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Air Pollution Sources in Offices and Assembly Halls, Quantified by the olf Unit

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SUMMARY

Pollution sources were quantified by the new olf unit in 20 randomly selected offices and assembly halls in Copenhagen. The spaces were visited three times by 54 judges, who assessed the acceptability of the air: (1) while unoccupied and unventilated to quantify pollution sources in the space; (2) while unoccupied and ventilated to quantify pollution sources in the ventilation system; and (3) while occupied and ventilated to determine pollution caused by occupants and smoking. Ventilation rates, carbon dioxide, carbon monoxide, particulates, and total volatile organic compounds were measured, but did not explain the large variations in perceived air quality. For each occupant in the 15 offices there were on average 6 - 7 olfs from other pollution sources; 1 - 2 olfs were situated in the materials in the space, 3 olfs in the ventilation system, and 2 olfs were caused by tobacco smoking. The ventilation rate was 25 l/s per occupant, but due to the extensive other pollution sources only 4 l/s per olf. This explains why an average of more than 30% of the subjects found the air quality in the offices unacceptable. The obvious way to improve indoor air quality is to remove pollution sources in the spaces and in the ventilation systems. This will at the same time improve air quality, decrease required ventilation and energy consumption, and diminish the risk of draughts.

INTRODUCTION

Since Pettenkofer [1] and Yaglou [2], it has been common to express ventilation requirements per human occupant present in a space. In offices and similar spaces it was assumed that the occupants were the exclusive polluters. It was implicitly assumed in ventilation standards that the spaces and ventilation systems were ideally clean and that they did not contribute to the pollution.

We had a suspicion that this was an oversimplification. Many field studies have reported high rates of complaints about indoor air quality ('sick-building syndrome'). Such complaints would be difficult to explain exclusively by the pollution caused by human beings. There had to be other sources of pollution causing the complaints. We therefore decided to investigate a random sample of offices and asembly halls to quantify possible air pollution sources in the spaces and in the corresponding ventilation systems.

The new olf unit [3] was used to quantify the pollution sources. One olf is the emission rate of air pollutants (bioeffluents) from a standard person. Any other pollution source is quantified by the number of standard persons (olfs) required to cause the same dissatisfaction as the actual pollution source.

METHOD

The traditional way of investigating how air quality is perceived in existing buildings has been to ask people to judge the air at their own workplace. Such enquiries may be influenced by psycho-social factors, e.g., the relationship to colleagues, management, building owners, etc. These confounding factors make it difficult to compare different buildings. The unique method used here was to hire independent judges to visit all the buildings under study. We have used this method once previously during an investigation of background odour in smoking spaces [4].

The other unique feature of this study was that our judges also visited the buildings when

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TABLE 1

Physical data of the 20 spaces under study

Number and type of space	Floor area (m^2)	Volume (m^3)	Age of building (years)	Time since last renovation (years)
1 Office	121	322	14	4
2 Office	180	459	15	3
3 Office	375	956	15	15
4 Office	129	340	14	14
5 Office	321	964	24	3
6 Office	106	275	14	2
7 Office	152	463	16	16
8 Office	181	551	16	16
9 Office	105	263	10	3
10 Office	163	461	24	1
11 Office	150	644	26	10
12 Office	136	347	12	12
13 Office	928	3480	11	11
14 Office	143	371	12	12
15 Office	265	954	12	2
16 Auditorium	200	1150	16	16
17 Conf. room	60	157	2	2
18 Conf. room	119	292	3	3
19 Cinema	150	563	10	10
20 Auditorium	123	627	45	10
Mean of offices (1 - 15)	230	723	16	8
Mean of assembly halls (16 - 20)	130	558	15	8
Mean of all spaces (1 - 20)	205	682	16	8

they were unoccupied. Since we had the suspicion that the occupants were not the exclusive polluters, it was logical to judge the spaces when the occupants were not present. The unoccupied spaces were visited twice: once without mechanical ventilation to quantify pollution sources in the space, and once with the ventilation system in operation to quantify pollution sources in the system. A third visit took place when the buildings were normally occupied and ventilated to quantify the pollution caused by the occupants.

BUILDINGS

Twenty spaces were selected for the study, situated in 18 buildings in the greater Copenhagen area. The selected spaces comprised 15 offices and 5 assembly halls. None of the buildings were known previously to have special problems concerning indoor air quality. They comprised a random sample of spaces from the existing building stock. The selected spaces had a minimum floor area of 60 m^2 and they were all mechanically ventilated. Due to the applied method for measuring outdoor air supply, none of the selected spaces had recirculation of the air, or doors leading to more than three adjacent spaces. Specifications for the spaces are listed in Table 1.

SUBJECTS

A total of 54 persons (27 men and 27 women) were hired as judges through advertisements in local newspapers. Of these, 17 were smokers. The subjects were students, white-collar workers or persons with similar vocations, and the age range was between 18 and 30 years.

MEASUREMENTS

When the subjects entered a space they judged the air quality by filling in the

PERSON NO.	ROOM NO.

OUTDOORS:	INDOORS:
Question 1	Question 1
How strong is the odour?	How strong is the odour in the room?
Please mark on the scale.	Please mark on the scale.
— No odour	— No odour
— Slight odour	— Slight odour
— Moderate odour	— Moderate odour
— Strong odour	— Strong odour
— Very strong odour	— Very strong odour
— Overpowering odour	— Overpowering odour
Question 2	Question 2
Imagine that your normal day-to-day routine required you to be outdoors frequently.	Imagine that during your daily work you would be exposed to the present odour.
Would you judge the odour of the air as acceptable?	Would you judge the odour as acceptable?
☐ Acceptable	☐ Acceptable
☐ Not acceptable	☐ Not acceptable
Question 3	Question 3
Do you think the air is fresh?	Do you think the air is fresh?
Please mark with a cross.	Please mark with a cross.
The air is: Very fresh ☐	The air is: Very fresh ☐
Fresh ☐	Fresh ☐
Neutral ☐	Neutral ☐
Slightly stuffy ☐	Slightly stuffy ☐
Stuffy ☐	Stuffy ☐

Fig. 1. Questionnaire for the subjective assessments by the judges.

questionnaire in Fig. 1, i.e., they assessed odour intensity and freshness on the scales shown as well as the acceptability of the air, imagining that they should be exposed to such air during their daily work.

At the same time as the subjective judgement, measurements were made of the following physical/chemical factors: rate of outdoor air supply, carbon dioxide, carbon monoxide, particulates, and total volatile organic compounds. On the two experimental days with mechanical ventilation, the system was turned on several hours before the measurements in order to attain steady-state conditions. On the experimental day without mechanical ventilation the system was turned off at least 12 hours before the measurements.

The air change rate was measured by the method developed by Dietz *et al.* [5] utilizing fluorcarbon tracer gas sources and corresponding passive samplers. One tracer gas was generated in the space under study. Different gases were generated in adjacent rooms. Passive samplers for all gases were distributed in the spaces for a period of 5 - 6 hours. A complete analysis of air flows was performed and the outdoor air supply to the space was determined as the total air supply minus the air flow from adjacent spaces.

Carbon dioxide and carbon monoxide were measured in the space and outdoor measurements were made through a window (1.5 - 2 m from the building). Volatile organic compounds were sampled in the space and analysed by gas chromatography as specified by Mølhave [6]. The concentration of particulates was measured indoors and outdoors, by a gravimetric method. All measurements were taken in the occupied zone, approximately 1.1 m above the floor.

PROCEDURE

Each of the 20 spaces was visited three times on three different days. As mentioned, each space was visited while unoccupied without mechanical ventilation, while unoccupied with mechanical ventilation, and while occupied and with mechanical ventilation. Ten spaces were studied in this order on a Saturday, Sunday and Monday (November 22 - 24, 1986). The remaining ten spaces were studied on a Friday, Saturday and Sunday (November 28 - 30, 1986) in the reverse order.

The judges were transported in a well-ventilated bus from building to building. After arrival at a building they left the bus and judged the outdoor air quality, using the questionnaire in Fig. 1. Half of the judges (including the smokers) were then escorted to the space where they immediately assessed the air quality (Fig. 1). They then went outdoors and were allowed to smoke while the non-smokers entered the space. The bus stopped approximately five minutes at each building and the entire trip to the ten buildings lasted about four hours.

RESULTS

During the six experimental days, the outdoor air temperature was 7 - 9 °C, the relative humidity 84 - 94%, and the mean wind velocity 10 m above the ground was 4 - 7 m/s. The subjective ratings of the outdoor air quality are listed in Table 2. It should be noted that the outdoor air had a low odour intensity, and that it was felt to be fresh and acceptable by nearly all the judges. The slightly different ratings in condition (3) was probably caused by higher traffic on the weekdays (Monday and Friday) near the experimental sites, in contrast to conditions (1) and (2) which were performed on Saturdays and Sundays. The air temperature in the spaces was 21.8 ± 1.3 °C and the relative humidity was 42 ± 5%.

The results of the physical measurements in the spaces are listed in Table 3. It is obvious that all the measured pollutants had low concentrations.

As expected, the carbon dioxide and carbon monoxide were low in conditions (1) and (2), where there were no occupants. But even with occupants present, CO_2 never exceeded 0.082% (above outdoor level) and the maximum of CO was 0.8 ppm (above outdoor level). Particulates were also at a low level, below the outdoors when unoccupied and above outdoors while occupied. All 60 measurements of total volatile organic compounds were at a moderate level below 0.5 mg/m^3.

TABLE 2

Psycho-physical assessments of outdoor air quality

Spaces*	Days	Condition in space	Odour intensity of outdoor air	Dissatisfied (%) in outdoor air	Freshness of outdoor air
2, 3, 4, 5,	Sat. (22 Nov.)	(1) Unoccupied; unventilated	0.7 ± 0.2	3	0.8 ± 0.3
7, 8, 9, 10,	Sun. (23 Nov.)	(2) Unoccupied; ventilated	0.5 ± 0.2	2	0.9 ± 0.2
16, 17	Mon. (24 Nov.)	(3) Occupied; ventilated	0.8 ± 0.4	6	0.7 ± 0.4
1, 6, 11, 12,	Sun. (30 Nov.)	(1) Unoccupied; unventilated	0.6 ± 0.2	3	0.8 ± 0.3
13, 14, 15,	Sat. (29 Nov.)	(2) Unoccupied; ventilated	0.8 ± 0.3	5	0.6 ± 0.3
18, 19, 20	Fri. (28 Nov.)	(3) Occupied; ventilated	1.1 ± 0.5	12	0.4 ± 0.3
All spaces	Mean all days	(1) Unoccupied; unventilated	0.6 ± 0.2	3	0.8 ± 0.3
		(2) Unoccupied; ventilated	0.6 ± 0.3	4	0.8 ± 0.3
		(3) Occupied; ventilated	0.9 ± 0.5	9	0.6 ± 0.4
All spaces	All days	Mean all conditions	0.7 ± 0.3	5	0.7 ± 0.3

*See Table 1 for type of space.

TABLE 3

Mean valu

particulate

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TABLE 3

Mean values of physical and psycho-physical measurements in the 20 spaces. The listed values of CO_2, CO and particulates are concentrations above the outdoor level

Space number	Condition	Air change (l/h)	ΔCO_2 (%)	ΔCO (ppm)	ΔPart. ($\mu g/m^3$)	VOC (mg/m^3)	Odour intensity	Dissatisfied (%)	Freshness
1	(1)*	2.1	0.001	0.0	−9	0.08	1.3	18	−0.2
	(2)	2.4	0.007	0.0	−21	0.06	1.6	34	−0.6
	(3)	2.4	0.031	0.6	66	0.43	1.8	41	−0.6
2	(1)	0.2	0.003	0.1	−9	0.08	1.8	39	−0.5
	(2)	2.7	0.000	0.1	−3	0.02	1.1	10	0.1
	(3)	2.3	0.026	0.2	40	0.09	1.4	18	−0.2
3	(1)	0.1	0.004	0.1	−25	0.14	1.7	34	−0.7
	(2)	0.9	0.002	0.0	−19	0.03	1.2	24	−0.2
	(3)	0.8	0.082	0.2	24	0.11	2.0	41	−0.7
4	(1)	0.2	0.013	0.0	−56	0.06	1.6	27	−0.4
	(2)	0.7	0.009	0.0	−7	0.06	1.5	22	−0.4
	(3)	0.9	0.043	0.5	57	0.13	1.4	18	−0.4
5	(1)	—	0.008	0.0	−78	0.19	2.9	75	−1.3
	(2)	0.4	0.000	0.1	—	0.09	2.2	61	−1.0
	(3)	0.3	0.031	0.3	46	0.12	1.6	44	−0.4
6	(1)	0.8	0.004	0.1	−6	0.26	1.5	25	−0.4
	(2)	2.8	0.000	0.0	—	0.07	1.5	25	−0.4
	(3)	2.3	0.028	0.8	—	0.10	1.3	16	−0.3
7	(1)	0.2	0.005	0.0	−20	0.07	1.5	11	−0.2
	(2)	1.8	0.000	0.0	—	0.05	1.2	12	−0.1
	(3)	2.7	0.033	0.2	18	0.29	1.7	23	−0.3
8	(1)	0.3	0.002	0.0	−30	0.14	1.5	14	−0.4
	(2)	2.4	0.000	0.2	−22	0.09	1.2	15	−0.2
	(3)	2.8	0.028	0.2	61	0.15	1.3	15	−0.3
9	(1)	0.2	0.005	0.0	−33	0.10	1.6	34	−0.5
	(2)	0.4	0.001	0.0	−19	0.06	1.9	43	−0.6
	(3)	0.7	0.059	0.0	129	0.11	1.8	46	−0.7
10	(1)	0.6	0.000	0.0	−30	0.12	1.5	20	−0.3
	(2)	1.3	0.000	0.0	−12	0.12	1.1	15	−0.2
	(3)	2.0	0.024	—	68	0.31	1.5	31	−0.4
11	(1)	0.3	0.003	0.0	−14	0.20	1.7	38	−0.6
	(2)	1.1	0.004	0.1	−29	0.16	1.9	48	−0.9
	(3)	1.7	0.033	0.2	20	0.28	1.6	43	−0.6
12	(1)	0.3	0.008	0.1	−6	0.28	1.3	16	−0.1
	(2)	3.2	0.000	0.0	−24	0.30	1.5	25	−0.3
	(3)	3.0	0.032	0.0	−16	0.35	1.7	41	−0.6
13	(1)	0.4	0.000	0.0	−4	0.05	1.9	47	−0.7
	(2)	1.7	0.005	0.0	−30	0.06	1.8	39	−0.6
	(3)	2.0	0.006	0.1	−5	0.05	1.8	49	−0.8
14	(1)	—	0.024	0.0	−4	0.14	2.1	51	−0.8
	(2)	3.5	0.000	0.0	−33	0.17	1.6	32	−0.5
	(3)	3.4	0.016	0.2	43	0.20	1.6	37	−0.3
15	(1)	0.4	0.003	0.0	10	0.29	2.5	67	−1.0
	(2)	4.4	0.000	0.0	−28	0.09	1.6	27	−0.3
	(3)	3.6	0.014	0.1	2	0.16	1.6	41	−0.2
16	(1)	0.2	0.000	0.0	—	0.04	1.8	32	−0.5
	(2)	3.7	0.000	0.0	−13	0.01	1.0	2	0.0
	(3)	3.2	0.022	0.0	−25	0.13	1.0	3	−0.1

(continued)

TABLE 3 *(continued)*

Space number	Condition	Air change (1/h)	ΔCO_2 (%)	ΔCO (ppm)	ΔPart. ($\mu g/m^3$)	VOC (mg/m^3)	Odour intensity	Dissatisfied (%)	Freshness
17	(1)	0.8	0.013	0.0	—	0.27	1.9	36	−0.6
	(2)	0.8	0.002	0.1	3	0.06	1.4	27	−0.3
	(3)	1.8	0.021	0.0	7	0.18	1.4	28	−0.2
18	(1)	0.4	0.002	0.0	—	0.15	2.0	57	−0.8
	(2)	4.9	0.000	0.0	0	0.11	1.1	16	−0.1
	(3)	4.9	0.038	0.6	15	0.11	1.2	10	−0.1
19	(1)	1.4	0.003	0.0	8	0.10	1.7	53	−0.5
	(2)	4.5	0.000	0.0	−27	0.11	1.5	32	−0.2
	(3)	5.4	0.002	0.5	−59	0.18	1.3	29	−0.2
20	(1)	0.6	0.003	0.0	—	0.06	1.3	16	−0.2
	(2)	5.9	0.000	0.0	−9	0.10	1.2	18	−0.2
	(3)	4.3	0.007	0.0	−46	0.08	1.1	12	−0.1
Offices (1 - 15)	(1)	0.4	0.006	0.0	−21	0.15	1.8	34	−0.5
	(2)	2.0	0.002	0.0	−21	0.11	1.5	29	−0.4
	(3)	2.1	0.032	0.3	40	0.20	1.6	34	−0.5
Assembly halls (16 - 20)	(1)	0.7	0.004	0.0	8	0.14	1.7	39	−0.5
	(2)	4.0	0.000	0.0	−9	0.08	1.2	19	−0.2
	(3)	3.9	0.018	0.2	−22	0.14	1.2	16	−0.1
All spaces (1 - 20)	(1)	0.5	0.005	0.0	−19	0.15	1.8	36	−0.5
	(2)	2.5	0.001	0.0	−17	0.11	1.5	26	−0.3
	(3)	2.5	0.029	0.2	23	0.19	1.5	29	−0.4

*(1) = no mechanical ventilation and no occupants.
(2) = with mechanical ventilation and no occupants.
(3) = with mechanical ventilation and with occupants.

For quantification of the subjective ratings, the following numerical scale was used for the odour intensity in Fig. 1: (0) No odour, (1) Slight odour, (2) Moderate odour, (3) Strong odour, (4) Very strong odour, (5) Overpowering odour. The following scale was used for freshness: (+2) Very fresh, (+1) Fresh, (0) Neutral, (−1) Slightly stuffy, (−2) Stuffy.

With the general low concentrations of the pollutants, one might predict that the judges would find the air quality in the visited spaces to be good. But as seen in Table 3, where the arithmetic means of the psycho-physical measurements are listed, this is not the case. The freshness of the air was rather low, nearly always negative, i.e., on the stuffy part of the scale. Only in a few of the 60 measurements did the freshness reach the neutral point of the scale. Similarly, there were surprisingly many who found the air unacceptable. There were large differences between the spaces from 2% dissatisfied up to 75%, but most of the judgements were between 20% and 40%. The odour intensities follow the same trend (Table 3).

In most of the spaces, mechanical ventilation improved the judgement of the air quality, although it was sometimes a rather small improvement. In some cases the percentage of dissatisfied even increased when the ventilation was turned on. The unclear impact of the ventilation is underlined in Fig. 2, showing the percentage of dissatisfied as a function of the outdoor air change rate. There is a tendency towards fewer dissatisfied when the ventilation increased. But for the same air change rate there is a wide range of percent dissatisfied in the different spaces. Widely different pollution sources in the different spaces may explain this.

For the occupied spaces, Fig. 3 shows the percentage of dissatisfied judges as a function of the indoor concentration of carbon dioxide above the outdoor concentration. In these spaces the carbon dioxide produced by the occupants is obviously a poor predictor of the

ed	Freshness
	−0.6
	−0.3
	−0.2
	−0.8
	−0.1
	−0.1
	−0.5
	−0.2
	−0.2
	−0.2
	−0.2
	−0.1
	−0.5
	−0.4
	−0.5
	−0.5
	−0.2
	−0.1
	−0.5
	−0.3
	−0.4

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anical ventila- ; of the air imes a rather :ases the per- creased when The unclear underlined in of dissatisfied r change rate. ver dissatisfied . But for the wide range of ferent spaces. urces in the s. ;. 3 shows the ; as a function carbon dioxide ion. In these duced by the redictor of the

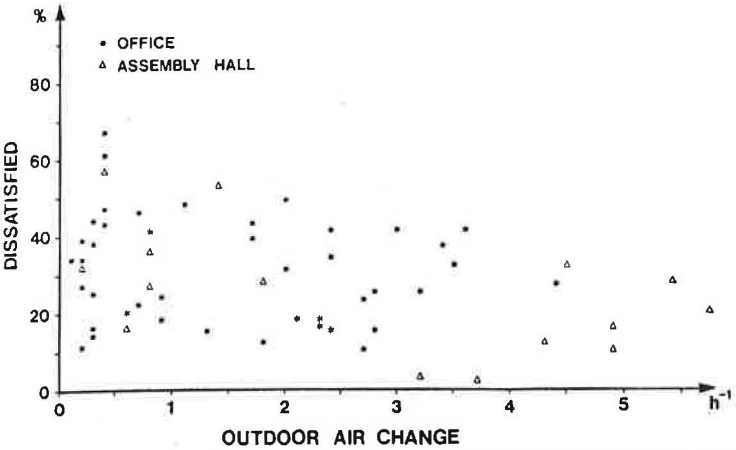

Fig. 2. Percentage of dissatisfied as a function of the outdoor air change.

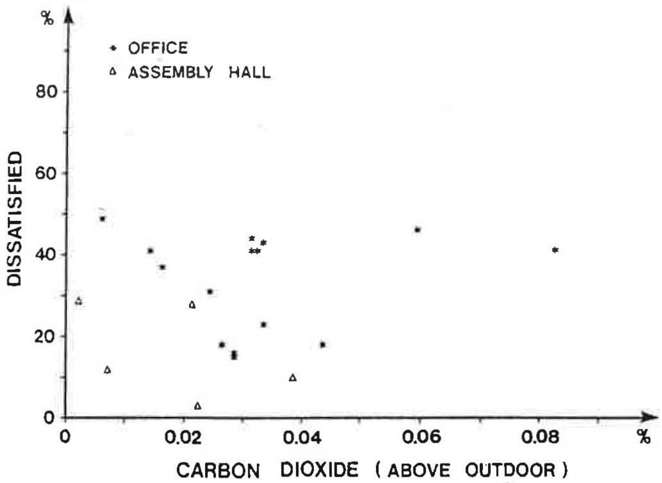

Fig. 3. Percentage of dissatisfied as a function of the carbon dioxide concentration above outdoor level (for the 20 occupied spaces).

air quality perceived by the judges. There must be other and more important pollution sources than the occupants.

The same applies to carbon monoxide. For the occupied spaces, Fig. 4 shows the percentage of dissatisfied as a function of the indoor concentration of carbon monoxide above the outdoor concentration. Carbon monoxide, which is produced by tobacco smoking, appears to have no clear impact on the dissatisfaction.

Figure 5 shows the percentage of dissatisfied as a function of the particulates in the air above the outdoor concentration. In many cases there was a smaller mass of particulates in the indoor air than outdoors, especially when the spaces were unoccupied. Still the indoor air was felt to be less fresh and less acceptable than the outdoor air. The concentration of particulates is obviously a poor predictor of perceived air quality.

This applies also to the volatile organic compounds. Figure 6 shows the percentage of dissatisfied as a function of total volatile organic compounds. The values are rather low and not clearly related to the percentage of dissatisfied judges.

Obviously none of the measured pollutants could be used to predict how the air quality was perceived by human beings. The large differences in air quality experienced by the judges must be caused by differences in the air pollution sources. Table 4 lists the pollution sources expressed by the new olf unit [3] and normalized per m^2 floor area. Figure 7 shows the definition curve for the dissatisfaction caused by one olf, when ventilated at different rates of outdoor air [3].

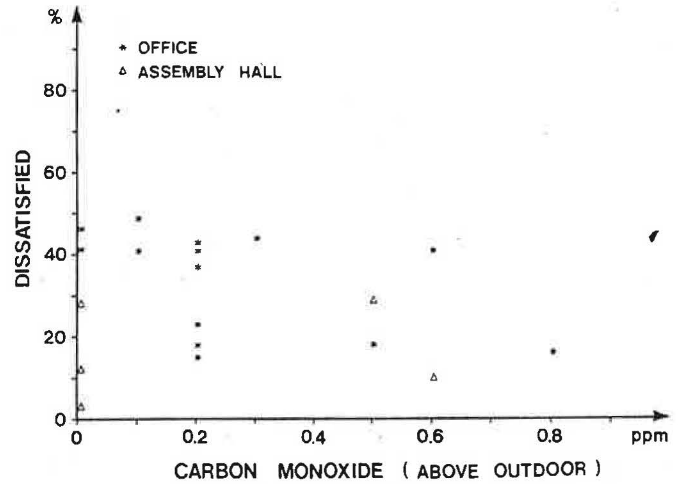

Fig. 4. Percentage of dissatisfied as a function of the carbon monoxide concentration above outdoor level (for the 20 occupied spaces).

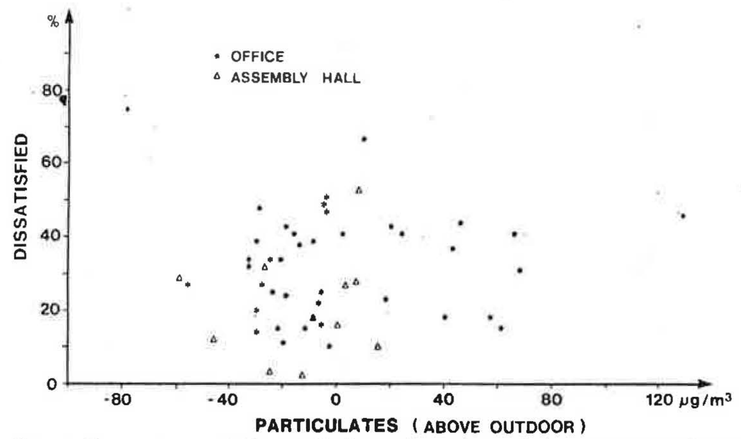

Fig. 5. Percentage of dissatisfied as a function of the concentration of particles above outdoor level.

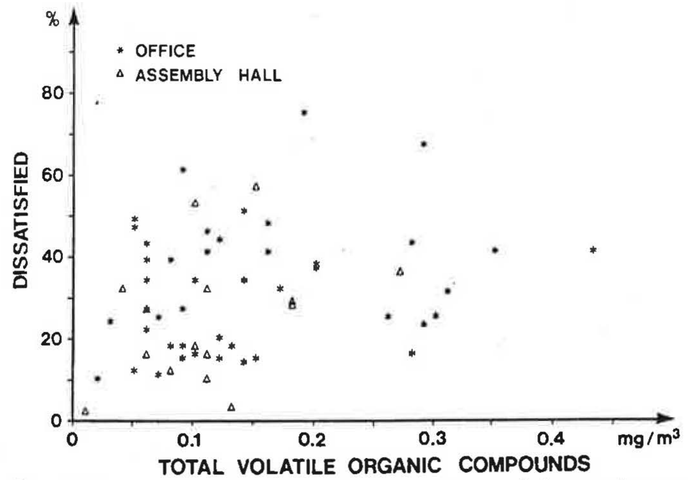

Fig. 6. Percentage of dissatisfied as a function of the total concentration of volatile organic compounds.

The calculations were made in the following way. For condition (1) with no occupants and no mechanical ventilation, the pollution sources must be situated in the space. From the measured percentage of dissatisfied judges the ventilation rate per olf (l/s olf) was determined from Fig. 7. Dividing this by the measured ventilation rate from infiltration

TABLE 4
Pollution sources in the 20 spaces

TABLE 4

Pollution sources in the 20 spaces

Space number	Floor area (m^2)	Outdoor air supply (l/s)	Pollution sources (olf/m^2 floor): Materials in space	Vent. system	Occupants	Smoking	Total: Sum	Total: Measured	Ventilation rate: l/s occup.	l/s olf	Perceived air pollution (decipol)
1	121	215	0.19	0.36	0.09	0.12	0.76	0.76	19.7	2.3	4.3
2	180	293	0.06	0.06	0.07	0.01	0.20	0.20	23.3	8.1	1.2
3	375	212	0.02	0.10	0.08	0.04	0.24	0.24	7.5	2.4	4.2
4	129	85	0.03	0.05	0.05	0.00	0.13	0.08	13.2	8.2	1.2
5	321	80	0.12	0.00	0.02	0.00	0.14	0.12	15.0	2.1	4.8
6	106	176	0.04	0.35	0.08	0.00	0.47	0.18	22.1	9.2	1.1
7	152	347	0.01	0.11	0.13	0.14	0.39	0.39	18.3	5.9	1.7
8	181	429	0.02	0.17	0.11	0.00	0.30	0.23	21.9	10.3	1.0
9	105	51	0.04	0.09	0.05	0.08	0.26	0.26	9.7	1.9	5.3
10	163	256	0.07	0.03	0.07	0.25	0.42	0.42	23.6	3.7	2.7
11	150	304	0.13	0.62	0.11	0.08	0.94	0.94	18.7	2.2	4.5
12	136	289	0.02	0.42	0.12	0.35	0.91	0.91	18.2	2.3	4.3
13	928	1933	0.23	0.46	0.03	0.52	1.24	1.24	83.3	1.7	5.9
14	143	350	0.36	0.36	0.07	0.10	0.89	0.88	36.7	2.8	3.6
15	265	954	0.45	0.50	0.08	0.51	1.54	1.54	43.2	2.3	4.3
16	200	1022	0.09	0.00	0.19	0.00	0.28	0.10	26.7	51.1	0.2
17	60	79	0.20	0.00	0.05	0.12	0.37	0.30	26.3	4.4	2.3
18	119	397	0.22	0.13	0.22	0.00	0.57	0.21	15.4	15.9	0.6
19	150	845	1.01	0.31	0.02	0.02	1.36	1.36	338	4.1	2.4
20	123	749	0.09	0.94	0.08	0.00	1.11	0.46	81.2	13.2	0.8
Mean values											
Offices (1 - 15)	230	398	0.12 (20%)	0.25 (42%)	0.08 (13%)	0.15 (25%)	0.60 (100%)	0.56	25.0	4.4	3.3
Assembly halls (16 - 20)	130	618	0.32 (43%)	0.28 (38%)	0.11 (15%)	0.03 (4%)	0.74 (100%)	0.49	97.5	17.8	1.3
All spaces (1 - 20)	205	453	0.17 (27%)	0.25 (40%)	0.09 (14%)	0.12 (19%)	0.63 (100%)	0.54	43.1	7.7	2.8

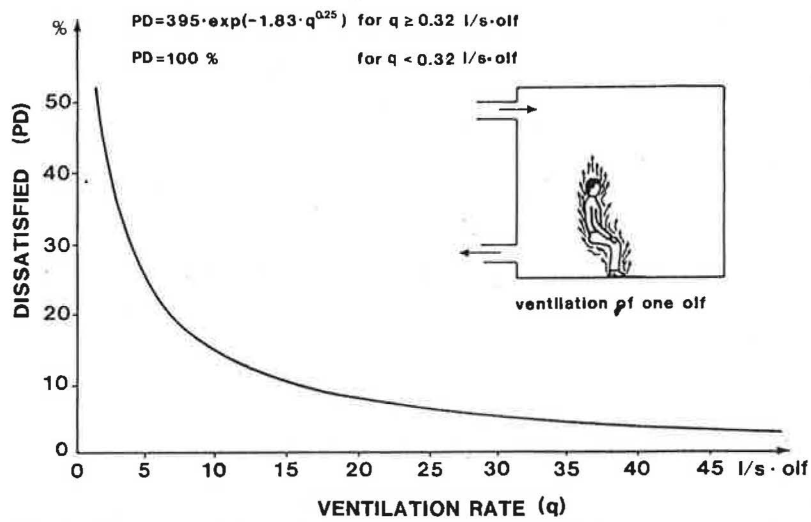

Fig. 7. The curve defines the percentage of dissatisfied persons caused by one standard person (one olf), when ventilated by unpolluted outdoor air at different ventilation rates [3].

gave the olf value from materials in the space. The olf value is the number of standard persons required to cause the same dissatisfaction as that caused by the materials in the space.

For condition (2) with no occupants but with mechanical ventilation, the pollution sources must be situated in the space + the ventilation system. The olf value for these two locations together was found from the percentage of dissatisfied judges in condition (2) and the corresponding measured ventilation rate. The pollution sources in the ventilation system were then calculated by subtracting the previously determined olf value for the space.

Condition (3) is similar to condition (2), but with the space occupied. The total olf value was determined as usual, and the olf value of the occupants and their activities was determined by subtracting the previously calculated pollution sources in the unoccupied space + the ventilation system.

Assuming a CO_2 production of 21.6 l/h per occupant for an activity of 1.2 met, the steady-state number of occupants (olfs) present could be calculated from the measured CO_2 concentration and the ventilation rate. By subtracting the bioeffluent olfs, the pollution sources from smoking and other human activities were determined.

It is obvious from Table 4 that there were large differences in pollution sources from space to space. Pollution sources in materials in the spaces varied two orders of magnitude, from 0.01 to 1.01 olf/m^2, with a mean value of 0.17 olf/m^2 for all 20 spaces. This is twice the pollution caused by the occupants. For the 15 offices there were on average 0.12 olf/m^2 caused by materials, i.e., one and a half times as much as the pollution from the occupants. But there were large differences among the 15 offices inside a range of 0.01 - 0.45 olf/m^2.

In Table 5 the mean values of pollution sources from materials are listed for the five most-dirty spaces, the five most-clean spaces, and the ten medium-clean spaces. The five spaces with the highest pollution sources from materials had an average of 0.45 olf/m^2, which is more than 20 times the average of the five most-clean spaces (0.02 olf/m^2) and more than five times the ten medium-clean spaces (0.08 olf/m^2).

The ventilation systems polluted even more than the materials in the spaces, but also with large differences from system to system. Several systems (nos. 5, 16 and 17) were virtually clean, while many systems were surprisingly dirty (up to 0.94 olf per m^2 floor area in no. 20). The average for all spaces was 0.25 olf/m^2 or three times the pollution caused by the occupants. In the ventilation system of some of the spaces (e.g., nos. 11, 12 and 20) the pollution sources were so severe that the air quality in the spaces was better without mechanical ventilation, i.e., at the much lower ventilation rate caused by air infiltration. Table 5 shows that the five most-polluted ventilation systems had an average of

TABLE 5

Mean values of pollution sources (olf/m² floor) in different categories of the investigated spaces

Pollution source	5 spaces with highest pollution source	10 spaces with medium pollution source	5 spaces with lowest pollution source
In materials in the space	0.45	0.08	0.02
In ventilation systems	0.59	0.20	0.02
Total (incl. smoking and occupants)	1.24	0.54	0.19

0.59 olf/m^2 or 30 times more than the 0.02 olf/m^2 for the five cleanest systems and three times more than the 0.20 olf/m^2 for the ten medium-clean systems.

Table 5 lists also the average of the five spaces with the highest total pollution load. They had a total load of 1.24 olf/m^2 and were nearly seven times higher than the five spaces with the lowest total pollution sources (0.19 olf/m^2), and more than double the ten spaces with the medium total pollution load (0.54 olf/m^2).

DISCUSSION

The present study quantifies for the first time the pollution sources contributing to the perception of stale, stuffy and unacceptable air occurring in many buildings. A surprising result is the magnitude of the pollution sources found in many of the investigated spaces and their corresponding ventilation systems.

Summarizing the 15 offices that were investigated, materials in the spaces produced 20% of the perceived air pollution, 42% was caused by the ventilation system, 25% by smoking, and only 13% by the occupants. For each occupant this means that there were 6 - 7 olfs ('stowaways') polluting the air in the space; 1 - 2 olfs were situated in the materials in the space, 3 olfs in the ventilation system, and 2 olfs were caused by tobacco smoking.

These results are in contrast to ventilation standards throughout the world, which assume that human beings are the principal or exclusive polluters in offices and similar spaces. It is implicitly assumed that spaces and ventilation systems are clean and do not contribute to the air pollution. Required ventilation has therefore normally been specified as outdoor air supply per occupant. The present study shows that there are other, and more important, pollution sources in the real world.

The air supply to the 15 offices was on average 25 l/s per occupant or 2 l/s per m^2 floor area. This is far above existing ventilation standards. From an engineering or hygienic point of view one would consider these spaces to be overventilated, yet 34% judged the air to be unacceptable. The reason is the heavy pollution sources that make the ventilation rate only 4 l/s per olf.

The pollution caused by materials in the space shows large differences between the investigated rooms as shown in Tables 4 and 5. In the five most polluted spaces the materials in the space contributed on average 0.45 olf per m^2 floor area (Table 5) and in one space a value as high as 1 olf per m^2 floor area was observed. Materials were obviously a heavy burden on the air quality and the ventilation requirement in those spaces. We do not know the type of materials in each space that caused the pollution. It may have originated from building materials, carpets, furniture, office machines, books, paper, etc.

Although many of the investigated spaces had a heavy load from materials, there were also spaces that were quite clean (Table 4). This may stimulate some optimism concerning the potential for redecoration of spaces, and for designing new and clean buildings. It *is* obviously possible to select materials for spaces that contribute little or nothing to the air pollution of that space.

To decrease pollution in spaces there is an urgent need to establish tables on olf values of common materials, so that architects and related professionals can select low-polluting materials in future buildings and for redecoration of existing spaces. Systematic studies to measure olf values of materials can be performed in the laboratory or in the field as described in ref. 3. In the future it would be essential that producers of building materials, furnishings, etc., quantify the olf value of their products.

It would also be essential to study how cleaning methods influence the olf values of materials in spaces. Cleaning is one of the most expensive operations in many buildings, but is normally designed to maintain simply an acceptable visual environment. Development of cleaning methods to maintain low olf values in spaces should be encouraged.

Even more serious than the materials in the spaces were the pollution sources identified in the ventilation systems. The five most-dirty systems polluted on average 0.59 olf/m^2 floor area (Table 5). The supply air had an average perceived air pollution of 4.0 decipol* corresponding to 40% dissatisfied. This means that the supply air had a quality as if the air had first passed an identical adjacent room occupied by 0.59 persons per m^2 floor area. In some of the systems the supply air was so polluted that the operation of the mechanical ventilation decreased the quality of the room air. For those cases, the quality of the air in the space was better, when the space was ventilated by a small flow of outdoor air through infiltration, than by the much higher flow of air, polluted by the ventilation system. Such heavily polluted ventilation systems may explain why naturally ventilated buildings in some previous field studies were found to provide better air quality than mechanically ventilated buildings [7 - 9].

The state of many of the ventilation systems was alarming. It has always been implicitly assumed that the outdoor air could pass through a ventilation system without deterioration. If anything, the quality should be improved by proper filtering of particulates. It has often been recommended that ventilation systems be properly maintained and cleaned, but without any quantification of the benefits. The present study quantifies for the first time the pollution sources in the systems and this emphasizes how important it is to maintain clean systems. Some of the present systems were fortunately clean, demonstrating that it *is* possible to avoid pollution sources in the ventilation systems. We do not know the exact origin of the pollution in the dirty systems. It may come from filters, dirty heating or cooling coils, sound attenuators, or ducts. There is a suspicion that the humidifiers used in some of the investigated systems (space nos. 1, 6, 9, 11, 13) may have contributed to the pollution. Further detailed studies on pollution sources in different components of ventilation systems are urgently needed to set up rigid specifications for maintenance and cleaning procedures required to keep pollution sources in ventilation systems at an acceptably low level. It is likely that the traditional design of components and systems should be changed to allow proper cleaning and maintenance. Development of efficient and economic methods for cleaning of existing and future systems are also essential.

There was indeed a poor correlation between the perception of air quality of our subjects and the concentration of the measured pollutants: carbon dioxide, carbon monoxide, particulates and total volatile organic compounds (Figs. 3 - 6). None of these pollutants, nor the air change, could be used to predict human perception of air quality in the present spaces. The human senses (olfactory and chemical) are obviously superior to chemical analysis. In the indoor air at low concentrations there are thousands of organic compounds that are difficult to measure, but these compounds contribute to making the air stuffy, stale and unacceptable. It is the advantage of the new olf unit that it integrates the impact of all these compounds in the same way as humans do. But it should be remembered that the olf unit does not provide information on any possible health risk. Any such effect should be considered separately. The low concentrations of the measured compounds indicate, however, that the health risk in the 20 spaces of the present study was small.

A systematic removal or reduction of pollution sources is the obvious way to improve conditions. It will at the same time improve air quality, decrease required ventilation and energy consumption, and diminish the risk of draught. Removal of unnecessary pollution sources may be the most rewarding energy-conserving action to take in the future.

*One decipol is the pollution caused by one standard person (one olf) ventilated by 10 l/s of unpolluted air [3].

CONCLUSIONS

Severe air pollution sources were quantified by the new olf unit in 20 randomly selected offices and assembly halls in Copenhagen, with large differences from building to building. For each occupant in the 15 offices there were on average 6 - 7 olfs from other pollution sources; 1 - 2 olfs were situated in the materials in the space, 3 olfs in the ventilation system, and 2 olfs were caused by tobacco smoking. This is in contrast to ventilation standards all over the world which implicitly assume that pollution in offices and similar spaces comes from the occupants.

In the offices the average ventilation rate of 25 l/s per occupant was much higher than ventilation standards prescribe. Nevertheless, due to the extensive pollution sources, the ventilation rate was only 4 l/s per olf. This explains why an average of more than 30% of the subjects found the air quality unacceptable.

The obvious way to improve indoor air quality is to remove pollution sources in the spaces and in the ventilation systems. This will at the same time improve air quality, decrease required ventilation and energy consumption, and diminish the risk of draughts.

No correlation could be established between perceived quality of the air and measured concentrations of carbon dioxide, carbon monoxide, particulates, or total volatile organic compounds.

Tables of olf values of building materials, furniture, carpets, etc., should be established, so that architects and others in the future can select low-polluting materials when designing buildings and spaces.

The pollution sources in the ventilation systems explain why natural ventilation sometimes provides better air quality than mechanical ventilation. The location of pollution sources in ventilation systems should be studied and quantified. Detailed recommendations for cleaning and maintaining components and systems should be established.

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