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Effect of Renovating an Office Building on Occupants' Comfort and Health

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Abstract An intervention study was performed in a mechanically ventilated office building in which there were severe indoor climate complaints among the occupants. In one part of the building a new heating and ventilation strategy was implemented by renovating the HVAC system, and a carpet was replaced with a low-emitting vinyl floor material; the other part of the building was kept unchanged, serving as a control. A comprehensive indoor climate investigation was performed before and after the intervention. Over a 2-week period, the occupants completed a daily questionnaire regarding their comfort and health. Physiological examinations of eyes, nose and lungs were performed on each occupant. Physical, chemical and sensory measurements were performed before and after the intervention. The renewal of the flooring material was performed after a sensory test of alternative solutions in the laboratory. Before the floor material was installed in the office building, a full-scale exposure experiment was performed in the laboratory. The new ventilation strategy and renovation of the HVAC system were selected on the basis of laboratory experiments on a full-scale mock-up of a cellular office. The severity of occupants' environmental perceptions and symptoms was significantly reduced by the intervention.

Key words Renovation; Intervention; Sick building syndrome; Indoor air quality; Comfort and health; Ventilation; Emission.

Practical Implications
Reducing the sensory pollution load on the indoor air by increasing ventilation effectiveness and by replacing high-polluting materials with low-polluting materials may reduce occupants' severity of environmental perceptions and symptoms.

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Introduction

The present study is the third and final part of the 5-year research program entitled "Healthy Buildings". In the first part of the program, the research focused on emission rates of indoor air pollution sources. Methods to characterize the emissions from materials in sensory and chemical terms in small-scale test chambers has been elaborated, and the impact of environmental parameters such as air velocity, age of pollutant, temperature and humidity has been studied in details (Fang et al., 1998, 1999; Knudsen et al., 1996, 1997, 1999; Wolkoff, 1998). The test protocol for the sensory charcterization of emissions was almost identical to the protocol used in the European Database on Indoor Air Pollution Sources in Buildings (Clausen et al., 1996). A procedure for evaluating the toxicological effect of emitted chemicals from building materials has been proposed by Nielsen et al. (1997).

The results of part one of the program showed that for some materials temperature and humidity may have an effect on both chemical and sensory emissions, that should be taken into account when comparing emission data from different laboratories (Fang et al. 1998, 1999; Wolkoff, 1998). However, for most materials the effect is secondary as long as the materials are ventilated constantly for a period of 3 weeks or more (Fang et al., 1999; Wolkoff, 1998). Fang have shown that the direct effect of temperature and humidity on the sensory perception may be significant (Fang et al., 1998). The air quality was perceived less acceptable with increasing temperature and humidity. This finding may have an impact on the ventilation requirements in

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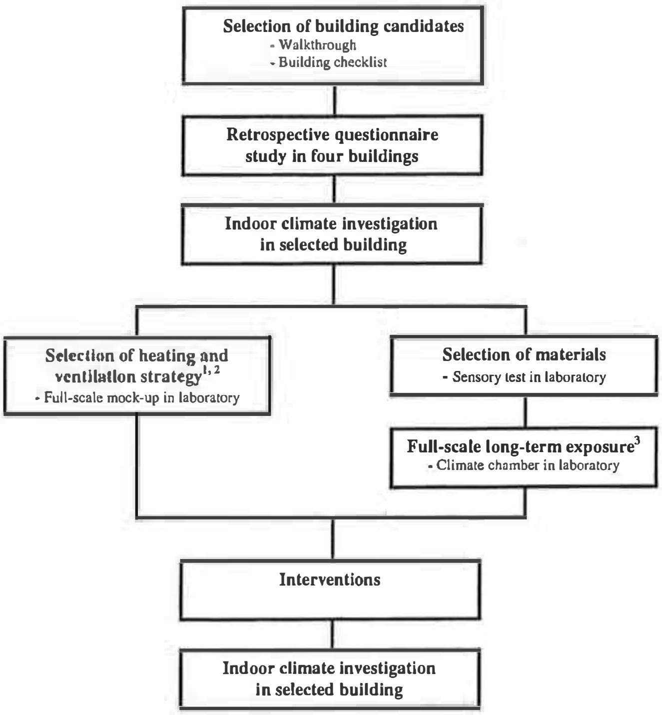
buildings and on the philosophy behind ventilation in the future (Fanger, 1998).

In the second part of the Healthy Buildings research programme, the transport process of the emitted pollutants from the source to personal exposure was studied. The local airflow around persons in ventilated spaces has been studied in detail and it has been verified that the presence of persons in a room has a strong influence on the concentration field in a room (Brohus, 1997). Brohus and Nielsen (1996) have suggested a personal exposure index, describing a person's exposure to specific contaminant sources in a room. Although the flow in a room is fully mixed on the macro level, persons may be exposed to high concentrations of local pollution sources, thus creating a low personal exposure index.

The aim of the research in part one and part two of the program was to reduce exposure to indoor air pollution sources either by source control or by more effective ventilation. In the third part, focus was on how indoor air pollution affects humans and how the results of parts one and two could be used to turn a problem building into a building with a healthier and more comfortable indoor environment. The aim of the present study was to investigate whether human comfort and health are improved by reduced exposure to indoor air pollution.



[1]Brohus et al, 1998
[2]Hyldgaard and Brohus, 1997
[3]Kjærgaard et al., 1999

Fig. 1 Structure of the Healthy Buildings 1993–1997, Part 3: The effect of indoor air quality on occupants' comfort and health

Material and Methods

Experimental Plan

An intervention study was performed in a mechanically ventilated office building in which there were severe indoor climate complaints among the occupants. The building was selected among four building candidates based on a retrospective questionnaire and a walkthrough in the buildings. In one part of the selected building a new heating and ventilation strategy was implemented by renovating the HVAC system, and a carpet floor material was replaced with a low-emitting vinyl floor; the other part of the building was kept unchanged, serving as a control. A comprehensive indoor climate investigation was performed before the intervention. The occupants completed two questionnaires regarding their comfort and health: a retrospective questionnaire looking back at the last 2 months and a daily questionnaire over a 2-week period. Physiological examinations of eyes, nose and lungs were performed on each occupant. The physical measurements in selected spaces comprised the following: detailed studies of the airflow pattern, measurements of ventilation effectiveness, air change rate, thermal parameters, static electricity, noise, illumination level and amount of dust in air and on surfaces. The chemical measurements comprised measurements of volatile organic compounds (VOCs) in the room air, determination of the emission of VOCs from the surfaces of the materials, and continuous measurements of carbon monoxide (CO) and carbon dioxide (CO_2). Thirty subjects assessed the perceived air quality when entering the spaces.

The renewal of the flooring material was performed after a sensory test of alternative solutions in the laboratory. Before the floor material was installed in the office building, a full-scale exposure experiment was performed in the laboratory. Subjects were exposed for six hours to the new floor covering and the floor covering from the office building, respectively. The subjects' assessment of symptoms and complaints during the exposure were registered by means of a questionnaire. Physiological examinations of eyes, nose and lungs on each occupant were performed immediately before and after the exposure.

The new ventilation strategy and renovation of the HVAC system were selected on the basis of laboratory experiments on a full-scale mock-up of a cellular office. The airflow pattern in the full-scale mock-up was re-created based on the detailed measurement of the ventilation and airflow measurement in the field. Several inlet devices and different ventilation strategies were tested and compared with the original.

To study the effect of the intervention on occupants' comfort and health, the indoor climate investigation in the office building was repeated six months after the intervention was implemented. The experimental design of the study and related sub-studies are shown in Figure 1.

Facilities

The experimental building was a three-storey town hall building from 1970 with approximately 100 employees. The building was made of bricks and had a flat roof construction. The inner surface of the outer walls was composed of painted concrete, while the partition walls were made either of gypsum with painted glass fibre or gypsum covered with vinyl. The ceiling in the building was a metal roof with acoustic damper of mineral wool above the ceiling. The majority of the employees were located on two almost identical floors. On each floor approximately 30 persons occupied an open-plan office while the remaining 20 were in cellular offices. The floor of the open-plan offices was covered with linoleum while the floor in the cellular offices was covered with carpet. All employees had their own PC or workstation and printers were placed in the offices. Small photocopiers were placed in the open-plan offices while a larger photocopier was placed in a separate room on the first floor.

The HVAC system was a dual-duct constant-air-volume system providing both the heating and the outdoor air supply to the spaces. A thermostat located in each room controlled the supply air temperature, which was allowed to vary from approximately 15°C to 37°C. At each inlet device, located on every second windowsill, a mixing box ensured that the required temperature of the airflow was delivered to the space. The air was exhausted through the light fittings mounted in the ceiling. Approximately 50% of the return air was recirculated. The same ventilation system served the entire building, but the ductwork was divided into four zones with two zones covering each floor.

The offices on the first floor were selected as the intervention area while the offices on the second floor were selected for the control measurements. On each floor measurements were performed in the open-plan offices and in four selected cellular offices. The offices were selected so that the intervention and control offices were similar in terms of size and orientation. One cellular office on each floor was selected for comprehensive physical, chemical and ventilation and airflow measurements.

Measurements

The retrospective questionnaire study in the four pre-selected office buildings were made in the beginning of February 1996 and repeated in the selected building at the end of January 1997. The daily questionnaire study, the physiological measurements and the indoor climate measurements were performed during 2 weeks in March/April 1996 and repeated mid-March 1997, 6 months after the renovation.

Physical measurements

In the two main measuring offices the air temperature, relative humidity and air velocity 1.1 m above the floor were measured continuously for 1 week using Brüel and Kjær Indoor climate analyser 1213. The A-weighted and C-weighted sound pressure level in the ten offices selected was measured using Brüel and Kjær 2213.

Measurement of maximum and minimum illuminance and evaluation of glare from ceiling lighting was made at nine selected workplaces in both the intervention and the control area. The measurements were made without daylight and with ceiling lighting on and, if any, also with adjustable local lamps in operation. The measurement of maximum and minimum illuminance was made by a Gossen luxmeter. The glare was evaluated through a number of measurements of luminance using a luminance meter (Hagner LS1–60). The lighting below an angle of 45° as well as above the workplace was taking into consideration. The glare index was not calculated, but changes from conditions before and after the intervention could be evaluated. Reflections on the video display units (VDUs) from daylight and from ceiling lighting at approximately 80 workplaces were evaluated visually. Reflections on laminated plastic desk pads were also evaluated visually.

The concentration of airborne dust was measured by filtration technique in the open-plan offices and the two main measuring offices. The amount of dust on the floor was measured using a modified HVS-3 vacuum cleaner, developed by Cascade Stack Sampling Systems (Oregon). The dust was collected with a special nozzle, using pressure and volume control. The dust was collected by a cyclone which allowed only 0.2% of the dust particles to pass the cyclone (Gyntelberg et al., 1994). More than 75 m^2 floor area was vacuum-cleaned in both the control and the intervention areas.

The static electricity load on persons walking on the floors was measured by a Keithly electrometer connected through a cable to a handprobe that was held by walking persons for about 1 min.

Chemical measurements

VOCs were sampled in the ten selected offices. Duplicate samples were taken on Perkin-Elmer Tenax TA steel tubes. The sample tubes were placed in the centre of a writing desk or on top of a bookshelf. A low flow-sampling pump (Alpha 1, AMETEK) was used. The sampling airflow was 45 ml/min (Alpha-1 pumps, AMETEK) and controlled prior to and after each sampling. The difference was less than 3%. The tubes were thermally desorbed and analysed by gas chromatography and a FID detector. Details concerning the qualitative and quantitative analyses are described elsewhere (Wolkoff, 1998). The sum of VOCs was calculated based on a five-point calibration curve for decane.

Emission from surfaces on-site was measured using an emission cell (Wolkoff, 1996). The FLEC was placed on the material surface (carpet, linoleum, and wall). A special device was used for the carpet to minimize the leakage through the cell perimeter. The air was supplied from a sampling pump (Alpha 1, AMETEK) coupled to the FLEC inlet. The air was cleaned by passing it through an activated charcoal sorbent tube in conjunction with a Tenax TA steel tube (Perkin Elmer). The air was not adjusted for relative humidity. The airflow through the FLEC was adjusted to 200 ml/min. The sampling tubes were attached to the FLEC outlets (Wolkoff et al., 1991). The sampling airflow was 45 ml/min (Alpha-1 pumps, AMETEK) (see above). Duplicate air sampling was carried out 20 min after the start. In the laboratory, the samples were taken 24 h after FLEC start. The sampling volume was 2.2±0.1 l. The sampling tubes were analysed as described above.

Continuous measurements of CO and CO_2 were performed in the main offices and the open-plan offices using the Brüel & Kjær Multigas Monitor 1302 together with Doser and Sampler 1303. The air was sampled in the return air outlet.

Ventilation and airflow measurements

In order to investigate the ventilation performance and room air distribution, tracer gas measurements combined

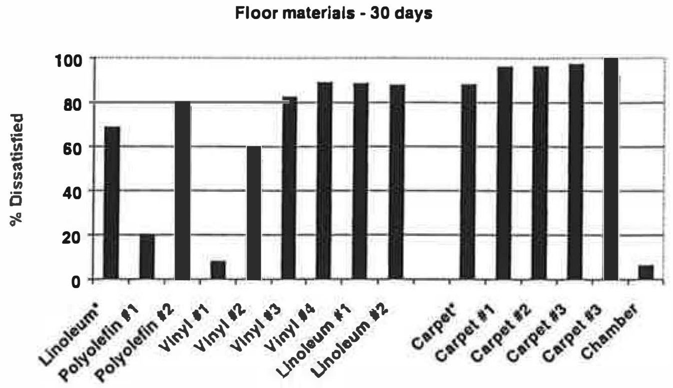


Fig. 2 Percentage of dissatisfied subjects assessing samples of floor materials which have been conditioned for 30 days. *Original materials from the town hall

with temperature and velocity measurements were performed in the two main measuring offices. Surface temperatures and air temperatures were measured with thermocouples, type K (uncertainty±0.2°C). Velocity measurements were performed by means of temperature-compensated anemometers (uncertainty ±0.02 m/s). Tracer gas measurements were made at 6 different locations with a sampling interval of approximately 1 min (uncertainty±2%) using a Brüel and Kjær Monitor 1302 and Doser and Sampler 1303. N_2O and SF_6 were used as tracer gases. The tracer gas measurements were used in order to determine the air change rate and the ventilation effectiveness (Brohus and Hyldgaard, 1998). The concentration distribution and the ventilation effectiveness were investigated for two different locations of a contaminant source. The contaminant source was simulated by nitrous oxide supplied through a porous foam rubber ball, ø 0.1 m. The air change rate in the cellular offices was found by means of the tracer decay method (Sutcliffe, 1990), while the air exchange rate in the open-plan offices was found by the constant dose method (Sutcliffe, 1990). Smoke visualization was used to gain an overview of the flow patterns in both the cellular and open-plan offices.

Sensory measurements

Sensory measurements were performed in the ten selected spaces. A panel of 30 subjects assessed the perceived air quality on a continuous acceptability scale immediately upon entering the space (Gunnarsen and Fanger, 1992). The assessments were performed in the ten measuring offices both when occupied and when unoccupied. The perceived air quality of the supply air was assessed by the subjects through exposure equipment connected to the inlet devices.

Questionnaire

The retrospective and daily questionnaires comprised questions on environmental perceptions and symptoms. The questions on environmental perceptions concerned the thermal environment, indoor air quality, noise and light. The symptoms concerned sensory irritation in eye, nose and throat, skin irritation, neurotoxic symptoms and asthma-like symptoms. In the retrospective questionnaire the frequency of perception and symptoms were reported using category-scaling technique, looking back over the past two months. The daily questionnaire monitored the severity of the perceptions and symptoms at the end of a working day, using visual-analogue scaling technique (VAS) (Mølhave et al., 1986; Wyon, 1994).

Physiological measurements

Objective assessment of effects included acoustic rhinometry (Hilberg et al., 1989) for measurement of changes in the thickness of the nasal mucosa. Measurements of tear film stability using a slitlamp and installation of 10 µl of a vital dye (Fluorescein, 1%) were made to evaluate possible destabilization of the corneal tear film (Kjærgaard, 1990). Conjunctival epithelium damage was measured using installation of 10 µl of 1% Lissamine green B in the conjunctival sack. The number of stained cells was then scored by slitlamp microscopy (Kjærgaard, 1992). Foam bubbles in

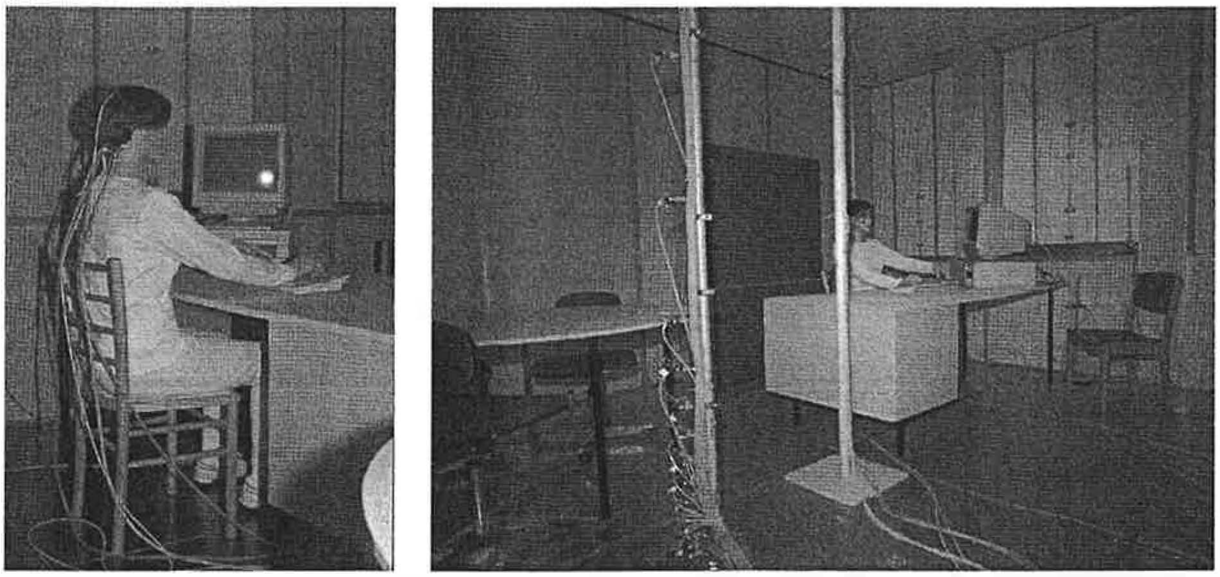


Fig. 3 Mock-up of a typical cellular office. A person was simulated by means of the breathing thermal manikin (Brohus, 1997)

the eye canthus were measured as an indicator of tear film effects (Kjærgaard, 1992). Finally, the eye sensitivity changes were measured using a CO_2-provocation test (Kjærgaard, 1990, 1992). Peak flow was monitored during one day of work using calibrated Wright peak flowmeters.

Selection of Materials

Small-scale sensory emission testing

Laboratory tests were made to investigate whether refurbishing the floor covering and the ceiling could reduce the pollution load from materials in the office building. Samples of the aluminium ceiling and the floor covering materials of carpet and linoleum were removed from the building. Alternative low-polluting materials on the market were investigated and 12 floor materials and 4 ceiling materials were selected for the final sensory test. Samples of the materials were tested after pre-exposure in 200-L glass chambers for 30 days. A sensory panel of 40 subjects assessed the perceived air quality of the air samples from the test chambers, using the continuous acceptability scale.

The sensory test, showed that the original ceiling caused 20% dissatisfied subjects and none of the alternative ceiling materials had a lower sensory pollution load than the original. The test of the floor materials, however, showed that the linoleum and the carpet from the town hall caused 70% and 90% dissatisfied subjects, respectively (Figure 2). None of the tested carpets, which all previously had been tested according to the Danish Indoor Climate Labelling system (Wolkoff and Nielsen, 1996), were acceptable alternatives to the original carpet. Even though the floor material polyolefin #1 caused more dissatisfied subjects than the vinyl #1, it was recommended by the research group in preference to the vinyl due to the environmental issue. However, the building owner rejected the polyolefin for aesthetic reasons. Therefore the carpet in the cellular offices of the intervention area was replaced by vinyl #1. Furthermore, the building owner did not want to change the linoleum in the open-plan office.

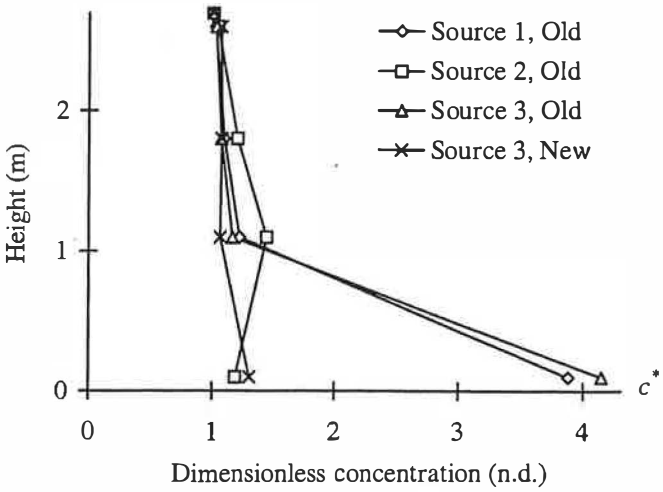


Fig. 4 Dimensionless vertical concentration profiles, c*, measured in the laboratory for the three different contaminant sources for the original ventilation strategy and for Source 3 (tracer gas supplied through the perforated plastic film) for the new ventilation strategy. $c^*=c/c_R$ where c_R is the return concentration measured in the exhaust air

Full-scale exposure experiment

Before installing the floor material in the office building, a full-scale exposure experiment was carried out in a climate chamber (Kjærgaard et al., 1999). A group of 20 subjects was exposed for six hours to each of the conditions: empty test chamber, linoleum from the town hall, carpet from the town hall, and the new vinyl flooring. The subjects' environmental perceptions and symptoms were generally not significantly different for the four exposures. The level of symptoms was very modest and no significant change was seen throughout the 6-h exposure time. The physiological measurements showed that only nasal volume (indicator of mucosal swelling and inflammation) and tear film stability (break-up time) were altered by exposure to the materials. Tear film stability was clearly reduced by exposure to linoleum, and nasal volume was reduced after exposure to carpet.

Selection of Heating and Ventilation Strategy

In order to improve the ventilation effectiveness in the office building, a new heating and ventilation strategy was selected. Two different approaches were applied, depending on the office size.

Cellular offices

The selection of a new heating and ventilation strategy was based on the results of the field experiments in the office building when using the original heating and ventilation strategy. A full-scale mock-up simulating a typical office in the building was built in the laboratory (see Figure 3). It was equipped with furniture with a geometry and location similar to the furniture of the real office. In order to control the surface temperature, the windows in the mock-up consisted of flat radiators supplied with chilled water. The mock-up was used to identify the most effective heating and ventilation strategy for the cellular offices in the building. Different inlet devices were modified and tested, together with appropriate combinations of air change rate and supply air temperature for simulated summer and winter conditions. The choice of air change rate, supply air temperature, and control strategy was made after examining the results of the thermal building simulation programme and the laboratory experiments (Hyldgaard and Brohus, 1997).

The personal exposure to three contaminant sources was assessed by means of a breathing thermal manikin in the laboratory experiments. The contaminant sources were simulated in the laboratory by means of tracer gas injection. The original heating and ventilation strategy

Table 1 Personal exposure index, ε_e, measured by means of the breathing thermal manikin in the laboratory measurements. The corresponding dimensionless concentration distributions are found in figure 4. $\varepsilon_e=c_R/c_e$ where c_R is the return concentration and c_e is the concentration of inhaled contaminant, i.e. the personal exposure (Brohus and Nielsen 1996)

Ventilation strategy	Contaminant source	ε_e
Original	1	0.53
	2	0.76
	3	0.42
New	3	0.85

was reproduced in the laboratory, based on measurement of the two contaminant sources in the field. Tracer gas supplied through a foam rubber ball located on the floor (Source 1) and a foam rubber ball located on the top of a bookcase (Source 2) simulated the contaminant sources. A third contaminant source (Source 3), representing the source of the floor covering material, was simulated by supplying tracer gas through a perforated and branched plastic tube located below a perforated plastic film covering the entire mock-up floor (Brohus and Hyldgaard, 1998). The original and the new heating and ventilation strategies were compared by means of the source representing the floor covering material (Source 3). This source was found to be the most critical regarding personal exposure and ventilation effectiveness. The dimensionless vertical concentration profiles for the two ventilation strategies are shown in Figure 4. The corresponding personal exposure index is shown in Table 1.

Measurements and smoke visualization, when the original heating and ventilation strategy was applied, showed two characteristic flow patterns for winter conditions and summer conditions respectively (see Figure 5). For a substantial heating demand such as the situation during the field study, the supply air had an excess temperature of approximately 15°C and it was not possible for the supply air jet to flush the room. Instead, a warm air layer was created in the upper part of the room. Due to the cold windows, substantial down draught was created along the windows without an inlet device. This flow pattern would cause considerable thermal discomfort. However, the down draught managed to create some mixing in the room when it transported some of the warm (unpolluted) air in the upper part of the room to the lower part of the room.

For a cooling demand, it was found that the subcooled supply air jet would leave the ceiling and drop down. This would cause serious draught problems for persons located in the centre of the room.

In the new heating and ventilation strategy, the heating and the ventilation systems were separated. Heat was supplied by new heating panels equipped with thermostats, mounted below each of the windows. The ventilation system was thus mainly used for the air supply. The inlet temperature was kept constant at 20°C. Another important change was a new inlet device with a better ability to create a recirculating flow in order to obtain a higher ventilation effectiveness aiming at a personal exposure index close to 1.

Open-plan office

For the open-plan office, the heating and ventilation systems were separated as in the cellular offices. However, another approach was used in the selection of an appropriate combination of air change rate, supply air temperature, and choice of a new and more efficient inlet device. Here, a thermal building simulation programme was used together with Computational Fluid Dynamics (CFD). In CFD the mathematical equations governing the fluid flow and the contaminant transport are solved numerically (see Figure 6) (Brohus, 1997). In the present work CFD, was used to estimate the temperature and the speed levels in the occupied zone, and to indicate whether it was possible

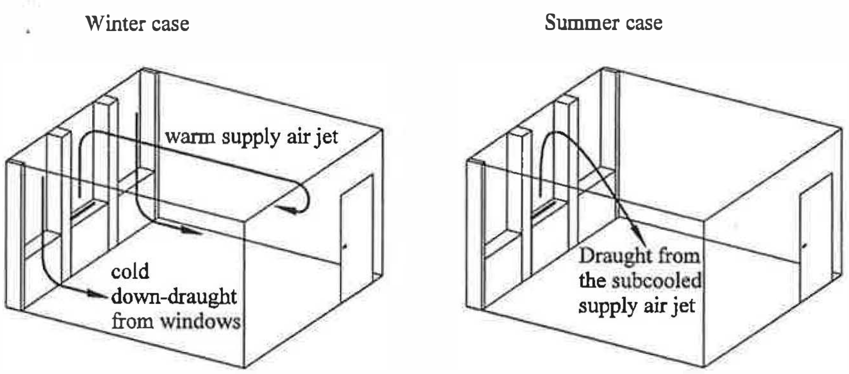


Fig. 5 Sketch of flow patterns found in the office when applying the original ventilation strategy

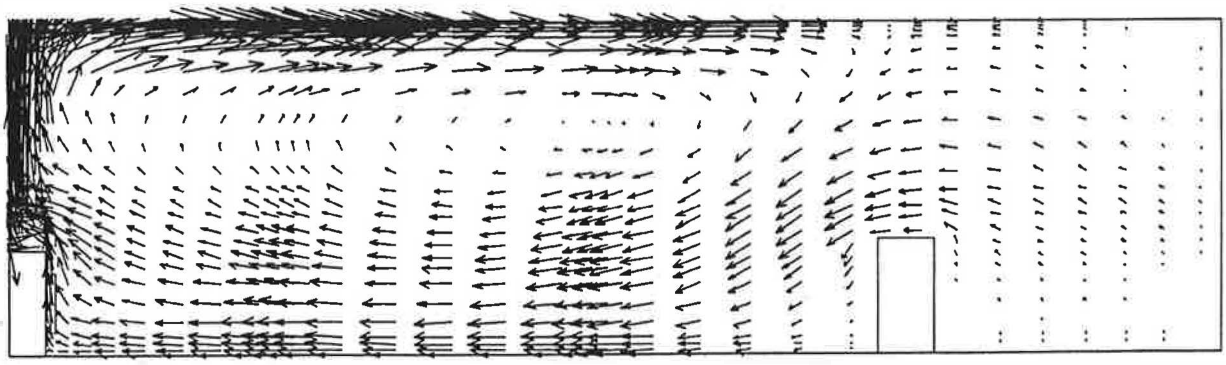


Fig. 6 Example of a numerical simulation of the flow field in a vertical section of the open-plan office, calculated by means of Computational Fluid Dynamics

for the supply air jets to flush the room and obtain a sufficiently high ventilation effectiveness. The latter was obtained by means of computer simulation of contaminant emission from the floor.

Laboratory measurements were performed on the flow field along the ceiling, generated by the supply air jet from the new inlet device. Measured velocity profiles below the ceiling were compared with the corresponding simulated velocity profiles. It was thus possible to calibrate and verify the numerical solution.

Intervention

The renovation of the ventilation system also included changing the filters and running the system with 100% outdoor air, which affected offices in both the control and the intervention area. The intervention was carried out between August and September 1996. However, the town hall administration decided also to install new lighting and a computer network in the intervention area so that the employees would only be disturbed once. This work did not follow the original time schedule and the last part was finished one week before the indoor climate investigation. Consequently the retrospective questionnaire study in January 1997 was performed in a period when some renovation work took place.

Results

Physical Measurements

The temperature and humidity variation during a typical working day in the main measuring offices is shown in Figure 7. After installation of the new heating system, the temperature in the invention area became more constant. However, the humidity in both the intervention and control offices was sligthly higher before the intervention than after.

The mean A-weighted and C-weighted sound pressure level, the amount of dust on floor and the static electricity load in the selected cellular and open-plan offices is shown in Table 2. Generally the sound pressure was lower after the intervention, the changes being most marked in the intervention offices. The changes in the A-weighted sound pressure level were greater than for the C-weighted, indicating that the high-frequency noise from the inlets had been reduced. The amount of dust on the floor when the floor material was linoleum was low in all situations (Table 2). In the intervention offices where carpet was replaced with vinyl flooring, the amount of dust was significantly reduced after the intervention compared to the control offices. However, the measured values from the carpet were much higher than the average amount of dust found for Danish offices with carpet (Gyntelberg et al., 1994). The amount of dust in the air both before and after the intervention was below the detection limit.

The measurement of static electricity showed that altering the carpet to vinyl reduced the load on persons

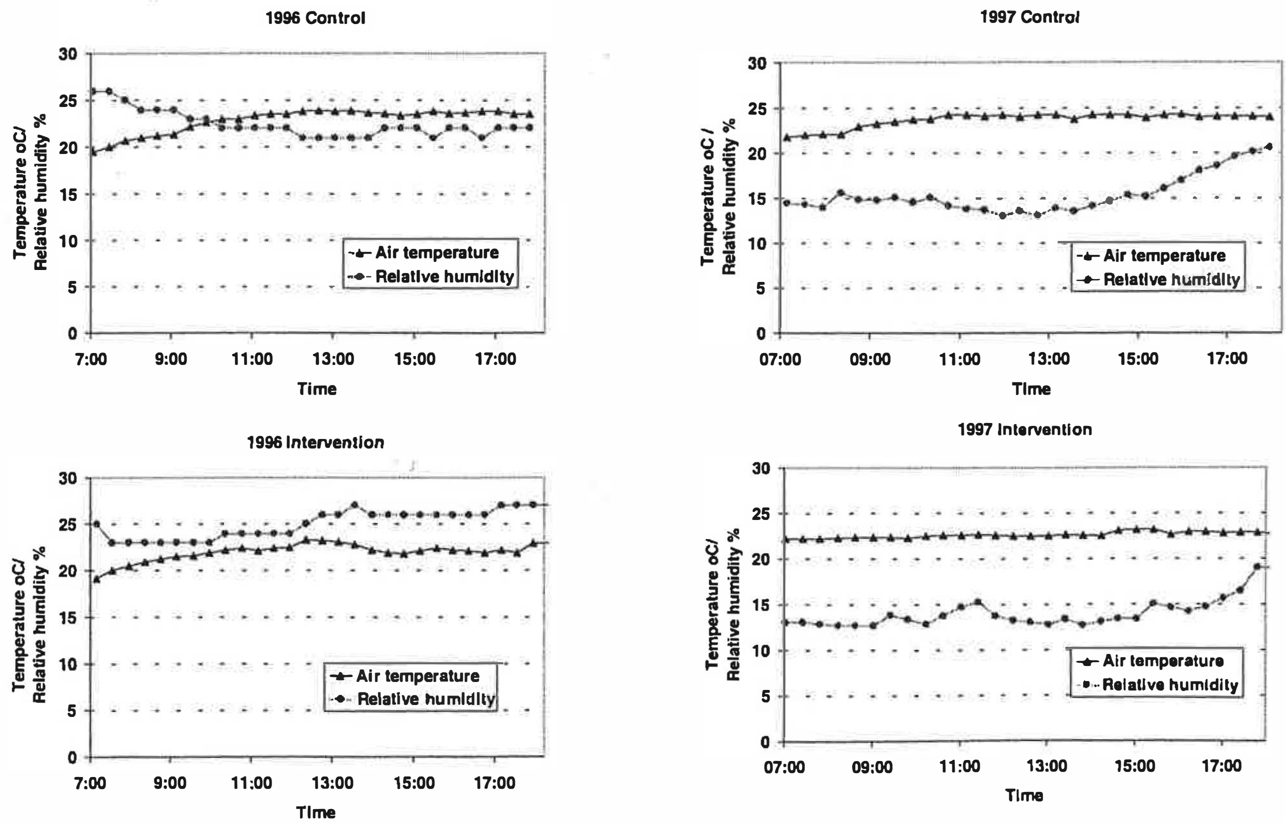


Fig. 7 Temperature and humidity in the two main measuring offices located in the control and intervention areas

Table 2 The mean A-weighted and C-weighted sound pressure level, the amount of dust on floor and the static electricity load in the cellular and open-plan offices

	Cellular offices				Open-plan offices			
	Control		Intervention		Control		Intervention	
	Before	After	Before	After	Before	After	Before	After
Sound pressure (dB(A))	45±7	41±5	47±7	38±7	50±4	44±5	48±4	37±5
Sound pressure (dB(C))	60±1	57±3	64±4	57±3	60	58±2	64±1	59±1
Dust on floor (g/m²)	0.57	0.38	0.37	0.1	0.03	0.06	0.03	0.08
Static electricity load (kV)	1.5±0.7	3.3±1.5	2.1±1.2	0.9±0.4	2.2±0.6	3.5±1.0	4.6±2.0	2.5±0.5

Table 3 The sum of VOCs in decane equivalents (μg/m³) measured for one hour in the selected offices at the town hall before and after the intervention. Number of persons present during sampling is given in parenthesis

Area	Office		Occupied		Unoccupied		Mean of 2xRSD
	No.	Type	Before	After	Before	After	Before-After
Intervention	A	Open-plan	60	43	40	34	14
	B	Cellular	51	30 (1)	c	39	8
	C	Cellular	103	32 (2)	c	28	24
	D	Cellular	46	32	c	21	27
	E	Cellular	76	48 (1)	c	26	33
Control	F	Open-plan	107 (a)	45 (15~)	c	39	21
	G	Cellular	101	38 (1)	42	43	17
	H	Cellular	60 88	72 (4, a), 41 (4)	37	32	14
	I	Cellular	137 (2 a, b)	37 (0), 56 (2)	84 desk, 51 shelf, 44 window 57 inlet	41 desk 37 shelf 26 inlet	13 27
	J	Cellular	156 (3, a), 101	39 (1, a), 26 (0)	38	26	10

a=door closed, b=smoking present, c=not measured

(Table 2). The results show that the average load after the intervention had increased in the control offices. This may have been caused by the lower relative humidity during the period when the measurements were made.

The illuminance intensity was increased in both the intervention area and in the control area after the intervention. In both cases the conditions after the intervention were found to be improved and up to modern standards concerning aside the working object (minimum 200 lux). After the intervention the illuminance at only one out of ten workplaces in the intervention area was below the Danish guideline value of 500 lux, while at six out of ten workplaces in the control area the illuminance was below the guideline value.

Glare occurred less frequently in the intervention area after the intervention, while no changes were seen in the control area. The occurrence of reflections on the VDU from daylight was higher in the intervention area than in the control area both before and after the intervention and was most likely caused by changes in the daylight illuminance. The reflections on the VDU from ceiling lighting did not differ significantly in either of the investigated areas, neither before nor after the intervention. Reflections on the laminated plastic desk pads in the intervention area occurred at 60% of the workplaces before the intervention but at 100% of the workplaces after the intervention when lighting had been changed. No changes in reflections were observed in the control area.

Chemical measurements

The sum of VOC measurements in the air is shown in Table 3. The following was observed before the intervention. The sum of VOCs was a factor 2–4 higher in

Table 4 The area specific emission rate of the sum of VOCs (decane equivalents) measured from different surfaces on-site at the town hall in 1996 by use of the FLEC

Room	Material surface	Specific emission rate μg/(hxm²)
I	Carpet	520
I	Door	110
I	Linoleum	730
I	Wall	230–475
A	Writing desk	190

Table 5 Relative ratios (peak areas) of emitted VOCs (increasing retention time) from carpet, linoleum, and wall measured on-site with the FLEC before the intervention, and relative ratios of emitted VOCs from carpet and linoleum in the laboratory

VOC	On-site testing			Laboratory testing after 24 h	
	Carpet	Linoleum	Wall	Carpet	Linoleum
Acetaldehyde	1	1	13	1	1.5
Pentane	1	2	35	1	11
Propanal	1	2	2	1	3
Acetone	2	1	2	1	8
Hexane	1	1.5	4	1	3
Butanal	1	29	–	–	
Butanone	1	40	–	1	–
Heptane	1	37	1	1	–
2-ethylfurane	1	32	–	–	–
2-butenal	–	1	–	1	–
Pentanal	7	5	1	1	–
Acetic acid	1	2.5	2	1	1
Toluene	1	13	2	2.5	1
2-pentenal	1	5.5	7	2.5	1
Hexanal	7	5.5	1	1	275
Propionic acid	3	1	4	1	5
Benzaldehyde	2	1	1	1	3
Octanal	2	3	1	1	8
2-(2-ethoxyethoxy)ethanol	1	–	–	1	52
X	1.5	1	1	1	3
2-hydroxybenzaldehyde	1.5	1.5	1	1	3.5
2-octenal	1	1	–	–	1
Nonanal	2	3	1	1	3
Dodecane	1	–	–	1	4
Phenol	1	2	1.5	1	1
X	3	1	3		
Naphthalene	2.5	1	2	2	1
Tridecane	1	–	–		
2-(2-butoxyethoxy)ethanol	1	2.5	1	19	1
Tetradecane	2.5	1	1.5	1	5
Sèquiterpene	1	1	1	1	2.5
2-(2-butoxyethoxy)ethyl acetate	1.5	1.5	1	4.5	1

the occupied offices than in the unoccupied offices. The level was less than 160 μg/m^3 and did not give rise to concern with regard to airway irritation. Smoking resulted in a higher sum of VOCs. Concentration gradients were observed within the same room.

The following was observed after the intervention. The difference in the sum of VOCs between occupied and unoccupied rooms appeared to be smaller, except when the room had high occupancy. The level was generally lower than before the intervention and the level was generally reduced more substantially in the rooms that had undergone intervention. However, the comparison was difficult due to different occupancies.

The area specific emission rates (μg/(m^2 h)) for the measured surfaces differed, the rate for linoleum being highest, followed by carpet, wall, and desk, in decreasing order (see Table 4). The emission of individual VOCs from the carpet, linoleum, and wall was studied in some detail (Tables 5–6). The data showed that the materials had different desorption characteristics. Emission of aldehydes, in addition to emission of some unsaturated aldehydes, ketones, some fatty acids, ethylfurane, and butoxyethoxyethanol characterized linoleum. While the carpet also desorbed some aldehydes, the wall was characterized by emission of some very volatile organic compounds. Several of the emitted VOCs are likely due to sorption processes (of VOCs from the environment) or from the use of cleaning agents, and deposited human debris and oxidative degradation thereof, i.e. secondary rather than primary emissions (Wolkoff, 1999). The data also showed the difficulty of comparing laboratory data with field data (Table 5). This is well known for linoleum (Wolkoff et al., 1995).

For a typical working day, the carbon dioxide con-

Table 6 Relative ratios of additional emitted VOCs (increasing retention time) from carpet and linoleum from laboratory measurements

Additional VOC	Laboratory testing	
	Carpet	Linoleum
2-Octenal	1	3
Heptanoic acid	–	1
Octanoic acid	1	1
2-decenal	–	1

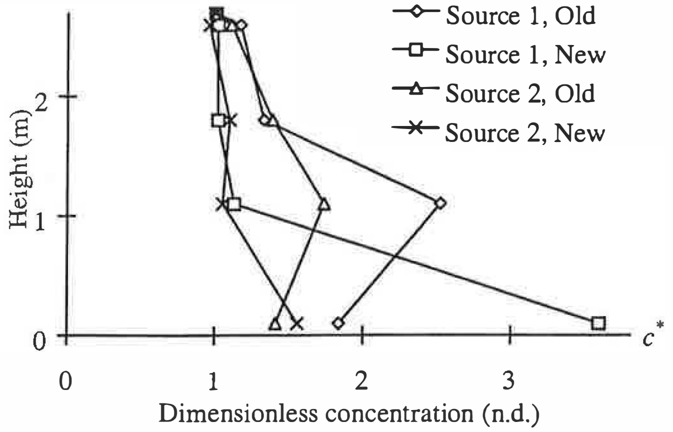


Fig. 8 Dimensionless vertical concentration profiles, c*, in the centre of the office measured in the case of both the original and the new ventilation strategy. The tracer gas was supplied through a porous foam rubber ball, ø 0.1 m. Source 1: foam rubber ball located on the floor. Source 2: foam rubber ball located on top of a bookcase. $c^*=c/c_R$ where c_R is the return concentration measured in the exhaust air

centration in the town hall offices before the intervention was approximately 600 ppm in the control offices and 500 ppm in the intervention offices. After the intervention the carbon dioxide concentration in the control offices was approximately 500 ppm and 450 ppm in the intervention offices. The carbon monoxide concentration in the non-smoking offices was typically below 0.6 ppm for both years.

Ventilation and Airflow Measurements

The vertical concentration profiles measured in the centre of the intervention office for two different contaminant sources in the case of both the original and the new heating and ventilation strategy are shown in Figure 8. After the intervention the dimensionless concentration in the breathing zone was almost 1, which means that the supply air was fully mixed with the room air. The temperature distribution in the office is presented in Figure 9 where the temperatures of the outside air, the supply air, and the air in the centre of the room at three different heights are shown. A vertical temperature gradient of approximately 1°C/m was found in the case of the original heating and ventilation strategy. In the case of the new strategy, the temperature gradient almost disappeared indicating a state of complete mixing. The measurement of the concentration profiles and the detailed temperature measurement in the control office showed no significant difference before and after the intervention.

The total air change rate in the cellular offices in both control and intervention area was on average 5 h^{-1} before the intervention and 6 h^{-1} after the intervention. However, since the rate of recirculated air in all offices was changed from 46% in 1996 to approximately 0% in 1997, the outdoor air change rate was almost doubled after the intervention in both areas. The total air change rate in the open-plan office of the control area was approximately 4 h^{-1} both years, whereas the total air change rate in the open-plan office of the intervention area was changed from approximately 7 h^{-1} to 4 h^{-1}. The results in the open-plan offices should be interpreted with caution since it was difficult to get the tracer gas fully mixed with the room air.

Sensory Measurements

The mean acceptability of the air at the inlet and in the spaces assessed by the sensory panel is shown in Table 7. The intervention had no significant effect on the perceived air quality in the offices. In the open-plan offices, the intervention showed a slightly positive effect on the perceived air quality in the unoccupied spaces but not in the occupied spaces. The perceived air qual-

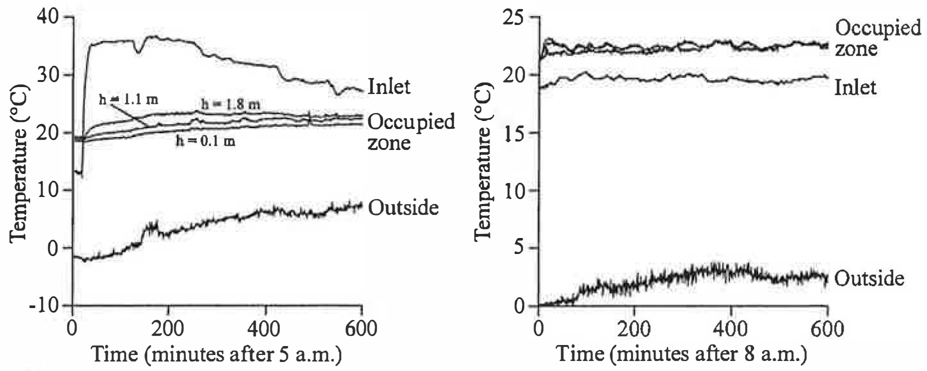


Fig. 9 Air temperatures measured in the supply air, outside the office, and at three different heights in the centre of the office in the case of the original ventilation strategy (left) and the new ventilation strategy (right). Please note the different ordinate axis

Table 7 Mean perceived air quality (% dissatisfied) in the occupied and unoccupied spaces and in the supply air inlet

	Cellular offices				Open-plan offices			
	Control		Intervention		Control		Intervention	
	Before	After	Before	After	Before	After	Before	After
Occupied offices	22	23	20	21	57	36	58	23
Unoccupied offices	15	12	15	23	47	23	34	33
Supply air inlet	9	9	8	9	10	25	11	25

ity at the inlet did not change when comparing intervention offices with control offices.

Questionnaire

The prevalence of general symptoms, mucous membrane symptoms and skin symptoms, defined as in the Danish Town Hall Study (Skov et al., 1987), before and after the intervention is shown in Figure 10. The categorical data were analysed in an analysis of variance for categorical data. The change in percentage of subjects having general symptoms ($P<0.002$) and irritation of mucous membranes ($P<0.02$) in the intervention group was significant compared to the change in the control group. The change in percentage of subjects having skin symptoms was not significant ($P<0.06$).

The occupants' perceptions and symptoms during the two-week period in 1996 and 1997 were examined in an analysis of variance. The analysis was made based on the difference in the response from 1996 to 1997 assessed on the VAS scale, and should verify if the intervention had a positive effect on occupants' perceptions and symptoms in the intervention group compared to the control group. The model took into account the factor of *zone (intervention or control; fixed effect), week (fixed), weekday (fixed), office type (fixed), subject nested within office type and zone (random)* and all two-factor interactions. Results of the analysis are shown in Table 8. In general there was a significant difference between the chances in the severity of perceptions and symptoms for the intervention group compared to the control group, Table 8. Except for the perception of *static electricity* the intervention had a positive effect on all of the occupants' perceptions and symptoms when comparing the changes in the intervention group with the changes in the control group. The effect of the intervention was most evident for occupants in the cellular offices compared with the occupants in the open-plan offices. However there was no significant difference between the changes in the cellular offices compared to the changes in the open-plan offices. A separate analysis was made for the cellular and open-plan offices, respectively. The analysis showed that the changes in the severity of perceptions and symptoms for the occupants in the cellular offices were determining for the results in the overall analysis. Table 9 shows the percentage of occupants who experienced a decrease in the severity of perceptions and symptoms from 1996 to 1997. The figures are based on each occupant's mean assessment each year.

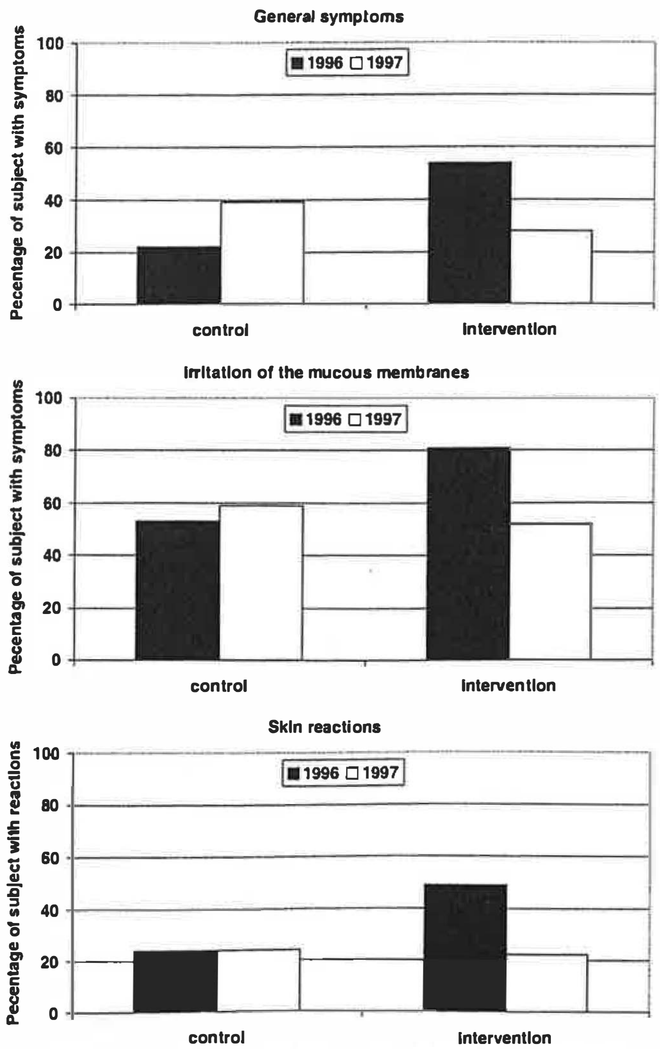


Fig. 10 Retrospective general symptoms, irritation of the mucous membranes and skin symptoms in control and intervention offices

Table 8 Changes in severity of environmental perceptions and symptoms for the intervention group from 1996 to 1997, compared to changes in the control group. (Negative value means worse conditions in 1997 than in 1996. Positive value means better conditions in 1997 than in 1996)

		Control (n=488) Mean (SD)	Intervention (n=351) Mean (SD)	Difference control/intervention (prob. level)
Environmental Perceptions[1]	Too low temperature	−8 (1.8)	4 (1.9)	0.001
	Too high temperature	11 (2.4)	15 (2.6)	ns
	Changing temperature	−3 (1.9)	17 (2.2)	0.001
	Draught	−7 (1.8)	9 (2.6)	0.002
	Cold feet	−7 (1.8)	6 (2.2)	0.01
	Dry air	5 (1.8)	21 (2.5)	0.006
	Stuffy air	0 (1.6)	15 (2.0)	0.003
	Unpleasant odour	−5 (1.2)	4 (1.3)	0.005
	Tobacco smoke	0 (0.9)	3 (1.2)	ns
	Noise	1 (2.1)	16 (2.4)	0.02
	Static electricity	0 (1.6)	−1 (2.0)	ns
	Dust and dirt	0 (1.1)	6 (1.7)	ns
	Poor lighting	−2 (1.7)	10 (1.6)	ns
	Did any of the above environmental perceptions have influence on your work performance?[2]	2 (1.4)	9 (1.6)	0.001
Symptoms[1]	Dryness or irritation in the eyes	2 (1.8)	9 (2.1)	ns
	Runny eyes	0 (1.0)	6 (1.8)	ns
	Dry, irritated or blocked nose	1 (1.9)	15 (2.4)	0.002
	Runny nose	0 (1.1)	5 (2.0)	0.04
	Dry or irritated throat	0 (1.8)	13 (2.2)	0.002
	Hoarseness or sore throat	−2 (1.4)	3 (2.0)	ns
	Dry or blushing facial skin	−2 (1.3)	6 (1.6)	ns
	Dry or itchy hands	−5 (1.1)	5 (2.1)	0.007
	Neck pain	−3 (1.5)	3 (1.7)	ns
	Headache	0 (1.9)	4 (1.8)	ns
	Difficulty in thinking clearly	1 (1.5)	7 (1.8)	ns
	Dizzy	−2 (1.2)	3 (1.5)	0.02
	Concentration difficulties	−2 (1.2)	5 (1.5)	0.01
	Fatigue	−1 (1.1)	4 (1.8)	ns
	Did any of the above symptoms have influence on your work performance?[2]	0 (1.2)	10 (1.6)	0.002
Perceived air quality[3]	Acceptability of air quality	0.05 (0.03)	0.37 (0.04)	0.001

[1] The endpoints of the vas scale: *No not annoyed at all* (value 0), *yes annoyed a lot* (value 100)
[2] The endpoints of the vas scale: *No not at all* (value 0), *yes a lot* (value 100)
[3] The end points of the acceptability scale: *Clearly unacceptable* (value −1), *Clearly acceptable* (value +1)

Physiological Measurements

About 60 occupants participated in both years and the two intervention groups had each 13 (cellular offices) and 14 (open-plan office) valid cases. A repeated type analysis of variance included the effect variable for the pre- and post-intervention sampling and the relevant factors (intervention groups, age and gender). In general, there was no effect of the interventions on the effect variables. A few significant findings were seen for interactions with gender for the CO_2 provocation. Men and women had opposite reactions to the intervention, which was almost impossible to explain. Therefore, they were considered as chance findings.

Discussion

Decreased sensory pollution load from the flooring material and increased ventilation effectiveness by a new ventilation strategy reduced the occupants' severity of environmental perceptions and symptoms. The analysis of the daily VAS questionnaire showed that the severity of the occupants' perceptions and symptoms were significantly reduced for the occupants in the intervention offices compared with the control, table 8. The severity of occupants' perception and symptoms in the control group was either unchanged or getting worse from 1996 to 1997. As this may reflect a natural change it makes the findings for the intervention group even more convincing.

The improvement of the indoor climate was most pronounced in the cellular offices, where both the floor material and the ventilation and heating conditions had been changed, compared to the improvement in the open-plan offices, where only the ventilation and heating system had been changed. In the overall statistic analysis there were no significant difference be-

Table 9 Percentage of occupant with a decrease in severity of environmental perceptions and symptoms

		Cellular offices		Open-plan offices	
		Control (%)	Intervention (%)	Control (%)	Intervention (%)
Environmental Perceptions	Too low temperature	28	47	13	40
	Too high temperature	67	60	69	88
	Changing temperature	39	60	24	81
	Draught	39	53	12	31
	Cold feet	33	53	15	19
	Dry air	61	80	50	81
	Stuffy air	56	87	46	63
	Unpleasant odour	31	73	15	33
	Tobacco smoke	44	47	15	36
	Noise	61	73	42	63
	Static electricity	61	47	27	47
	Dust and dirt	22	47	27	20
	Poor lighting	33	60	31	27
	Did any of the above environmental perceptions have influence on your work performance?	44	80	50	63
Symptoms	Dryness or irritation in the eyes	61	53	38	44
	Runny eyes	22	47	19	50
	Dry, irritated or blocked nose	47	67	32	69
	Runny nose	33	47	27	31
	Dry or irritated throat	35	67	38	56
	Hoarseness or sore throat	28	60	35	21
	Dry or blushing facial skin	50	60	15	36
	Dry or itchy hands	39	53	12	40
	Neck pain	22	47	27	38
	Headache	33	60	38	44
	Difficulty in thinking clearly	39	87	50	50
	Dizzy	39	40	27	53
	Concentration difficulties	28	67	46	56
	Fatigue	29	67	29	50
	Did any of the above symptoms have influence on your work performance?	33	80	62	56
Perceived air quality	Acceptability of air quality	44	87	58	93

tween cellular and open-plan offices however, the separate analysis for the cellular and open-plan offices showed that the changes in the cellular offices was determining for the results of the overall analysis. Removal of carpets has previously been shown to decrease symptoms and environmental perceptions (Norbäck and Torgén, 1989; van Beuningen et al., 1994).

The occupants' complaints about thermal environment and air quality (dry air, stuffy air, unpleasant odour, perceived air quality) together with the symptoms irritation in nose and throat, itchy hands, dizziness and concentration difficulties were significantly reduced by the intervention. Both the laboratory studies on heating and ventilation strategies and the actual measurements in the field showed that occupants in the intervention offices were exposed to a more comfortable thermal environment after the intervention. The chemical measurements together with the ventilation and airflow measurements showed that the intervention reduced the occupants' exposure to indoor air pollution. However, this was not supported by the sensory assessments performed by the independent subjects, since the intervention had no effect on the sensory assessments of the panel in the offices. The sensory panel assessed the air quality rather acceptable even before the intervention, whereas the laboratory studies showed that the sensory pollution load from the both the carpet and linoleum was significant and much higher than the sensory pollution load from the vinyl flooring (Kjærgaard et al., 1999). An explanation for the acceptable air quality in the building, in spite of the high pollution load from the carpet and the linoleum, might be the rather high outdoor ventilation rate during the assessments in the building.

The positive effect of the intervention on occupants' self-reported perceptions and symptoms was not supported by the physiological measurements in the field. However, the power of this part of the study was not very strong since only 60 occupants participated in the physiological examination both years, and of those only 13 occupants were placed in the cellular offices and 14 occupants were placed in the open-plan offices in the intervention area.

The full-scale exposure experiment in the climate chamber was performed to study the single effect of the renewed materials on humans' comfort and health (Kjærgaard et al., 1999). The subjects' perceptions and symptoms after six hours' exposure for the different floor materials were very modest and there was no significant difference when compared with the perceptions and symptoms experienced in the empty chamber. No adverse physiological changes were seen when subjects were exposed to vinyl, whereas subjects' tear film stability was reduced when exposed to linoleum, and nasal volume was reduced when exposed to carpet. During exposure, subjects were sedentary and allowed to read their own books, but they were not forced to engage in office work. The moderate mental activity may be an explanation for the very modest symptoms. In a study with a simulated office in the laboratory, subjects were exposed for an office environment with the carpet that originated from the present study and an office environment without carpet while they were doing office work such as typing and correcting text (Wargocki et al., 1999). Subjects had more symptoms and typed 6.5% fewer characters in the office with carpet than in the office without carpet. It seems that when stressing the subjects with demanding task they are having more symptoms than when they are not forced to do anything as in the present experiment.

The occupants evaluated the negative influence of the perceptions and symptoms on their work performance. After the intervention the perception and symptoms had significant less influence on occupants self-reported work performance in the intervention group compared to the control group (Table 8). This was in accordance with the results from Wargocki et al. (1999).

The daily questionnaire was completed during two weeks each year, the weeks before and after Easter. The analysis showed that within the same year the complaints after the Easter holiday were in general significantly lower than before Easter. Since the analysis was made as a repeated measurement analysis so each subject's response on a particular week and weekday the first year was compared with the corresponding response the second year the finding had no influence on the main conclusion. The result emphasizes that perceptions and symptoms are a subjective measure and that caution must be taken when comparing questionnaire results.

A drawback with the experimental design of the field study was that changing the recirculation rate from 50% to 0% (100% outdoor air) and changing the filter in the ventilation system affected both the intervention area and the control area. It was not possible to evaluate the effect of the changed recirculation rate, because the effect was confounded with a possible natural change in the occupants' response from 1996 to 1997. It was expected that changing the system to 100% outdoor air would decrease perceptions and symptoms (Jaakola et al., 1991). The opposite happened, since perception and symptoms was unchanged or increased in the control group after the intervention (Table 8). However this was in accordance with other interventions studies which have investigated the effect of changing ventilation rates (Menzies et al., 1993; Turiel et al., 1983).

Except for the very technical modifications of the ventilation system the intervention was not blinded. This may have resulted in an expectation towards better conditions in the intervention group and maybe a disappointment in the control group. The physical, chemical and sensory measurement did not indicate that the environmental condition in the control offices had been worse from 1996 to 1997, whereas they did indicate better environmental conditions in the intervention offices. It was impossible so say if the increase in perceptions and symptoms in the control group was due to a disappointment among occupants since they have seen that changes occurred for their colleagues and therefore where more annoyed or it reflect a natural change for the cohort. If the latter was true the effect of the intervention was even more convincing than seen directly from the changes in the intervention group. If the occupants in the control group were disappointed this has supported the statistical analysis in an unwanted manner. However the occupants created the expectation themselves, since it was clear from the beginning that the renovation would be made in two steps.

The retrospective questionnaire study supported the findings from the detailed daily questionnaire study. The intervention had a strong significant effect on the prevalence of general symptoms ($P<0.002$), a significant effect on the prevalence of mucous membrane symptoms ($P<0.02$) whereas the prevalence of skin symptoms were reduced but the change was not significant ($P<0.06$). As seen for the daily VAS questionnaire the symptoms increased in the control group after the intervention especially for the prevalence of general symptoms. Before the intervention there was a large difference in the prevalence of symptoms for the control and intervention group. The distribution of women and men was almost the same in the two groups whereas there were differences in the job function. The intervention area comprised the economic, the social security and the tax department whereas the control area comprised the technical department and the mayor's office. From the Danish Town Hall Study

(Skov et al., 1989a) it was know that with this distribution of job function the intervention group was expected to have a higher prevalence of symptoms than the control group.

The prevalence of skin symptoms was rather high even after the intervention compared with the townhall study. The relative humidity was low (15–25% RH) and even that this could not explain the high prevalence of skin symptoms by itself it might have contributed to the symptoms (Andersen et al., 1974).

After the intervention the prevalence of general symptoms was 28% in the intervention group compared to 40% for the average townhall in the town hall study (Skov et al., 1987, 1989b). The figures for the prevalence of irritation of mucous membranes were 55% for the intervention group and 44% for the average town hall. The figures are the overall prevalence inclusive non-work related symptoms. The intervention group was not representative of the whole town hall and was expected to have a higher prevalence of symptoms than if the group had been a homogeneous townhall population. The prevalence of general symptoms for the intervention group after the intervention was comparable to the townhalls with the lowest prevalence, whereas the prevalence of irritation of mucous membranes was comparable to a mean townhall (Skov et al., 1987).

Conclusion

Decreased sensory pollution load from the flooring material and increased ventilation effectiveness by a new ventilation strategy reduced the occupants' severity of environmental perceptions and symptoms.

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