound masking
9	1989/ 90	Quebec City	public	spring 2002	3 (3 visited)	15,300	1' x 4' parabolic	fan-coil with occupant-controlled ceiling vents, perimeter electric heating	non-operable	no sound masking

2.1.1 Building 1 details.

Parts of four floors in the eastern half of this building were visited. Office accommodation at this location was primarily open-plan, with some enclosed offices on the perimeter and at the centre of the floor plan. In the majority of cases, open-plan workstations were formed using free-standing fabric partitions, and free-standing furniture elements. Lighting was provided, almost universally, by surface mounted prismatic luminaires housing a single 4ft fluorescent lamp. These luminaires were located at the centre of 5ft x 5ft ceiling coffer elements. Sound masking was not in use at this location. The HVAC system comprised a ducted-air variable air volume (VAV) cooling system, and a perimeter hot-water heating system, both controlled by zone thermostats. Perimeter zones stretched between structural columns along the perimeter (33ft) to a depth of about 10ft; interior zones were up to 30ft x 30ft in size. The building operators controlled zone thermostats. Thermostats were generally fixed at 22^{o}C, although certain thermostats had been adjusted to accommodate local preferences. The VAV system utilised two compartment fans in each tower of each floor. Each fan served approximately half the floor plate, and was capable of supplying up to 25,500 cfm, with the outside air fraction fixed at 10%. Manual controls ensured that the flow rate to the interior zones never fell below 50% of maximum, and that the flow rate to the perimeter zones never fell below 20% of maximum. These fans were switched off between 6pm – 6am each night; only the fans serving the building lobby and retail floors operated for 24 hours/day.

2.1.2 Building 2 details.

Areas of three floors were visited. Office accommodation at this location was primarily open-plan, with some enclosed offices on the perimeter and at the centre of the floor plan. In the majority of cases, open-plan workstations were formed using systems furniture elements. Lighting was provided, almost universally, by recessed paracube parabolic luminaires housing a single 4ft fluorescent lamp. Orange-painted hollow ceiling beam-like elements formed a 5ft x 5ft ceiling grid, and each of these 5ft x 5ft areas contained one (usually) luminaire at the centre (usually). Sound masking was not in use at this location. The ceiling beams also contained slot air diffusers. The HVAC system comprised a ducted-air VAV cooling system, and a perimeter convection heating system. Zones served by individual VAV boxes were approximately 1500 ft^2, though some smaller perimeter zones had been created where solar gain was problematic. The building operators controlled zone thermostats. The target thermostat setting was 22°C, though many thermostats had been adjusted to accommodate local preferences. The building had two main fresh air fans with in-line heating and cooling coils; there was also a cooling coil in the main return air duct. The VAV system utilised two compartment fans on each floor. Each fan served approximately half the floor plate, with the outside air fraction fixed at 15%. Controls ensured that the flow rate to the interior zones never fell below 10% of maximum. These fans were switched off between 6pm – 2am each night.

2.1.3 Building 3 details.

Sections of four floors were visited, two in spring and two in winter. Office accommodation at this location was primarily open-plan, with some enclosed offices at the centre of the floor plan. In the majority of cases, open-plan workstations were formed using systems furniture elements. Lighting was provided, almost universally, by ceiling-recessed prismatic luminaire housing a single 4' fluorescent lamp, though there were "paracube" parabolic luminaires in a few locations. These luminaires were located in a regular grid on 5ft x 5ft centres. Sound masking was used on all floors at this location. The HVAC system comprised a ducted-air VAV cooling system, and a perimeter hot- and chilled-water system. The perimeter system was locally controlled by occupants. The VAV system was controlled by zone thermostats in the interior; interior zones were up to 15ft x 20ft in size. Zones were originally aligned with office locations, but rearrangement of office furniture over the years means that this is no longer the case. The building operators controlled interior zone thermostats. Thermostats were initially set at 20-22 °C, although certain thermostats had been adjusted to accommodate local preferences. The VAV system utilised a total of seven fans, four dedicated to the interior and three to the perimeter. Perimeter fans served South, North-east and North-west zones. The outside air fraction varied with external climate, but never fell below 15 %. These fans were switched off between 6pm – 6am each night.

2.1.4 Building 4 details.

Measurements were taken in various areas of one floor of this building. The office accommodation was primarily open-plan, with some enclosed. In the majority of cases, open-plan workstations were formed using systems furniture elements. Lighting was provided, almost universally, by ceiling-recessed 2ft x 4ft, prismatic lens luminaires housing a two 4ft fluorescent lamps, these luminaires were located in a regular grid on 6ft x 10ft centres. There were supplemental undershelf task lighting in most workstations. The HVAC system comprised a VAV system, with hot water perimeter heating. The VAV system was controlled by pnuematic control thermostats in each zone; the zone sizes are 1200 ft^2 on the interior, and every 10 linear ft on the perimeter. Building occupants chose the local thermostat settings. Total air flow to the floor was 40,000 cfm; the outside air fraction varied between 20% and 100%. The system fans were switched off between 9pm – 6 am.

2.1.5 Building 5 details.

Data were collected from all three floors of this building. The office accommodation was primarily open-plan, with some enclosed offices on the 1st floor. In the majority of cases, open-plan workstations were formed using systems furniture elements. Lighting was provided, almost universally, by ceiling-recessed 2ft x 4ft, 18-cell, deep-cell parabolic luminaires housing three 4' fluorescent lamps, these luminaires were located in a regular grid on 8ft x 12ft centres. There were some supplemental 2ft x 2ft luminaires in some locations, as well as undershelf task lighting. Sound masking was in use in this building. The HVAC system comprised a VAV system, with hot water reheat. The VAV system was controlled by pnuematic control thermostats in each zone; the zone sizes vary based on design, exposure, and usage. The facilities managers set the thermostats at approximately 72 F (22.2 ^{o}C). The outside air fraction varied with external climate, but never fell below 20%; free cooling was utilized and outside air fraction could rise to 100% to maximize this. The system fans were switched off between 6pm – 4.30 am each workweek night, and was off all weekend. The organisation we visited at this building had a policy allowing occupants to bring pets, principally dogs, to work. This policy was indicated to be a privilege, and there were requirements for behavioural standards to be met. This organisation also supported work-from-home arrangements.

2.1.6 Building 6 details.

One floor was visited in this building. The office accommodation was a mixture of enclosed offices and open-plan, though measurements were conducted in open-plan offices only. In the majority of cases, open-plan workstations were formed using systems furniture elements. Lighting was provided, almost universally, by ceiling-recessed 2ft x 4ft, 18-cell, deep-cell parabolic luminaires housing three 4ft fluorescent lamps, these luminaires were located in a regular grid on 8ft x 12ft or 8ft x 10ft centres. There was some use of supplemental undershelf task lighting. There was no sound masking system in use in this building. The HVAC system comprised a VAV system, with hot water perimeter coils. The VAV system was controlled by pnuematic control thermostats in each zone; there were typically 3-4 offices per zone. The building managers and tenants interact in setting the thermostats at approximately 70-72 F (21.1-22.2 ^{o}C) in summer and 74F (23.3 ^{o}C) in winter. Air flow rates were around 1.5-2 cfm/ft^2. The outside air fraction was 15-20%. The system fans were switched off between 6pm – 6 am (except Monday when they were started earlier at 4.30 am). The organisation visited at this building also had pets-at-work and work-from-home policies.

2.1.7 Building 7 details.

Measurements were taken on one floor of this building. The office accommodation was entirely open-plan, with a few enclosed conference rooms. Open-plan workstations were formed using systems furniture elements. Lighting was provided, almost universally, by 8ft direct/indirect luminaires housing a single fluorescent lamp, these luminaires were suspended 18 inch. from the ceiling in regular rows. The HVAC system comprised a VAV system only. The VAV system was controlled by zone thermostats in each zone; zones varied in size. The tenants set the thermostats locally at typically 71-73 F (21.7-22.8 ^{o}C). Outside air supply was 20 cfm/person, based on 133 ft^2/person. The outside air fraction was at least 20% of total air flow. The system fans were switched off between 6pm – 7 am each weekday night. Windows at the building perimeter were openable. The organisation visited at this building also supported work-from-home arrangements.

2.1.8 Building 8 details

Two floors were visited in this building. The office accommodation was mostly open-plan, formed using systems furniture elements. Fifty percent of the lighting in the areas visited was provided by indirect lighting luminaires (2 lamps per 4ft length), suspended 16 inch. From the ceiling. The remaining lighting was provided by 2ft x 4ft parabolic "paracube" luminaires housing 2 lamps. These luminaires were located in a regular grid on 8ft x 6ft centres. Workstations also had adjustable "angle-arm" task lights. Sound masking was not in use in this building. The HVAC system comprised a VAV system, capable of supplying 18,265 l/s airflow, and was supplemented with perimeter heating. The VAV system was controlled by direct digital control for each 100 m^2 zone. The fraction of outside air varied with external climate, but was never allowed to fall below 17%. Outside airflow was typically around 0.9-1.2 cfm/ft^2. Thermostats were located at the centre of groups of four workstations, and were usually adjusted by occupants. The system was switched off between 6pm and 2.30am each workweek night, and were off all weekend.

2.1.9 Building 9 details

All three floors of this building were visited. The office accommodation was mainly open-plan, formed using systems furniture elements. Lighting was provided by 1ft x 4ft deep-cell parabolic luminaires, housing 2 lamps, with one luminaire assigned for every 50 ft^2 of floor area. Sound masking was not in use in this building. The HVAC system used fan coil units to provide local cooling needs. Constant airflow volume was provided meeting a minimum outdoor air supply rate of 10 ls^{-1}/person. Occupants had control of a ceiling diffuser dedicated to their workstation, and could change the direction of airflow, or close the diffuser entirely. Thermostats, to which occupants had access, controlled zones of 400-500 ft^2. Perimeter heating was provided by electric baseboard heaters. The HVAC system was turned off at night and on weekends.

2.2 Participants

Participants were the occupants of floors visited by the research team. All occupants present on the visit days were eligible to participate, and approximately 90% of those invited agreed to take part. Table 2 shows the number of occupants who participated at each site.

Table 2. Number of workstations visited at each site.

Site	N
Full sample	779
Building 1	132
Building 2	160
Building 3	127
Building 4	52
Building 5	85
Building 6	48
Building 7	72
Building 8	47
Building 9	56

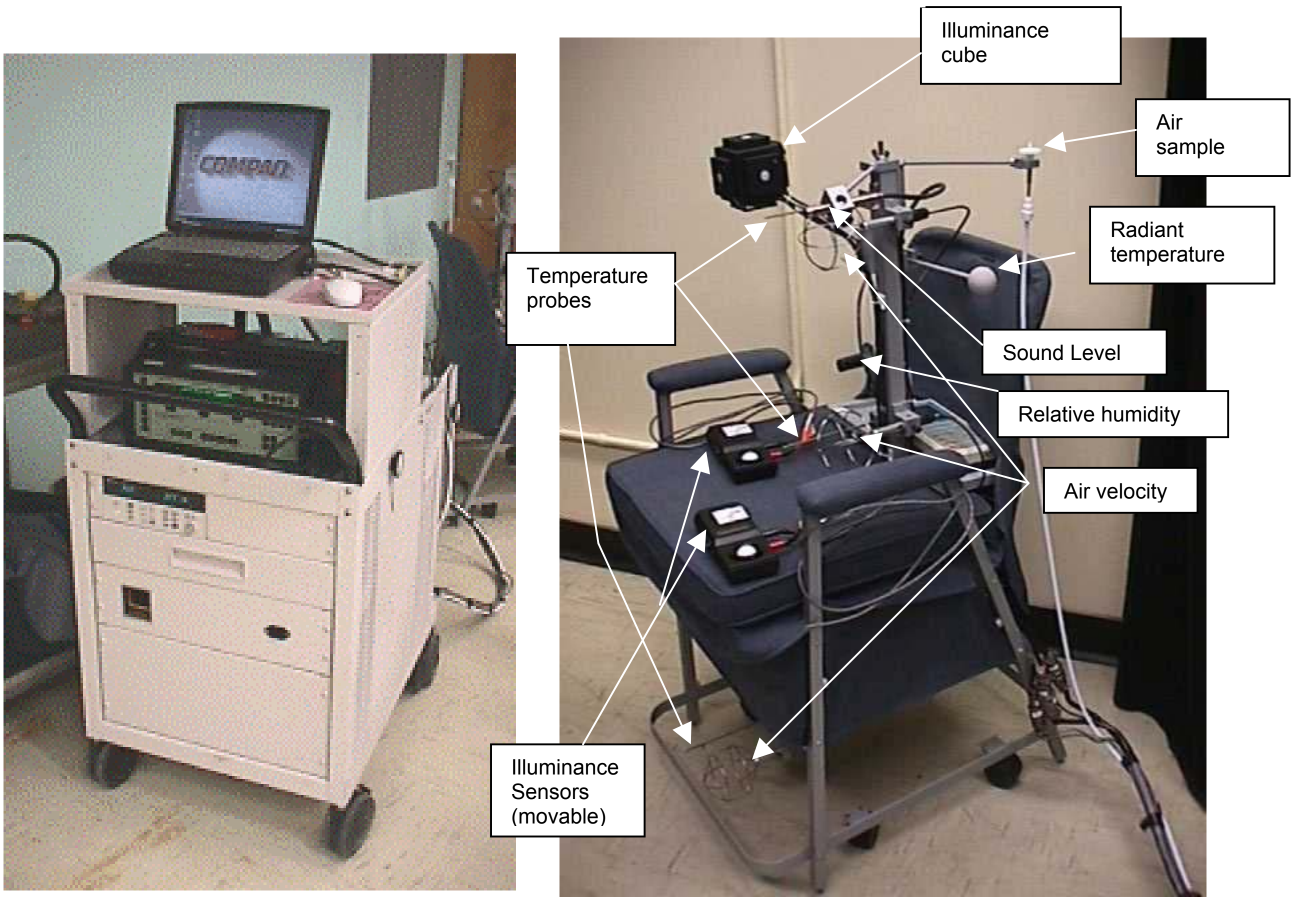
2.2 Physical Dependent Measures

Physical measurements were made using two systems. A cart+chair system was used to make measurements of a representative set of variables at each workstation during daytime and at night. Additional equipment was used to make more detailed acoustics measurements at night. These systems are described below.

2.2.1 Cart+chair System

We developed a custom, mobile system to measure the microclimate at the position occupied by an employee in an open-plan office workstation. This system consists of two main components, the cart and the chair, both wheeled for mobility. The chair served as a platform for the indoor environment sensors. In taking measurements, we temporarily replaced the occupant's own chair with ours; fabricating our sensor platform in the shape of a chair meant that it had a similar effect on the microclimate as the occupant's own chair, adding to the validity of the measurements.

Figure 1. The cart and chair used for physical measurements.



The various sensors mounted on the chair are described in Table 3, and the appearance of the chair is shown in Figure 1. The sensors were chosen to give as broad a characterisation of the indoor environment as possible within a reasonable time (< 15 mins.) and with reasonable mobility (cart+chair system to be moved by two staff through narrow openings typical of open-plan layouts). The selection and location of sensors related to thermal comfort (air temperature, radiant temperature, humidity, and air velocity) were designed to be as similar as possible to those followed in ASHRAE studies [Benton et al., 1990]. Illuminance measurements were taken in defined locations in the workstation (Figure 2), corresponding to locations defined in lighting recommended practice documents (Canada Labour Code, 2002; Illuminating Engineering Society of North America [IESNA], 1993).

The chair was connected to the cart by an “umbilical cord” of sensor lines, power cords, and communications cables. The cart (Figure 1) held a laptop computer, battery and power supply, data acquisitions equipment, and instrumentation for the air quality analysis. A custom data acquisition program on the laptop communicated with all instrumentation on the chair and cart, co-ordinated measurement cycles, and stored the resulting data. The cart also housed a camera, tape measures, open-ended questionnaire envelopes, and other miscellaneous equipment. The cart was plugged in a wall socket (building’s regular 120V-AC power) overnight to charge the batteries. On a full charge it could operate independently for a full day of measurements.

Table 3. Description of the various sensors used on the chair.

Measures	**Sensor**	**Manufacturer**	**Location**	**Range**	**Accuracy**
Illuminance (light falling on a surface)	Silicone photocell	Minolta T1	Desktop (various)	0.01 to 99,900 lx	± 5%
Illuminance	Silicone photocell	Minolta T1	6 faces of cube at seated head height	0.01 to 99,900 lx	± 5%
Air velocity	Hot wire	TSI- 8475	0.1m, 0.7m, 1.1m	0 to 1m/s	± 3%
Octave band analyzer	Microphone	Rion NA-29	Seated head height	27 to 130 dB(a) 31.5Hz to 8kHz	± 0.1 dB
CO, CO_2, THC, CH_4	Photo-acoustic IR	B&K 1302	Seated head height		± 0.3 ppm (TVOC)
Temperature	RTD	Omega	0.1m, 0.7m, 1.1m	Room temp	< 0.1 deg C.
Relative Humidity	Resistance change of bulk polymer	General Eastern RH2	Seated torso height	20 to 95% 0 to 20%	± 2% ± 7%

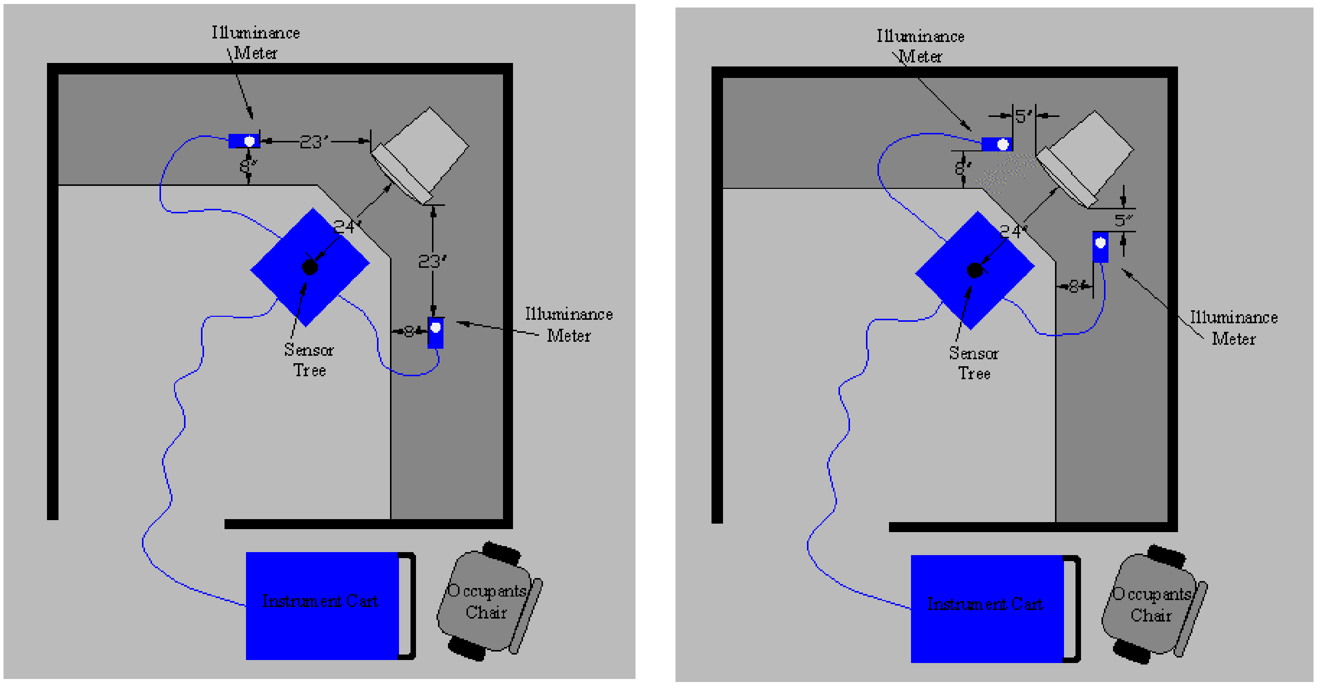


Figure 2. Placement of sensor chair and desktop illuminance sensors for daytime measurements.

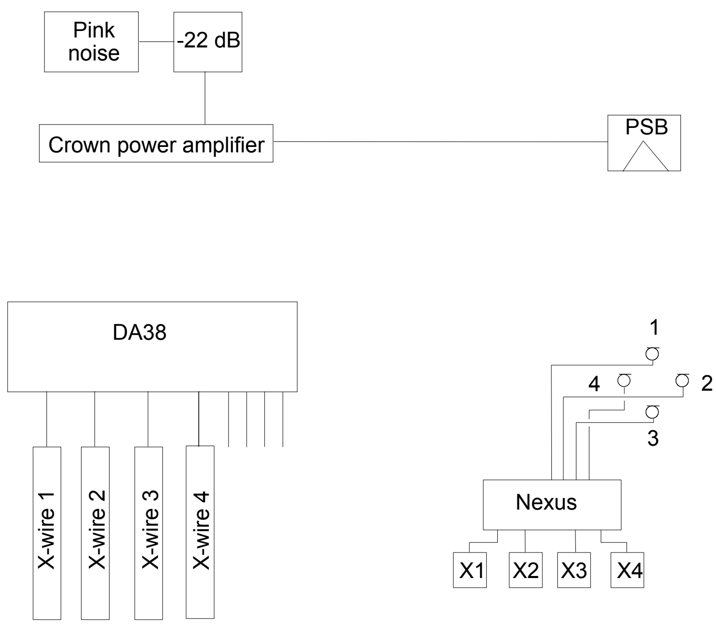
Chair-based octave band noise level measurements were supplemented by $^1/_3$ octave band measurements at a sample of locations.

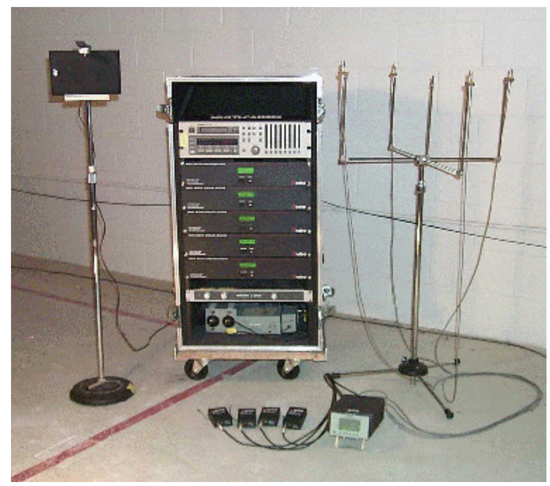
2.2.2. Additional Acoustics Measurements at Night

Measurements of sound propagation between adjacent workstations were performed at night. The source was a small Alpha Mite PSB loudspeaker with directionality similar to that of a human. The receivers consisted of an array of four microphones located at the corners of a square, 46cm on each side.

Measurements were made by radiating a known level of pink noise (equal sound energy in each octave) from the source and measuring the levels at the four microphones in the adjacent workstation. The sound power output of the source was separately measured in a laboratory sound power measurement. This measured sound power output was then used to calculate a reference output level of the source for a distance of 0.9m in a free field (a location with no reflected sound). The microphone signals were transmitted to receivers connected to 4 channels of an 8-channel digital tape recorder, as illustrated in the block diagram of Figure 3(a), and the photo in Figure 3(b). Calibration signals were also recorded on each channel at the beginning and end of each measurement session. The tape recordings were played back under computer control into a B&K 2144 real-time analyzer. The reduction of intruding speech sounds was estimated by subtracting these recorded levels from the known level of the source.

Figure 3. Schematic diagram and photo of equipment for night-time acoustic measurements. (a) Block diagram of equipment used for the night-time sound propagation measurements. The upper half of the figure shows the PSB loudspeaker powered by a Crown power amplifier and the pink noise source. The lower half of the figure shows the 4-microphone array, the Nexus microphone power supply, the X-wire transmitters and receivers and the DA38 digital tape recorder. (b) Photo of equipment.





2.3 Data Collection Procedure

Announcements about the study were sent in advance of the NRC team's visit, and where possible were coordinated with representatives of both management and employees (e.g., through safety and health committees). During the measurement visits, NRC staff spent full days making individual visits to workstations in the selected areas of the target building. They attempted to visit every occupied workstation in the identified area, returning later if the employee was occupied or momentarily absent.

When the NRC team arrived at an occupied workstation, the members identified themselves and invited the employee to participate. If the employee agreed to participate, he or she was asked to step outside of the workstation in the company of the one of the NRC staff. The NRC staff member took the participant to a nearby location, typically a vacant workstation similar to his or her own, and gave instructions about the questionnaire (because this report is not concerned with questionnaire data, further details on the questionnaire are not provided here). The NRC staff member then left the participant to answer the questionnaire in private, and returned to help the other member of the NRC team with the physical measurements in the workstation. The participant was instructed to return to his or her workstation for assistance from the NRC staff if it were needed.

The measurements in the workstation began with two photographs. The first was a close-up of the computer screen with the screen turned off, principally to identify potential sources of reflected glare. The second photograph was an overall workstation picture, taken from the entrance to the workstation. Both photographs were taken with a Kodak™ DC 260 digital camera with a wide-angle lens. A small blackboard featuring an ID code for the workstation was included in the photographs, and the same code was recorded on the building plans. In addition, the photographs were automatically time-stamped, and the time of the visit was recorded on the building plans. These measures helped ensure that all data associated with a particular workstation could be collated later.

Once the instruments were in place, software on the laptop on the cart automatically co-ordinated measurements from the various sensors. Initially, the operator entered the workstation ID code, and initials identifying him- or herself. The process began with the B&K 1302 taking an air sample for analysis; this process took about 2.5 minutes. While this was happening, NRC staff took measurements of workstation size, partition height and ceiling height, and noted them down for later data entry.

Next the noise level measurements were made; this process took about 1.5 minutes, during this time the NRC team took no actions that might disturb the measurement. The goal was to get a 20-second measurement without intelligible speech sounds (a person talking on the telephone in the next cubicle, for example), as a measure of prevailing background noise. Measurements were repeated 3 times, or until a measurement without speech was captured, whichever occurred sooner. Other noises occurring during the measurement, such as ventilation noise or noise from outside the building, were noted.

Next, temperature, air speed, humidity and illuminance measurements were taken. Measurements of all these parameters were taken every 10 seconds, and six measurement cycles were completed in a one-minute period. The last of the six measurements for each variable were shown on the screen, whereas all six measurements, and the mean of all six for each variable, were written to file. On completion, the desktop illuminance sensors were moved to a second location, and the measurements for those sensors were repeated.

Finally, NRC staff entered additional information describing the workstation. These data included relative location of entrance and computer screen, workstation size, partition height and finish, ceiling height, floor finish, lighting type and location, diffuser type and location, whether the VDT had an anti-glare screen, and whether the occupant was wearing headphones when first approached. After completing this screen the operator was prompted to enter any additional comments.

At each stage in this process the operator could visually check the data and redo measurements if necessary. All data were recorded to a time-stamped text file on the laptop computer. Typically the physical measurements were completed before the questionnaire, in which case NRC staff simply waited for the participant to return to the workstation with the palmtop computer.

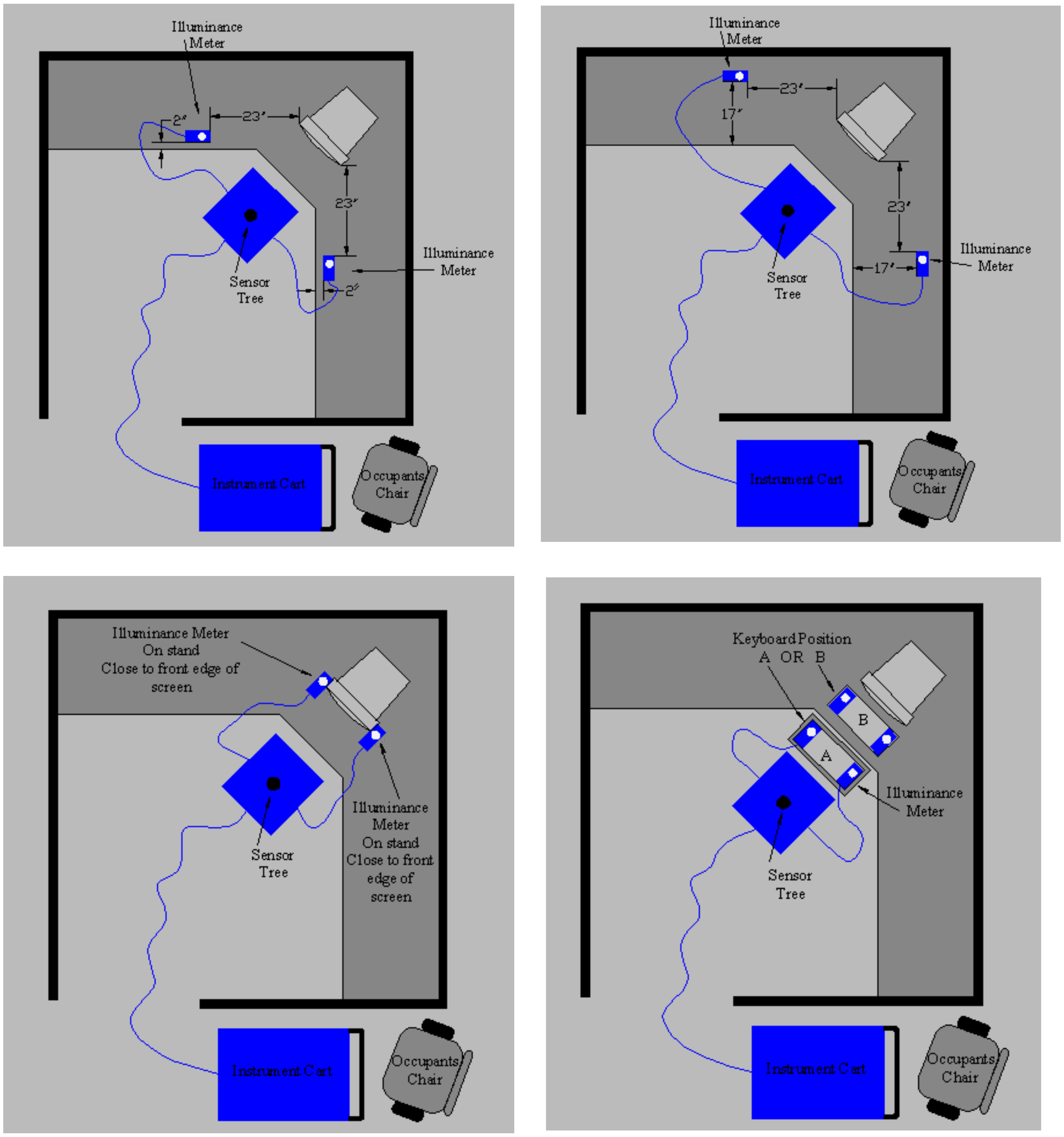


Figure 4. Illuminance sensor locations for additional night-time measurements (electric lighting only).

The NRC team then moved on to invite the next available person to participate. There was no set plan as to which employees were approached when, and some work areas were revisited several times to recruit employees who had been unavailable on previous visits to the work area.

2.3.1. Measurements at Night

NRC staff returned after normal working hours (typically 7 – 10 pm) to perform additional measurements with the cart+chair system. These measurements provided baseline data without occupants, and data on the light level provided by the electric lighting system independent of any daylight contribution. Measurements were made in a subset (around $^1/_3$) of the workstations that were visited during the day.

Measurements at night with the cart+chair system followed essentially the same protocol as the daytime measurements, with the following exceptions:

- Photographs were not taken, as they would have added little more information to the daytime photographs.
- Additional desktop lighting measurements were made (Figure 4).
- Workstation information was not entered as it would have only duplicated the daytime data.

At night we also took the opportunity to take additional photographs not related to a particular workstation (e.g., overall views, luminaires, diffuser types).

At the end of every evening of measurements all data collected with the cart+chair system that day, including questionnaire responses and photographs, were backed up to disk and CD-ROM.

Two additional NRC staff conducted the night-time sound propagation measurements. Night-time sound propagation measurements were made in every workstation where daytime measurements had been made (although not necessarily on the same day). The participant's workstation acted as the receiver workstation, and the source workstation was selected as the adjacent workstation from which speech sounds could most readily propagate.

The sound source was located at the centre of the source workstation and was pointed towards the receiver workstation. The centre of the square receiver array was located at the centre of the receiver workstation. Locating the source and receivers at the centres of each workstation approximated the average of the many possible occupant positions.

These sound propagation measurements were combined with the daytime ambient noise levels measured using the cart+chair system to assess the expected speech privacy between adjacent workstations. A number of other acoustical measures were also derived from these two sets of measurements.

2.4 Data Analysis Procedure

We conducted a series of regressions to test the relationships between important dependent variables and the independent variables expected to predict them. Our primary goal was to test complete models involving multiple predictors, because these account for the interactions of predictor variables. Nevertheless, we did look at single predictor models when comparing to results from the non-field studies, which were able to control conditions such that only a single predictor was varied independently. For example, we predicted the effect of workstation size, partition height and enclosure, and daylight, on illuminance in one 4-predictor model. We also looked at the effect of partition height on illuminance separately to compare the result to simulation studies that had varied only this one independent variable.

Table 4 describes the dependent and independent variables that were addressed in these analyses.

Table 4. Description of the dependent and independent variables addressed in these analyses.

Variable Name	Unit (*or range*)	Description
Dependent Variables		
LNOISEA	dB(A)	A-weighted background noise level at approximately the position of a seated occupant's head, measured during the day.
SII	*0 – 1*	Speech Intelligibility Index, calculated from an assumed standard speech level, the sound propagation between workstations measured at night, and LNOISEA
SIIRC30	*0 – 1*	Speech Intelligibility Index, calculated from an assumed standard speech level, sound propagation between workstations measured at night, and an assumed standard (low level) background noise (RC30)
ACO_HI	dB(A)	A-weighted sound level for 1000-8000 Hz background noise.
ACO_LO	dB(A)	A-weighted sound level for 16-500 Hz background noise.
LOHI_DBA	dB(A)	ACO_LO – ACO_HI
E_CUBE	lux	The mean illuminance on the six sides of a cube at approximately the position of a seated occupant's head, measured during the day.
E_DESK	lux	The mean illuminance on at the four points on the desktop, measured during the day.
E_DESKUNI	*0 – 1*	(Maximum of four desktop illuminance points – Minimum of same four points) / Maximum
RTD_H	^oC	Air temperature measured during the day 1.1 m from the ground, at the approximate location of a seated occupant.
AIR_V_H	ms^{-1}	Air velocity measured during the day 1.1 m from the ground, at the approximate location of a seated occupant.
REL_HUMID	%	Relative humidity measured during the day at the approximate location of a seated occupant.
FDCO2	ppm	Carbon-dioxide concentration at approximately the position of a seated occupant's head, measured during the day.
Independent Variables		
SQRTAREA	ft	The square root of the workstation area. The square root is used rather than the area itself because it is better distributed, and better facilitates comparison to non-field studies.
MINPH_NOOPEN	inch.	The minimum (non-zero) partition height of all partitions making up the cubicle, but excluding any fully open sides.
TIME_CHECK	*0 – 1*	Fraction of how much of the day had passed when the daytime measurements were made. E.g. 9am = 0.38 (9/24); 4pm = 0.67 (16/24).
PANELS_CAT	*0, 1*	A measure of enclosure. =1 if the only zero height gap in the partitions was the entrance to the cubicle; =0 if the gap was more extensive.
WINDOW	*0, 1*	=1 if the cubicle contained an external window; =0 if it did not.
DAYLIGHT	*0, 1, 2*	=2 if the cubicle contained an external window; =1 if it did not have a window but was within 15ft of a window; =0 if the cubicle was more than 15ft from a window. (treated as a numerical variable in regressions)
DFLOCATE	*1, 2*	=2 if nearest air diffuser was outside the cubicle; =1 if it was inside the cubicle
MONTH	*1, 2, …, 6*	Surrogate for external climate =month number for the date on which the daytime measurements were made. Minimum value =1 (January), maximum =6 (June). Note, measurements made in December were given a month value of 1 to preserve the simple 'higher month, warmer climate' trend (No measurements were made in July – November.

Univariate outliers for each variable were identified by examining frequency distributions of standardised scores. Scores greater than 3 standard deviations from the mean were excluded from the analysis. Multivariate outliers were detected by examining the values of the Mahalanobis distance statistic. Cases for which the Mahalanobis distance statistic was greater than the critical value at $p<.001$ (translated into a critical leverage value, which is the statistic reported by the statistical analysis package used, SYSTAT) were excluded from the analysis. Correlation matrices were examined to check for multicollinearity and singularity. Circumstances in which items are highly correlated ($r>.80$) indicate potential multicollinearity problems, because understanding their separate relations to other variables becomes difficult. Items that are only weakly correlated with other variables ($r<.30$) suggests that the variable is singular, and does not have meaningful relations to other items.

3.0 Results

The results are divided into sections by aspects of the indoor environment: acoustics, followed by lighting, followed by ventilation-related measures. Table 5 shows the descriptive statistics for all of the dependent and independent variables in the analyses.

Table 5. Descriptive statistics for variables in these analyses. Values shown for numerical variables are after the univariate outliers have been removed. s.d. = standard deviation.

Variable Name	Unit (*or range*)	N	Min.	Max.	Medn.	Mean	s.d.	
Dependent Variables								
LNOISEA	dB(A)	729	36.2	56.8	46.6	46.3	3.6	
SII	*0 – 1*	729	0.08	0.91	0.51	0.51	0.15	
SIIRC30	*0 – 1*	728	0.47	1.00	0.83	0.84	0.11	
ACO_HI	dB(A)	774	29.4	55.1	42.7	42.1	4.7	
ACO_LO	dB(A)	776	35.0	55.0	44.2	44.2	3.4	
LOHI_DBA	dB(A)	768	-7.3	11.6	1.9	2.0	3.0	
E_CUBE	lux	770	9	911	202	243	151	
E_DESK	lux	770	4	1654	400	447	239	
E_DESKUNI	*0 – 1*	779	0.01	1.00	0.41	0.43	0.20	
RTD_H	^{o}C	770	20.5	26.1	23.3	23.2	0.9	
AIR_V_H	ms^{-1}	766	0.01	0.25	0.08	0.09	0.04	
REL_HUMID	%	779	13	59	29	30	11	
FDCO2	ppm	767	470	935	638	643	87	
Independent Variables								
SQRTAREA	ft	778	3.5	14.5	8.7	8.9	2.0	
MINPH_NOOPEN	inch.	776	36	81	64	61	9.5	
TIME_CHECK	*0 – 1*	775	0.34	0.70				
		Categories						
		0	*1*	*2*	*3*	*4*	*5*	*6*
PANELS_CAT	*0, 1*	203	576					
WINDOW	*0, 1*	461	318					
DAYLIGHT	*0, 1, 2*	330	131	318				
DFLOCATE	*1, 2*		590	187				
MONTH	*1, 2, …, 6*		66	0	51	336	223	100

3.1 Acoustics

The results of the regressions on Acoustics-related dependent variables (DVs) are summarized in Table 6. For each DV, the initial highlighted section shows the final multiple-predictor model, including the constant, the coefficients (or slopes) associated with predictors (or independent variables, IVs) that are significant in the model, the overall percentage of variance in the DV explained by the model (R_{adj}^2), and the F-statistic and degrees-of-freedom for the test (F(df)). Following that are relevant single-predictor models. Finally, shaded, are models of relationships between acoustic variables and ventilation variables, which we looked at to explore the role of the ventilation system as a substantial source of noise.

Also shown, for each significant IV, is the maximum change in the DV that could be caused by a realistic change in the IV. This is calculated by simply multiplying the coefficient for that IV by the largest realistic change that might be effected in that IV by a designer. We provide this number as a guide to relative magnitude of each effect. The largest changes assumed for this calculation were: SQRTAREA= 5 (equivalent to a change from an 11 ft x 11 ft area cubicle to a 6 ft x 6 ft); MINPH_NOOPEN= 30 (equivalent to a change from a 72 inch high partition to a 42 inch high partition); PANELS_CAT= 1 (equivalent to a change from a cubicle with only one zero-height gap in the partitions, the entrance, to a cubicle with more than one zero-height gap); FDCO2= 400 (equivalent to a change in carbon-dioxide concentration from 900 ppm to 500 ppm); and, AIR_V_H= 0.20 (equivalent to a change in air velocity from 0.05 ms^{-1} to 0.25 ms^{-1}).

Table 6. Summary of results related to Acoustics dependent variables. "n.s." indicates the variable was not significant.

DV	Const.	IV	Coeff.	R^2_{adj}	F (df)	Mx. Effect.
SIIRC30	1.3169	SQRTAREA	n.s.	0.4895	231.5 (3, 718)	
		MINPH_NOOPEN	-0.0048			-0.14
		PANELS_CAT	-0.0955			-0.10
	1.0725	SQRTAREA	-0.0265	0.2557	250.4 (1, 725)	-0.13
	1.2059	MINPH_NOOPEN(11)	-0.0064	0.3061	239.2 (1, 539)	-0.19
		FDCO2(sealed)	n.s.			
	0.7912	AIR_V_H	0.3361	0.0165	11.9 (1, 651)	0.07
LNOISEA	55.4325	SQRTAREA	-0.3650	0.1577	46.0 (3, 719)	-1.8
		MINPH_NOOPEN	-0.0861			-2.6
		PANELS_CAT	n.s.			
	52.1056	SQRTAREA	-0.6446	0.1284	108.1 (1, 726)	-3.2
	53.0600	MINPH_NOOPEN(11)	-0.1136	0.0607	36.1 (1, 542)	-3.4
	51.3401	FDCO2(sealed)	-0.0083	0.0397	28.1 (1, 655)	-3.3
	45.2432	AIR_V_H(sealed)	8.1434	0.0072	5.7 (1, 654)	1.6
SII	0.7083	SQRTAREA	0.0121	0.0936	25.9 (3, 719)	0.06
		MINPH_NOOPEN	-0.0018			-0.05
		PANELS_CAT	-0.1126			-0.11
		SQRTAREA	n.s.			
		MINPH_NOOPEN(11)	n.s.			
	0.2758	FDCO2(sealed)	0.0004	0.0399	28.2 (1, 652)	0.16
		AIR_V_H(sealed)	n.s.			
ACO_HI	54.4494	SQRTAREA	-0.5566	0.1884	59.6 (3, 755)	-2.8
		MINPH_NOOPEN	-0.0975			-2.9
		PANELS_CAT	-0.8460			-0.8
	50.3649	SQRTAREA	-0.9297	0.1605	146.9 (1, 762)	-4.6
	53.4864	MINPH_NOOPEN(11)	-0.1931	0.1026	65.0 (1, 559)	-5.8
	46.8205	FDCO2(sealed)	-0.0080	0.0205	15.2 (1, 680)	-3.2
	40.5777	AIR_V_H	12.2122	0.0095	7.6 (1, 681)	2.4
ACO_LO	52.3086	SQRTAREA	-0.2878	0.1459	44.3 (3, 757)	-1.4
		MINPH_NOOPEN	-0.0914			-2.7
		PANELS_CAT	n.s.			
	49.0947	SQRTAREA	-0.5575	0.1098	95.3 (1, 764)	-2.8
	49.2810	MINPH_NOOPEN(11)	-0.0874	0.0433	26.4 (1, 560)	-2.6
	50.0263	FDCO2(sealed)	-0.0097	0.0631	46.9 (1, 680)	-3.9
		AIR_V_H(sealed)	n.s.			
LOHI_DBA	-1.8173	SQRTAREA	0.2630	0.0678	19.4 (3, 758)	1.32
		MINPH_NOOPEN	n.s.			
		PANELS_CAT	0.9076			0.91
	-1.1692	SQRTAREA	0.3541	0.0566	47.0 (1, 765)	1.77
	-3.1301	MINPH_NOOPEN(11)	0.0877	0.0513	31.3 (1, 560)	2.63
		FDCO2(sealed)	n.s.			
		AIR_V_H(sealed)	n.s.			

SIIRC30 is the DV closest to a controlled laboratory measurement; it is derived from a sound propagation measurement made at night, and a standard background noise assumption (rather than that measured during the day). The simple 3-predictor (SQRTAREA, MINPH_NOOPEN, PANELS_CAT) model explains fully 49% of the variance in SIIRC30. The amount of variance explained is not higher because we did not include other predictors in the model that we know to be important but which were not recorded in the field, such as: the sound absorption properties of the partitions and other cubicle surfaces, the properties of the ceiling, and the location of reflecting surfaces external to the workstation. All of the regressions discussed in this report suffer to an even larger degree from this inevitable lack of inclusion of predictor variables. SQRTAREA is not significant in the overall model, which is surprising given our non-field study results. However, the field study regressions are complicated by a high negative correlation between SQRTAREA and MINPH_NOOPEN (r= -0.61) – smaller workstations also tend to have lower partitions, and so associations between a DV and SQRTAREA may be "taken up" by MINPH_NOOPEN, and vice versa. As discussed below, the single-predictor model of SIIRC30 vs. SQRTAREA is significant, and with a relatively large effect. MINPH_NOOPEN and PANELS_CAT are significant with negative coefficients, this is as expected: taller partitions with more enclosure have lower values of speech intelligibility.

The single-predictor model of SIIRC30 vs. SQRTAREA is significant, and the percentage of variance explained is relatively large, at 26%. (Remember, in this single-predictor model, any variance due to differing partition heights at any given workstation size is now 'unexplained'). The effect of workstation size on sound propagation was measured under controlled conditions in a study in a mock-up office laboratory [Bradley & Wang, 2001]. These data were then used in the development of an analytical model to predict SII in open-plan workstations [Wang & Bradley, 2001a; Wang & Bradley, 2001b]. We compared the relationship between SIIRC30 and SQRTAREA from the field study with the predictions from the analytical model. For the model we made the following assumptions: cubicles have a square footprint; partition height is equal on all sides at the sample median of 64 inches; the only zero-height opening in the partitions is a single entrance; ceiling height is the sample median of 106 inches; floor type is the sample mode of carpet (SAA= 0.19); ceiling tile is typical of casual field study observations (SAA= 0.55) partitions are typical of casual field observations (SAA= 0.60, STC= 21); and, the background noise level is RC30. The result is shown in Figure 5. The best-fit linear regression line from the field data predicts SIIRC30~ 1 as SQRTAREA tends to 0, which is appropriate. The variation in SIIRC30 with SQRTAREA appears larger (slope steeper) for the field data regression line. However, remember that in the field smaller workstations also tended to have lower partitions. In the output from the analytical model shown in Figure 5 we have assumed the same partition height at all workstation sizes. If we assumed a 54 inch partition at a workstation size of 6 ft x 6 ft, the analytical model predicts SIIRC30= 0.89, much closer to the value predicted by the field data regression line.

For the single-predictor model of SIIRC30 vs. partition height, we chose only those workstations with "full" enclosure (PANELS_CAT= 1); this is indicated by the addition of "(11)" to the MINPH_NOOPEN variable name. We did this to facilitate comparison to the non-field study results, which modelled a fully enclosed condition. This regression is significant, and the percentage of variance explained is relatively large, at 31%. We compared the relationship between SIIRC30 and MINPH_NOOPEN(11) from the field study with the predictions from the analytical model. The assumption for the model calculations are the same as those above, except that we varied partition height, and fixed workstation size at the sample median of 8.7 ft x 8.7 ft. The result is shown in Figure 6. Note, the analytical model predicts no effect of partition height on SIIRC30 until the partition is at least as high as the speech source, the mouth of a seated occupant, at 48 inches. At this height the field data and analytical output are almost identical. They continue to be very close over most of the observed range of partition heights, and begin to diverge only at heights exceeding 70 inches, with the trend from the analytical model becoming non-linear. Again, this can be partly explained by the correlation in the field data between workstation size and partition height. If the analytical model is run with larger workstations at higher partitions, the predictions would more closely match the regression line from the field data. For example, for a partition height of 84 inches and a workstation size of 12 ft x 12 ft, the analytical model predicts SIIRC30= 0.72.

SIIRC30 was calculated using a fixed background noise level. However, the field study data suggest that background noise level (LNOISEA) varies with changes in workstation design parameters. The 3-predictor model explains 16% of the variance. Both SQRTAREA and MINPH_NOOPEN are significant with negative coefficients, indicating that background noise tends to increase if workstations are made smaller and partitions are lowered. This is easily explained, given that a substantial fraction of background noise is due to office equipment, non-speech sounds made by occupants, and distant (unintelligible) speech. Smaller workstations would increase the density and proximity of such sources, lower partitions would facilitate their propagation. This effect is not currently accounted for in our analytical models, but is worth considering at design time. The single-predictor models add nothing further to the interpretation of effects on LNOISEA. Note that the maximum magnitude of the effects on LNOISEA are in the range of perceivable differences (3dB(A)).

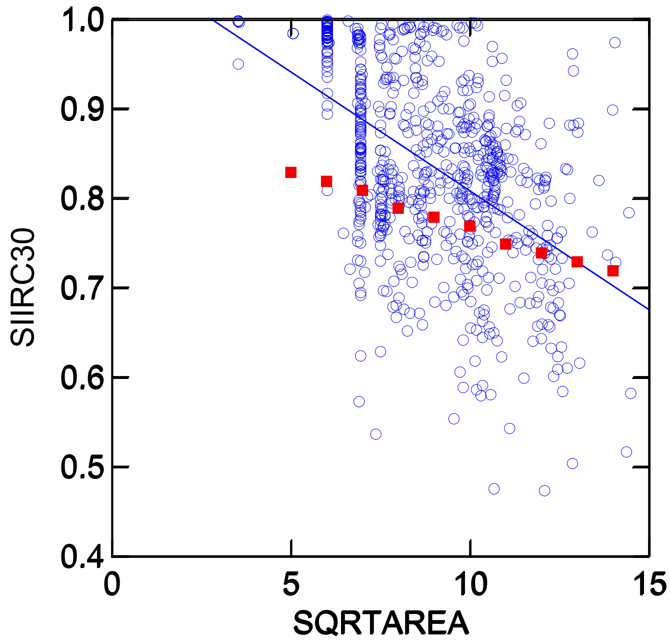


Figure 5. A comparison between field measured SII (with assumed constant background noise) and results from an analytical model, for variation with workstation size. Individual field measurements are blue open circles, and the best linear fit line to these data is also shown. Analytical model output is shown by red solid squares.

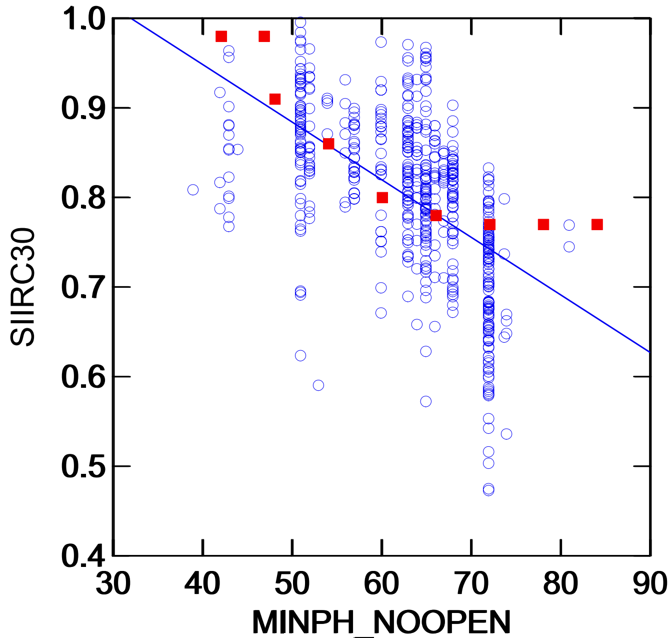


Figure 6. A comparison between field measured SII (with assumed constant background noise) and results from an analytical model, for variation with partition height. Individual field measurements are blue open circles, and the best linear fit line to these data is also shown. Analytical model output is shown by red solid squares.

SII is similar to SIIRC30, except that it is calculated using the background noise level measured during the day (LNOISEA). The 3-predictor model explains 9% of the variance. MINPH_NOOPEN and PANELS_CAT are significant with negative coefficients, this is as expected: taller partitions with more enclosure have lower values of speech intelligibility. However, SQRTAREA has a positive coefficient, though the expectation is that large workstations would have lower speech intelligibility. But remember that SII is a function of sound propagation and the reciprocal of background noise. Larger workstations have lower sound propagation (see SIIRC30 results), but also lower levels of background noise (see LNOISEA results). These two effects will tend to counteract each other, and may explain the unexpected positive coefficient for SQRTAREA. A similar phenomenon will occur for partition height, it may not be enough to reverse the sign of the coefficient, but the magnitude of the effect of MINPH_NOOPEN is clearly smaller than for the SIIRC30 relationship. This probably also explains the lack of the significance in the single-predictor models.

We suggested above that a substantial fraction of background noise was due to office equipment, non-speech sounds made by occupants, and distant (unintelligible) speech. We can partially test this assumption by considering the high and low frequency components of the background noise. The effects of workstation design choices would be expected to be more effective at reducing high frequency sound. This is supported in the regression results. The 3-predictor models for ACO_HI and ACO_LO are both significant, explaining 19% and 15% of the variance respectively. Both SQRTAREA and MINPH_NOOPEN are significant with negative coefficients, indicating that background noise tends to increase if workstations are made smaller and partitions are lowered (as expected). PANELS_CAT is also significant for ACO_HI, and the coefficient for SQRTAREA is approximately twice as large in the ACO_HI model compared to the ACO_LO model. Also, in the single-predictor model with MINPH_NOOPEN, the coefficient is more than twice as large in the ACO_HI model compared to the ACO_LO model.

In a laboratory human factors experiment [Veitch et al, 2002b], we found that the difference between the high and low frequency components of background noise (LOHI_DBA) was predictive of acoustic satisfaction, with higher values of LOHI_DBA tending to yield higher satisfaction. Therefore, we were interested in how it might be affected by office design choices. The 3-predictor model explains 7% of the variance. Both SQRTAREA and PANEL_CAT are significant with positive coefficients, indicating that the low-frequency component tends to increase relative to the high-frequency component if workstations are made larger and more enclosed. This is consistent with the findings above. MINPH_NOOPEN is significant in its single-predictor model, and with a positive coefficient, as expected.

We also explored the possibility of a relationship between ventilation-related and acoustic-related parameters, based on the assumption that the ventilation system is a major contributor to background noise. We also made the reasonable assumption that a “harder working” ventilation system, in which airflows are higher for longer periods, would make more noise. We did not measure the ventilation system operation directly, so we tried two surrogate measures. These again are based on reasonable assumptions, that higher air flows from the ventilation system will lead to higher air velocities and lower carbon-dioxide concentrations at the locations of measurement. One building in the sample had openable windows that were used during the period of our visit. Open windows would likely increase background noise, and increase air velocity and lower carbon-dioxide concentration, independent of the effect of the mechanical system. Because we were interested in mechanical system noise only, we excluded the data from the building with openable windows from this analysis, this is indicated by the addition of “(sealed)” to the FDCO2 and AIR_V_H variable names. The analyses show that for those DVs directly related to background noise (LNOISEA, ACO_HI, ACO_LO), the single-predictor regressions are significant, and in the expected direction. The magnitude of the variance explained suggests the FDCO2 is a better single predictor than AIR_V_H.

3.2 Lighting

The results of the regressions on Lighting-related dependent variables (DVs) are summarized in Table 7. Note that when calculating the maximum effect of the IVs there is an additional IV to consider compared to the Acoustics-related results, DAYLIGHT. The maximum change possible in the DAYLIGHT variable is 2 (equivalent to a change from a cubicle having its own window to a cubicle being more than 15 ft from a window).

E_CUBE and E_DESK are both measures of illuminance, and would be expected to behave in a similar way. In some senses, E_CUBE is the more reliable measurement: desktop sensors could be shaded by objects on the desktop, or prevented from being placed in their intended locations; the cube was always placed in the intended, unobstructed, location relative to the occupant's computer screen. However, E_DESK is very familiar to practitioners, whereas E_CUBE is not, so we performed regressions for both. The overall models contain four predictors, and the result is similar in form for both E_CUBE and E_DESK. In both cases, SQRTAREA, MINPH_NOOPEN and DAYLIGHT are significant predictors, and PANELS_CAT is not. The coefficients are consistent with expectations, and with our non-field studies [Newsham and Sander, 2002; Reinhart, 2002], indicating that illuminance increases with increasing workstation size, decreasing partition height, and proximity to a window. The 4-predictor model explains a greater percentage of variance in E_CUBE (28%) than in E_DESK (16%), which is perhaps partly explained by the greater reliability in the E_CUBE measure, as described above.

The single-predictor models suggest that proximity to a window is the most important predictor of illuminance. The effect of workstation size and partition height was studied using computer simulations [Newsham and Sander, 2002; Reinhart, 2002]. In one set of simulations we included electric lighting effects only, in another set we looked at daylight penetration explicitly. Therefore to compare the relationships from the field study with the simulation results, we performed separate single-predictor regressions for data from workstations in each of the three DAYLIGHT categories. We also limited the partition height regressions to workstations with "full" enclosure (PANELS_CAT= 1), this is indicated by the addition of "(11)" to the MINPH_NOOPEN variable name, as this was the design assumption in the simulations. For these single-predictor models there is no significant effect of SQRTAREA on E_DESK. This is surprising, and not consistent with our simulation results. For E_CUBE there is a small effect of SQRTAREA in the non-daylit case (DAYLIGHT=0), the coefficient is positive, consistent with our simulations. There is a larger effect for workstations within 15 ft of a window, but without a window of their own. In this case, the coefficient is negative, this is consistent with our simulations, because decreasing the size of a cubicle in such circumstances would take it closer to a window.

The single-predictor models related to partition height are generally as expected. The models explain 2-7% of variance, and all have negative coefficients: illuminance increases as partition height decreases. For the E_DESK, DAYLIGHT=0 case we can make a direct comparison to our simulation results. The simulations generated the relative effect of partition height on average desktop illuminance, and indicated that increasing partition height from 30 inch. (no partition above the desktop) to 72 inch would reduce desktop illuminance by ~33%. The regression results indicates a reduction of:

$$\frac{(715 - 5.36 \bullet 30) - (715 - 5.36 \bullet 72)}{(715 - 5.36 \bullet 30)} \times 100\% = 41\%$$

The comparison is quite good, especially considering all of the unknowns in the field measurements. Note that the coefficient is substantially larger for the DAYLIGHT=2 case. One likely reason for this is that for a cubicle next to a window, lower partitions would increase the exposure to the windows of neighbours on either side.

The regressions on our measure of illuminance uniformity (E_DESKUNI) were not very successful. The 4-predictor model was not significant, and the single-predictor effects were small and inconsistent. Our simulations indicated that it was difficult to develop general relationships for uniformity, but that illuminance tended to be more uniform for larger workstations with lower partitions, in a non-daylit scenario. For the DAYLIGHT=0 case, the relationship with SQRTAREA is significant (4% of variance explained), and the coefficient is negative. The definition of E_DESKUNI is such that a lower value indicates greater uniformity, therefore a negative coefficient for SQRTAREA is as expected. For the DAYLIGHT=0 case, the relationship with MINPH_NOOPEN is also significant (5% of variance explained), and the coefficient is negative. This would mean that illuminance becomes more uniform as minimum partition height *increases*, counter to expectations.

Table 7. Summary of results related to Lighting dependent variables. "n.s." indicates the variable was not significant.

DV	Const.	IV	Coeff.	R^2_{adj}	F (df)	Mx. Effect.
E_CUBE	327.9722	SQRTAREA	14.7876	0.2778	74.5 (4, 760)	74
		MINPH_NOOPEN	-4.5252			-136
		PANELS_CAT	n.s.			
		DAYLIGHT	73.4942			147
	138.5557	SQRTAREA(day=0)	3.6135	0.0093	4.1 (1, 328)	18
	412.5458	SQRTAREA(day=1)	-25.0898	0.0839	12.9 (1, 129)	-125
		SQRTAREA(day=2)	n.s.			
		MINPH_NOOPEN(11)(day=0)	n.s.			
	385.9484	MINPH_NOOPEN(11)(day=1)	-3.2180	0.0935	9.7 (1, 83)	-97
	644.5817	MINPH_NOOPEN(11)(day=2)	-4.9629	0.0321	9.0 (1, 241)	-149
	165.2294	DAYLIGHT	80.2873	0.2330	234.6 (1, 768)	161
E_DESK	566.4370	SQRTAREA	16.5366	0.1605	37.5 (4, 760)	83
		MINPH_NOOPEN	-6.6389			-199
		PANELS_CAT	n.s.			
		DAYLIGHT	84.2577			169
		SQRTAREA(day=0)	n.s.			
		SQRTAREA(day=1)	n.s.			
		SQRTAREA(day=2)	n.s.			
	710.4607	MINPH_NOOPEN(11)(day=0)	-5.2913	0.0676	18.1 (1, 235)	-159
	764.3216	MINPH_NOOPEN(11)(day=1)	-6.1540	0.0905	9.4 (1, 83)	-185
	1207.9090	MINPH_NOOPEN(11)(day=2)	-10.3761	0.0545	15.0 (1, 242)	-311
	356.9471	DAYLIGHT	92.1285	0.1220	107.8 (1, 768)	184
E_DESKUNI	n.s	SQRTAREA				
		MINPH_NOOPEN				
		PANELS_CAT				
		DAYLIGHT				
	0.6050	SQRTAREA(day=0)	-0.0206	0.0372	13.7 (1, 328)	-0.10
		SQRTAREA(day=1)	n.s.			
	0.3361	SQRTAREA(day=2)	0.0129	0.0113	4.6 (1, 315)	0.06
	0.7963	MINPH_NOOPEN(11)(day=0)	-0.0058	0.0465	12.5 (1, 235)	-0.17
		MINPH_NOOPEN(11)(day=1)	n.s.			
		MINPH_NOOPEN(11)(day=2)	n.s.			
	0.4212	DAYLIGHT	0.0167	0.0045	4.5 (1, 777)	0.03

3.3 Ventilation

The results of the regressions on Ventilation-related dependent variables (DVs) are summarized in Table 8. Note that when calculating the maximum effect of the IVs there are four additional IVs to consider compared to the previous analyses, DFLOCATE, MONTH, TIME_CHECK, and WINDOW. The maximum change possible in DFLOCATE is 1 (equivalent to a change from a cubicle having a diffuser within a cubicle to having a diffuser outside the cubicle); the maximum change possible in MONTH is 5 (equivalent to measurements made in June rather than January); the maximum change possible in TIME_CHECK is 0.333 (equivalent to measurements made at 4pm rather than at 8am); the maximum change possible in WINDOW is 1 (equivalent to a change from a cubicle not having a window to a cubicle having a window).

In general, the Ventilation-related regressions reveal only small effects related to office design, which are sometimes contradictory and not easy to interpret. However, this is not unexpected. Our non-field studies [Shaw et al., 2003] suggest that office design parameters, in the context of an HVAC system meeting minimal standards for outside air delivery, have little effect on ventilation efficiency and thermal comfort. [Shaw et al., 1993]

The overall models contain six predictors, with TIME_CHECK and MONTH included to try to account for changes in occupancy and external climate during a day, and changes in external climate during the year, respectively. The six-predictor model for air temperature (RTD_H) explains 15% of the variance, with SQRTAREA, MINPH_NOOPEN, PANELS_CAT, DFLOCATE, and TIME_CHECK significant, though the maximum magnitude of all effects is no more than 0.5 ^{o}C. TIME_CHECK has a positive coefficient, this is expected: occupancy and external temperature tend to increase over the period in which we made our daytime measurements, both of these effects would tend to increase internal air temperature. DFLOCATE has a positive coefficient, this is expected: the diffuser is generally a source of cooling air, so cubicles with a diffuser above them would tend to be cooler. SQRTAREA has a negative coefficient, this is also expected: larger areas would imply a lower density of heat sources such as occupants and their associated office equipment and desk lamps. Both MINPH_NOOPEN and PANELS_CAT have negative coefficients, suggesting that higher, more enclosing partitions are associated with cooler temperatures. One explanation might be that, for cubicles with a local diffuser, the greater enclosure serves to entrain the cool air within the workstation.

We explored this entrainment hypothesis through single-predictor models. We performed separate single-predictor regressions for data from workstations in each of the DFLOCATE categories (1= diffuser within cubicle; 2= diffuser outside cubicle). We also limited the partition height regressions to workstations with “full” enclosure (PANELS_CAT= 1), this is indicated by the addition of “(11)” to the MINPH_NOOPEN variable name, as this was the design used in our most recent non-field study of ventilation in open-plan office spaces. We see that the effect of workstation size and partition height on temperature is greater (coefficient more negative) for cubicles without their own diffuser, which tends to contradict the entrainment concept. Nevertheless, as seen below, there are other results to support it.

The six-predictor model for air velocity (AIR_V_H) explains only 9% of the variance, with SQRTAREA, MINPH_NOOPEN, DFLOCATE, MONTH, and TIME_CHECK significant, though the maximum magnitude of all effects is no more than 0.03 ms^{-1}. TIME_CHECK has a positive coefficient, this is expected: occupancy and external temperature tend to increase over the period in which we made our daytime measurements, both of these effects would tend to increase air flow in a VAV system. MONTH has a positive coefficient, this is expected: external temperature tends to increase over the period in which we made our daytime measurements, which would tend to increase air flow in a VAV system. This effect might also reflect the use of openable windows at one building visited in the month of June. DFLOCATE has a negative coefficient, this is expected: cubicles with a diffuser above them would tend to be have higher air velocities.

SQRTAREA has a negative coefficient; larger areas would imply a lower density of heat sources such as occupants and their associated office equipment and desk lamps, and therefore lower flow rates in a VAV system. However, looking at the single-predictor models for SQRTAREA, we see that the effect is only significant for workstations with their own local diffuser. This suggests an alternate explanation: that larger areas, on average, take the occupant further from a diffuser. MINPH_NOOPEN has a negative coefficient and it might be expected that higher partitions would tend to present barriers to airflow. However, looking at the single-predictor models for MINPH_NOOPEN, we see that the effect is only significant for workstations with their own local diffuser, which doesn't support this explanation.

The six-predictor model for humidity (REL_HUMID) explains fully 31% of the variance, with MINPH_NOOPEN, MONTH, and TIME_CHECK significant. MONTH is the single most important predictor. It has a positive coefficient, this is expected and reflects the rise in moisture content in the external air that occurs in the climates where our study sites were situated during the transition from winter to early summer. TIME_CHECK has a negative coefficient, which is unexpected because one of the major sources of water vapour in office buildings is the occupants, whose numbers tend to increase over the course of a day. However, the magnitude of the TIME_CHECK effect is small, and similar to our measurement error.

MINPH_NOOPEN has a negative coefficient, which supports the entrainment hypothesis. Supply air is generally of lower humidity than return air, so, for cubicles with their own diffuser higher partitions would tend to entrain the lower-humidity air. This is reinforced by the single-predictor models. For cubicles with their own diffuser, the coefficient is negative, but for cubicles without their own diffuser the coefficient is positive, suggesting that higher partitions would limit their access to lower humidity supply air. Although SQRTAREA was not significant in the overall model, it does show significance in the single-predictor regressions. For cubicles with their own diffuser, the coefficient is negative. Larger workstations mean a lower density of water vapour producing occupants. However, for cubicles without their own diffuser, the coefficient is positive. In this case, larger areas would mean a greater distance to the source of lower-humidity air, which might outweigh the effect of a lower occupant density.

The six-predictor model for carbon-dioxide concentration (FDCO2) explains only 5% of the variance, with SQRTAREA, MINPH_NOOPEN, DFLOCATE, and TIME_CHECK significant. TIME_CHECK is the single most important predictor. It has a positive coefficient; this is expected: occupancy tends to increase over the period in which we made our daytime measurements, and occupants are the primary internal source of carbon-dioxide. DFLOCATE has a negative coefficient, which is unexpected, implying that the closer the source of supply air the higher the value carbon-dioxide concentration. However, the magnitude of the effect is small. SQRTAREA has a negative coefficient, as expected: larger areas would imply a lower density of carbon-dioxide producing occupants. MINPH_NOOPEN has a positive coefficient, suggesting that higher partitions are barriers to carbon-dioxide dilution and argues against the entrainment concept. The single-predictor models for carbon-dioxide are not significant.

We also explored the possibility of a relationship between ventilation-related DVs and windows. This was based on observations in the descriptive data that people in cubicles with windows often had lower levels of satisfaction with ventilation [Charles and Veitch, 2002]. We had supposed that people close to windows would tend to experience colder temperatures in the winter, and warmer temperatures in the summer due to the external climate, although this was complicated by the existence of perimeter heating systems in some buildings. Due to this consideration, we divided the data into two separate groups: data collected in December – March (denoted "winter"), and data collected in April – June (denoted "spring"). The regressions on temperature are significant, and have negative coefficients in both cases. This indicates that temperatures are lower close to windows in both seasons of measurement. Further, and as expected, the coefficient is more negative in the winter. The only other significant effect is for humidity, and in the winter only, but the magnitude of the effect is very small.

Table 8. Summary of results related to Ventilation dependent variables. "n.s." indicates the variable was not significant.

DV	Const.	IV	Coeff.	R^2_{adj}	F (df)	Mx. Effect.
RTD_H	23.7835	SQRTAREA	-0.0633	0.1475	22.9 (6, 752)	-0.3
		MINPH_NOOPEN	-0.0123			-0.4
		PANELS_CAT	-0.1750			-0.2
		DFLOCATE	0.1699			0.2
		MONTH	n.s.			
		TIME_CHECK	1.3720			0.5
	24.1629	SQRTAREA(df=1)	-0.1097	0.0590	37.7 (1, 584)	-0.5
	24.7812	SQRTAREA(df=2)	-0.1613	0.0916	19.2 (1, 179)	-0.8
	24.2416	MINPH_NOOPEN(11)(df=1)	-0.0185	0.0266	13.5 (1, 456)	-0.6
	24.8295	MINPH_NOOPEN(11)(df=2)	-0.0231	0.0530	7.2 (1, 109)	-0.7
	23.3602	WINDOW(spring)	-0.2573	0.0205	14.6 (1, 650)	-0.3
	23.4250	WINDOW(winter)	-0.4970	0.0400	5.9 (1, 116)	-0.5
AIR_V_H	0.1429	SQRTAREA	-0.0023	0.0846	12.6 (6, 748)	-0.01
		MINPH_NOOPEN	-0.0008			-0.02
		PANELS_CAT	n.s.			
		DFLOCATE	-0.0115			-0.01
		MONTH	0.0046			0.02
		TIME_CHECK	0.0309			0.01
	0.1399	SQRTAREA(df=1)	-0.0052	0.0581	36.8 (1, 579)	-0.03
		SQRTAREA(df=2)	n.s.			
	0.1865	MINPH_NOOPEN(11)(df=1)	-0.0015	0.0806	40.6 (1, 450)	-0.05
		MINPH_NOOPEN(11)(df=2)	n.s.			
		WINDOW(spring)	n.s.			
		WINDOW(winter)	n.s.			
REL_HUMID	42.7861	SQRTAREA	n.s.	0.3106	58.6 (6, 761)	
		MINPH_NOOPEN	-0.4187			-13
		PANELS_CAT	n.s.			
		DFLOCATE	n.s.			
		MONTH	3.4881			17
		TIME_CHECK	-9.1422			-3
	42.5063	SQRTAREA(df=1)	-1.4239	0.0565	36.2 (1, 587)	-7
	19.9518	SQRTAREA(df=2)	1.6318	0.1116	24.4 (1, 185)	8
	78.0599	MINPH_NOOPEN(11)(df=1)	-0.7612	0.2645	166.0 (1, 458)	-23
	8.0998	MINPH_NOOPEN(11)(df=2)	0.3943	0.1152	15.5 (1, 110)	12
		WINDOW(spring)	n.s.			
	19.6643	WINDOW(winter)	4.4662	0.0918	13.0 (1, 118)	4
FDCO2	552.9375	SQRTAREA	-4.6355	0.0488	7.5 (6, 749)	-23
		MINPH_NOOPEN	1.1956			36
		PANELS_CAT	n.s.			
		DFLOCATE	-16.6738			-17
		MONTH	n.s.			
		TIME_CHECK	170.9824			57
		SQRTAREA(df=1)	n.s.			
		SQRTAREA(df=2)	n.s.			
		MINPH_NOOPEN(11)(df=1)	n.s.			
		MINPH_NOOPEN(11)(df=2)	n.s.			
		WINDOW(spring)	n.s.			
		WINDOW(winter)	n.s.			

4.0 Discussion

The percentage of variability explained by the regression models detailed in this report might seem disappointingly low in many cases. After all, the variables involved are physical quantities, and relatively strong associations have been observed in non-field studies. But it is important to remember the conditions under which measurements are made in the field are not as controlled as in a laboratory or a simulation. The primary issue is the number of parameters other than those measured that are known to affect the dependent variables we were interested in. For example, in acoustics we did not record the acoustical properties of the ceiling tile or the partitions, although we know them to be important. In lighting we did not record surface reflectances, or window properties. In ventilation, we did not monitor the operation of the mechanical HVAC system, or the external climate conditions. These parameters, and others were not recorded for a variety of reasons. We had limited time in each workstation and building, and limited resources; furthermore, more time in each workstation would have been too disruptive to the occupant and would have reduced the number of workstations in the sample. In some cases, there was no practical way to measure a particular parameter. In other cases, the importance of the missing measurements only became apparent months later.

In addition, field conditions inevitably introduce additional errors compared to measurements made in a laboratory setting, adding more variability to the data. In the laboratory sensors are generally in fixed locations as the conditions change. In the field, the sensors are moved in between every measurement. The desktop illuminance sensors were placed at pre-assigned positions on the desk, measured relative to the location of the occupant's computer screen. The desks in our simulations had no objects (such as phones, piles of paper, coffee mugs), or partition-hung storage elements that could affect the illuminance measurements; offices in the field have such things, and they differ between individuals. Sometimes the pre-assigned measurement location did not correspond to a real desktop location, and we placed the sensor at the closest available location.

Our non-field study work in the laboratory and simulations assumed workstations with a square footprint, and partitions of equal height and uniform properties on all sides. This was often not the case in field settings, further complicating comparisons to the non-field study results.

Ideally we would have been able to make measurements in a very large number of randomly-sampled buildings and workstations, with very low correlations between independent variables. In practice, this is not possible. We believe our sample to be large and varied compared to other studies that have gone before, but it is far from randomly-sampled. In general, smaller workstations have lower partitions; that is reality, but that relatively large inter-correlation complicates interpretation of results. It is also reality that each building has relatively little variation in things like workstation size and partition height, because facilities managers tend to buy many copies of the same workstation. In other words, some buildings have mostly large cubicles, and others have mostly small cubicles, and expected effects of workstation size might be masked by, or due to, other differences in the buildings.

Despite all of these issues, in most cases the expected relationships are found, with statistical significance, in the field. Effects were small, and sometimes contradictory, in the area of ventilation, but this was expected from non-field studies. We learned some lessons that will improve field study data collection in the future, but it is inevitable that measurements made in the field will be compromised to some extent compared to carefully controlled laboratory measurements, or analytical simulations. For this reason, for explaining the effect of design choices on indoor environment conditions, we regard the field study results primarily as a check on results from non-field studies, rather than using them to supplant results from non-field studies. For example, in the design of a software tool to help designers with the acoustical design of workstations, we will use the relationship between partition height and speech propagation derived from the analytical model we have developed, rather than that from field measurements. In cases where the non-field studies did not or could not address a certain relationship (e.g., the relationship between workstation area and background noise), the field studies do provide the primary source of information.

In Tables 6, 7 and 8 we included an indication of the maximum change in indoor environment parameters (DVs) that could be caused by a change in office design parameters (IVs). This is one way of indicating how office design can have a substantial effect on physical conditions. These maximum effects are based on the largest realistic changes in individual IVs, given the uncertainties in the data discussed above, it might be more reasonable to focus on relationships in which half the maximum effect makes a substantial difference. For example, in the area of acoustics, changes of 3 dB(A) in sound levels are considered “just noticeable”. A combination of reduced workstation area *and* reduced partition height is associated with an increase in background noise of this magnitude. Similarly, simultaneously increasing workstation area and partition height can substantially lower background noise. Our results also suggest that the operation of the HVAC system can have noticeable effects on background noise. Whether increasing background noise to improve speech sound masking, or decreasing it to reduce annoyance from the background noise itself is the best strategy will depend on the prevailing conditions in the space. A recent literature review of acoustic satisfaction in open-plan offices recommended average background noise levels of 45-50 dB(A) [Navai and Veitch, 2003]. Variations in workstation area, partition height and HVAC system operation are also associated with changes in SII of ~0.1, which may be large enough to make the difference between meeting and not meeting recommended levels; an SII < 0.2 is suggested for “acceptable” speech privacy in the open plan [Veitch et al., 2002b].

In interior lighting, changes of the order of 100 lux are considered substantial, and have been associated with satisfaction effects [Newsham and Veitch, 2001]. Not surprisingly, close proximity to a window is associated with an increase in illuminance of this magnitude. Changes in partition height can also have such an effect. This is particularly true in combination with a nearby window, where higher partitions reduce access to daylight. Unfortunately, we do not yet have any basis on which to evaluate the effects on the measure of uniformity we used.

Proximity to a window can also effect air temperature by an average of ~0.5 ^{o}C, which is associated with a reduction in satisfaction with temperature [Charles and Veitch, 2002]. Our measurements were made in Winter and Spring, where temperatures were generally lower close to windows. This suggests that attention to temperature control at the perimeter and, where possible, envelope insulation, might be beneficial. In some of the buildings we studied there were anecdotal reports of poorer air quality later in the afternoons. Our data show, on average, a substantial increase in carbon-dioxide concentration from the start of the working day to the end (TIME_CHECK effect). It is important to note that we rarely observed levels above the ASHRAE-recommended maximum of 1000 ppm [ASHRAE, 2001]. The likely explanation for this increase in carbon-dioxide is an increase in building population over the day. Increasing the outdoor air supply rate later in the day might be one solution to this perceived problem.

This study also highlights areas for future research. The relationships between workstation area, partition height and background noise are interesting. They suggest that the increases in speech sounds associated with smaller workstations and lower partitions may be offset to some extent by parallel increases in background noise, due to office equipment, non-speech sounds made by occupants, and distant (unintelligible) speech. This warrants further study in a more controlled experiment. The relationship between HVAC operation and background noise was already well-established before this study. Nevertheless, it highlights the potential to design HVAC system operation for both optimal ventilation and acoustic performance. A very quiet ventilation system with a well-designed sound masking system is probably the best solution, but if a dedicated sound masking system is not available, optimizing ventilation sounds for speech masking might be a practical alternative.

In lighting, we observed an interesting interaction between daylight availability and partition height. This relationship was examined in detail in a simulation study [Reinhart, 2002], but for a relatively simple workstation layout. Broadening the scope of these studies to look at the effect workstation design on daylight availability in a wider variety of layouts may be fruitful.

Having a window in one's cubicle brings satisfaction effects in almost every area except satisfaction with temperature. A rigorous study of the thermal climate in windowed offices might suggest mitigating strategies. Our data also suggested the possibility of cubicle partitions entraining supply air from diffusers local to the workstation. However, the observed effects were not always consistent with this hypothesis, and future work could clarify whether entrainment is, in fact, taking place.

5.0 Conclusions

The conclusions are presented with reference to the goals of the analyses, outlined in the Introduction. These goals were:

1. *To check the findings against those of the "non-field" studies to ensure there were no important conflicts.*
   Overall, results are consistent with the findings of the non-field studies. Analyses of Acoustics and Lighting data supported the relationships and expectations from other work. In Ventilation, the regressions generally showed only small effects, which were sometimes contradictory and not easy to interpret. However, this was also in line with expectations. Other studies have indicated that office design parameters have little effect on ventilation efficiency and thermal comfort when the HVAC system meets minimal standards for outside air delivery.
2. *To explore relationships that were not, or could not, be addressed in the "non-field" studies.*
   The analyses did reveal some interesting, additional relationships. We found that background noise tended to increase with decreasing workstation size (increasing occupant density), and decreasing partition height. We also observed that background noise tended to be higher with higher air velocity and lower carbon-dioxide concentrations, perhaps indicating how the operation of the HVAC system might generate noise. Finally, we were able to confirm that temperatures near to windows are generally a little cooler than temperatures in non-windowed workstations, during the winter and spring months.

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