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Relationship between Occupant Discomfort as Perceived and as Measured Objectively

Key Words
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CO_2
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Abstract
This paper examines the relationships between the indoor environment parameters on two floors of an eleven-storey building, as perceived by the occupants and as measured objectively. The parameters measured are dry-bulb temperature, relative humiditiy, total dust, formaldehyde, volatile organic compounds and CO_2. Questionnaires were also distributed to the building occupants. All parameters and questionnaires were recorded on both floors and analyzed simultaneously for comparative reasons. Our investigation showed that complaints reported by the occupants were associated with perceived rather than measured levels of indoor environmental parameters.

Introduction

More than one third of the energy consumed in North America is used in buildings for heating, cooling, lighting, and ventilation [1]. The conditioning and transportation of ventilation air account for 50–60% of the total building energy requirements. In spite of this, a recent survey has shown that 65% of buildings operate under sick building syndrome (SBS) conditions; resulting in an estimated loss of annual productivity equivalent to several billion dollars, excluding the medical expenses [2].

Guidelines have been developed to measure the quality of indoor air in terms of environmental parameters (thermal and mass) [3–5]. The measurement of environmental parameters alone [6], or the combined use of the measurement of environmental parameters and questionnaires [7], have been applied to identify the association between certain building-related complaints and environmental parameters. However, this technique has failed in some cases to identify these associations, indicating there may be other factors contributing to this problem [8].

The main objective of this paper is to show that in some cases the complaints reported by occupants are associated with perceived rather than measured levels of indoor environmental parameters.

Test Facility and Measurement Procedure

Building

The building in which the investigation was carried out is an eleven-storey building with, but not including, a basement. The eleventh floor is the cafeteria, and the basement contains a parking area, a delivery station for mail and merchandise, and a maintenance equipment storage room. Occupants of this building expressed symptoms believed to be associated with poor air quality and irritating odours.

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The eighth and ninth floors were used for this investigation. Figure 1 shows the typical floor plan.

Each floor is comprised of:

- approximately 60 white-collar workers; however, since the building is open to the public, the number of occupants varies;
- a minimum floor area of 1,800 m^2;
- a ceiling height of 3 meters;
- synthetic floor carpeting;
- 75% of walls are exterior walls;
- 90% of facade area is covered with fenestration equipped with blinds;
- four conference rooms;
- 60–80 work stations;
- 14 closed offices;
- two public and two private washrooms;
- one lounge room;
- one photocopy machine (eighth floor only);
- six elevators, and
- one mechanical room equipped with two independent HVAC systems; one system ventilates the partitioned offices, and the second ventilates the conference rooms and closed offices.

Experiments were designed to find out whether there is any relationship between the amount of fresh air (ventilation rate), and occupants' complaints. To answer this question, the position of the outdoor supply air dampers was varied from 0° (total recirculated air) to 25°, 75° and 90° (total fresh air). The damper modulation was performed in a random order so as to ensure that the occupants were unaware of any pattern of change (week 1, 0°; week 2, 90°; week 3, 25°; week 4, 75°). This study was conducted over a 4-week period and consisted of measuring environmental parameters, and of administering a questionnaire on comfort and health.

Thermal Comfort Parameters

Temperature and relative humidity measurements were made during the course of our investigation. These measurements were made on two consecutive days (Tuesday and Wednesday), at half-hour intervals, at nine different work stations per floor, at two different heights. A psychrometer was used.

Indoor Air Quality Parameters

Chemical contaminants measured include: dust (37 mm polyvinyl chloride filter), nicotine (XAD-2 adsorbent tube), Volatile Organic Compounds (VOCs; activated charcoal adsorbent tube), formaldehyde (Orbo adsorbent tube impregnated with n-benzylethanolamine), carbon dioxide (ADC infra-red analyzer), and carbon monoxide (Ecolyzer direct reading instrument). The dust, nicotine, VOCs (toluene, xylene, and stoddard compounds), and formaldehyde were all collected using personal air sampling pumps using from 0.5 to 2.0 litres/min air flows. These were installed throughout the floors for periods of up to 48 h each week. The carbon dioxide was sampled with a direct reading instrument, from 7:00 a.m. to 7:00 p.m., at half-hour intervals, at three different heights at the work stations, in supply ducts, and in return ducts, for 3 consecutive working days per week. The carbon monoxide was also sampled with a direct reading instrument, before, during, and after each traffic hour, for three consecutive working days per week.

Questionnaires

A questionnaire was distributed every Wednesday morning, to all occupants, and collected every Wednesday evening.

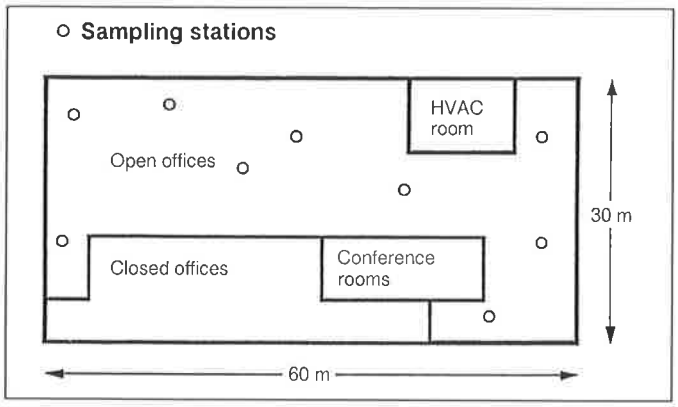

Fig. 1. Building plan.

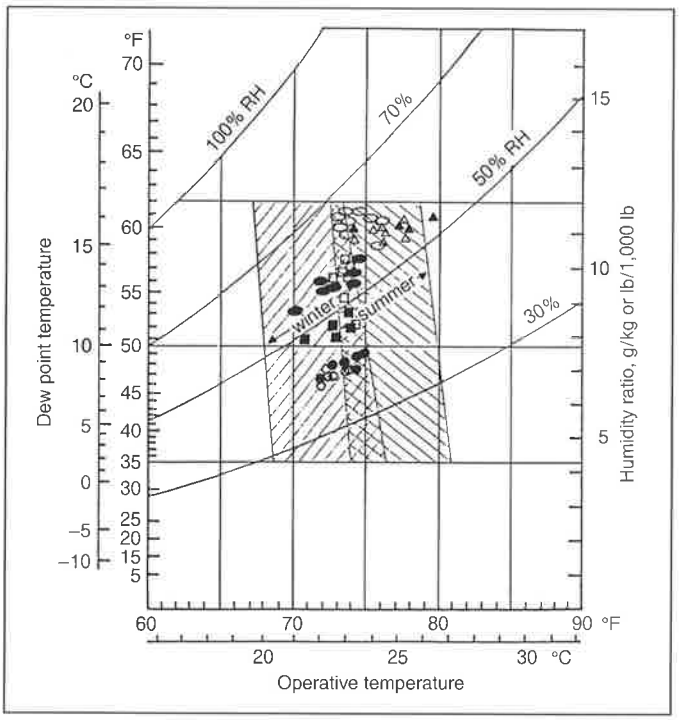

Fig. 2. Temperature and relative humidity readings with respect to the comfort zone as described by ASHRAE Standard 55-1981. Filled symbols = 8th floor; open symbols = 9th floor. ●, ○ = week 1 at 0 °; ▲, △ = week 2 at 90°; ■, □ = week 3 at 25°; ⬬, ⬭ = week 4 at 75°.

Results

Dry-Bulb Temperature and Temperature Gradients

Dry-bulb temperature readings are shown in figure 2. It was assumed that dry-bulb temperature was equivalent to operative temperature. The temperature measured during the 4 weeks varied between 21.5 and 26.6 °C with most of them falling between 22.5 and 24.0 °C.

The temperature difference between the floor and the work level, for weeks 1–4, are in the order of 0.2 °C.

Humidity

Relative humidities measured ranged from 40 to 65%. Figure 2 indicates that as the damper degree increases (week 1-3-4-2), the relative humidity increases, contrary to the fact that recirculated air should contain more humidity. This high humidity may be due to the location of the building, which is situated along the St. Lawrence river.

Dust

Average dust levels, as measured in the office sites, vary from 13.4 to 45.3 μg/m³. These results are shown in table 1. The total average of each floor is 29.0 and 33.0 μg/m³ (8th and 9th, respectively). The difference between them is insignificant.

Nicotine

Nicotine was measured as an indicator of environmental tobacco smoke. The average concentration was very low, less than 2 μg/m³ (table 2). In most cases there was no detectable level of nicotine. Nicotine was detected only at the stations where smoking was noted; thus only on the 9th floor.

Volatile Organic Compounds

The measured value varied between 0.7 and 9.2 mg/m³ (table 3). The total VOCs detected, during weeks 1 and 3, when the damper positions were minimum, were significantly greater than those detected on weeks 2 and 4 (90 and 75° damper position, respectively). The total average for each floor is 2.4 and 3.5 mg/m³ (8th and 9th, respectively). The difference between them is insignificant; however, the higher level on the 9th floor may be due to the fact that renovations on that floor had just been terminated.

Formaldehyde

Table 4 gives the concentration of formaldehyde measured during the course of our studies. The total average for each floor is 27.83 and 21.84 μg/m³ (8th and 9th, respectively). The difference between them is insignificant.

Carbon Dioxide

The levels of CO_2 as a function of time are shown in figures 3 and 4. The highest CO_2 level found throughout the study was 750 ppm, with levels exceeding 600 ppm only when the outdoor air dampers were completely shut. Exterior carbon dioxide levels remained in the order of 370 ppm. Higher levels were found on the 8th floor,

Table 1. Dust concentrations

Floor	Station	Concentration, μg/m³			
		week 1	week 2	week 3	week 4
8	1	37.6	23.9	17.7	39.8
	2	42.3	44.7	28.8	36.6
	3	24.0	41.7	16.7	30.4
	4	n.d.	–	12.5	37.4
	5	41.0	9.40	47.0	47.2
	6	14.7	17.2	9.5	46.8
Average		36.60	27.38	22.03	39.70
9	1	49.4	29.3	8.9	46.4
	2	18.0	51.4	13.2	41.7
	3	48.0	20.0	6.0	63.1
	4	8.7	15.1	6.0	34.7
	5	23.6	41.3	17.4	32.1
	6	57.6	76.9	28.9	53.7
Average		34.20	39.00	13.40	45.28

n.d. = Not detected. ASHRAE: 260 μg/m³ for 48 h.

Table 2. Nicotine concentrations

Floor	Station	Concentration, μg/m³			
		week 1	week 2	week 3	week 4
8	1	n.d.	n.d.	n.d.	n.d.
	2	n.d.	n.d.	n.d.	n.d.
	3	n.d.	n.d.	n.d.	n.d.
	4	n.d.	n.d.	n.d.	n.d.
	5	n.d.	n.d.	n.d.	n.d.
	6	n.d.	n.d.	n.d.	n.d.
Average		–	–	–	–
9	1	3.6	n.d.	n.d.	n.d.
	2	n.d.	n.d.	n.d.	n.d.
	3	3.0	n.d.	n.d.	n.d.
	4	n.d.	n.d.	n.d.	n.d.
	5	n.d.	n.d.	n.d.	n.d.
	6	n.d.	–	10.5	n.d.
Average		1.1	–	1.75	–

n.d. = Not detected. ACGIH: 0.5 mg/m³.

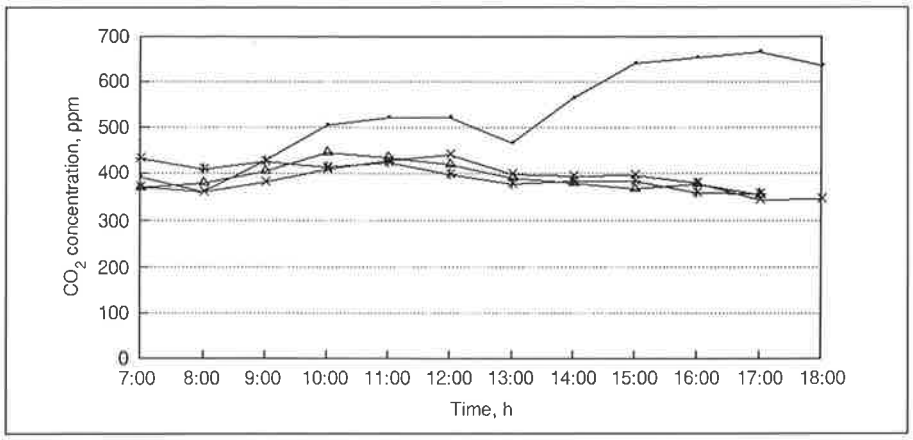

Fig. 3. Carbon dioxide readings, 8th floor. ● = Week 1 (0°); * = week 2 (90°); X = week 3 (25°); △ = week 4 (75°).

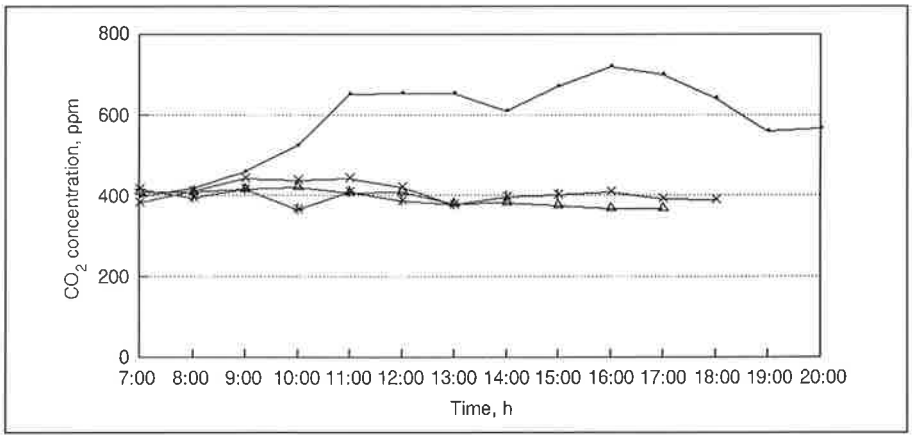

Fig. 4. Carbon dioxide readings, 9th floor. ● = Week 1 (0°); * = week 2 (90°); X = week 3 (25°); △ = week 4 (75°).

Table 3. Volatile organic compounds

Floor	Compound	Average concentration, µg/m³			
		week 1	week 2	week 3	week 4
8	Toluene	25.80	17.24	24.96	30.97
	Xylene	76.07	n.d.*	151.88	184.92
	Stoddard	3,298.60	1,259.20	3,604.50	1,113.38
Total		3,400.50	1,276.40	3,604.50	1,329.27
9	Toluene	27.38	n.d.	29.35	17.30
	Xylene	n.d.	n.d.	124.08	110.88
	Stoddard	9,167.03	715.15	3,050.12	859.80
Total		9,196.03	715.15	3,250.12	987.98

n.d. = Not detected. ACGIH: 433 mg/m³.

Table 4. Formaldehyde concentrations

Floor	Station	Concentration, µg/m³			
		week 1	week 2	week 3	week 4
8	1	14.60	27.10	34.70	23.50
	2	33.20	27.90	38.70	17.20
	3	27.80	24.70	35.10	n.d.*
	4	39.70	–	22.00	16.00
	5	26.30	23.20	46.60	26.00
	6	31.70	26.30	53.80	24.00
Average		28.80	25.53	38.48	17.78
9	1	27.10	9.30	35.90	n.d.
	2	25.40	23.80	52.80	8.01
	3	23.10	18.20	n.d.	9.53
	4	28.60	23.60	–	11.90
	5	30.60	20.00	32.40	8.79
	6	26.60	–	47.30	17.65
Average		26.90	18.98	33.68	9.31

n.d. = Not detected. ASHRAE: 1.3 mg/m³.

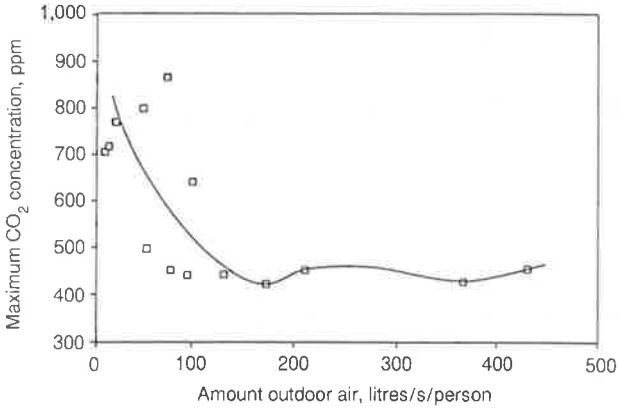

Fig. 5. Outdoor air versus carbon dioxide.

probably due to the higher occupation density. However, the maxima of both floors varied within 50 ppm of each other.

In figure 5, the supplied outdoor air flow rate to the zone is plotted against CO_2 concentration in ppm. These data refer to the maximum concentration level found at any particular work station in the zone. It is quite obvious that the CO_2 is diluted as the outdoor air flow is increased. It is important to note that the outdoor air rates supplied to the occupants were very large. When the dampers were completely closed, an average of 5 litres/s/person was noted, whereas the maximum supply rate found was as high as 450 litres/s/person. The reasons for such high rates are (1) the low occupancy during vacation weeks, and (2) the large capacity of the ventilation system. There are fewer results at the greater outdoor air rates, due to the variation in occupancy. It is interesting to note that at the lowest outdoor air rate, the maximum CO_2 was under 900 ppm.

Carbon Monoxide

Carbon monoxide was not detected in any of the office areas on both floors.

Questionnaires

During the course of our study, 448 questionnaires were distributed and 54% were returned fully answered; which is satisfactory. Since no significant difference was noted between the 8th- and 9th-floor responses, they were combined and analyzed as a whole.

Discussion

Dry-Bulb Temperature and Temperature Gradients

In general, most of the readings fell within the comfort range. During the 1st week (when total recirculated air was used), as shown in figure 2, half of the temperature readings were outside the comfort zone for summer conditions, indicating temperatures that are too cold. However, during the 2nd week (when total fresh air ventilation was introduced), figure 2 shows that the temperature readings were inside the comfort zone except for a value of 26.6 °C around 2 p.m. The reason for this rise is the exterior conditions, mainly the outside high of 30 °C. During the third week, figure 2 indicates temperatures below comfortable levels. During the 4th week, figure 2 shows that some of the readings were below comfortable levels, while the majority were within the limits.

The vertical temperature gradients complied with the ASHRAE guideline of 3 °C.

Humidity

During the entire study, the relative humidities measured remained within the acceptable levels.

Dust

ASHRAE recommends a dust concentration of 260 $\mu g/m^3$ for a period of 48 h and 75 $\mu g/m^3$ is applicable over a period of 1 year. ACGIH recommends a maximum time-weighted average concentration for a normal 8-hour work day and 40-hour work week of 2 mg/m^3. All dust levels respect the above-mentioned standards.

Nicotine

ACGIH recommends a limiting exposure of 0.5 mg/m^3, which is 47.5 times greater than the greatest measured concentration, which occurred on the 3rd week, at station 6.

Volatile Organic Compounds

The total acceptable VOC level in the work place is 332 ppm or 433 mg/m^3. The measured levels were less than 3% of the standard.

Formaldehyde

The ASHRAE standard recommends a maximum allowable concentration of formaldehyde of 0.1 ppm or 1.3 mg/m^3. The ACGIH recommends a maximum time-weighted average concentration of 0.3 ppm or 0.45 mg/m^3. All of the values were less than 9% of the standards.

Carbon Dioxide

ASHRAE recommends a maximum of 1,000 ppm, at any time, whereas ACGIH sets the limit at 5,000 ppm. The highest CO_2 level found never exceeded 900 ppm.

Carbon Monoxide

ACGIH recommends an allowable level of carbon monoxide of 50 ppm, and the ASHRAE standard recommends a level of 9 ppm (8 h exposure). Carbon monoxide was never detected.

Difference between Perception and Objective Values

A summary of the level of comfort experienced by the occupants is given in table 5. Most noteworthy in the responses was that more than 34% of the occupants expressed that the air is dry. As indicated, the measured relative humidity ranged from 40 to 65%. Another interesting finding in the responses was that more than 32% of the occupants expressed that in general, the thermal environment was unsatisfactory, even though almost all the measured thermal comfort parameters complied with the standards.

During the 1st week, 32% of the occupants complained it was too cold, coinciding with the results shown on figure 2, where half of the temperature readings were outside the comfort zone for summer conditions, indicating temperatures that are too cold. During the 2nd week, 39% of the occupants complained it was too hot, however, the temperature readings were inside the comfort zone except for a value of 26.6 °C. During the 3rd week, the majority of the occupants (23%) found that the temperature was adequate; however, figure 2 indicates temperatures below comfortable levels. During the 4th week, 45% of the occupants complained it was too cold. Figure 2 shows that some of the readings were below the comfortable levels, while the majority were within the limits.

A summary of the health concerns expressed in the questionnaire is given in table 5. Most important in these responses was that more than 41% of the occupants complained of dry throat, regardless of the ventilation rate (damper position). Similarly, more than 29% of the occupants responded positively to eye irritation; more than 22% to breathlessness; more than 29% to drowsiness, and more than 26% to difficulty in concentration. In response to odour, 25–53% responded that they did not perceive odours; while 6–32% responded that they perceived odours regularly.

Table 5. Questionnaire results (% of respondents)

Question	week 1	week 2	week 3	week 4
The air is:				
Dry	48	34	35	45
Slightly dry	22	18	23	9
Satisfactory	24	13	23	16
Slightly humid	1	10	8	19
Humid	0	11	5	6
Not answered	5	14	6	5
In your opinion, the quality of the air is:				
Very good	3	0	0	0
Good	3	3	8	12
Satisfactory	27	22	32	13
Unsatisfactory	33	37	29	29
Bad	24	32	20	35
Not answered	10	6	11	11
In general, the thermal environment is:				
Very comfortable	1	0	0	0
Comfortable	4	5	8	3
Adequate	27	20	29	19
Slightly unacceptable	29	29	20	35
Unacceptable	32	41	38	38
Not answered	7	5	5	5
Do you perceive odours regularly?				
No	53	36	52	25
< Once a day	19	17	23	22
Once a day	3	5	5	16
> Once a day	12	6	2	3
Regularly	6	29	8	32
Not answered	7	7	10	2
Do you experience any of these problems?				
Dry throat	54	44	47	41
Sore throat	8	5	8	6
Irritated throat	20	20	26	32
Dry cough	11	17	14	3
Eye redness	17	13	14	16
Burning eyes	37	25	29	22
Blurred vision	27	17	23	12
Swollen eyes	9	3	5	6
Irritated eyes	35	29	32	32
Breathlessness	22	24	23	29
Asthma	9	1	2	6
Wheezing	4	3	2	0
Chest tightness	19	18	23	16
Headaches	35	43	35	19
Drowsiness	40	29	46	35
Faintness	0	1	0	0
Dizziness	11	18	20	19
Difficulty in concentration	37	31	26	29

ASHRAE defines acceptable indoor air quality as being 'air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction' [3]. ASHRAE also defines an acceptable thermal environment as 'an environment which at least 80% of the occupants would find thermally acceptable' [4]. As was testified in the questionnaire responses, more than 20% of the occupants were neither satisfied with the indoor air quality, nor the thermal environment. However the results of the measured parameters should satisfy at least 80% of the occupants.

Summary

The office building under consideration, during our study, was considered 'sick' due to the fact that more than 20% of the occupants complained of health problems such as dry throat, eye irritation, breathlessness, drowsiness, and a difficulty in concentration. There is no correlation between the questionnaire responses and the actual environmental conditions. The measurements of the parameters satisfied the air quality and thermal environment standards. Therefore, this investigation showed that complaints reported by the occupants were associated with perceived rather than measured levels of indoor environmental parameters.

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