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Perceived and Measured Indoor Climate with Dilution versus Displacement Ventilation: an Intervention Study in a Sewing Plant

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Abstract Mechanical ventilation of workrooms was formerly based mainly on the dilution principle. In recent years, however, 50% of new investments in industrial ventilation in Scandinavia have been spent on displacement ventilation. Very little data exist from industrial settings on the relative performance of displacement ventilation versus dilution ventilation as regards air quality and thermal comfort. The present study collected data on the indoor climate in a sewing plant before and after the ventilation was changed from dilution to displacement. The indoor climate was evaluated by hygienic measurements of air pollution, temperature, air velocity, etc., and 40 employees were interviewed about perceived thermal comfort, air quality, and irritative symptoms.

Changing the ventilation from dilution to displacement induced a slightly higher air change in the occupied zone of the plant and entailed higher temperature gradients. In spite of these findings, complaints of draught decreased significantly, and temperature was perceived to be more pleasant after the change. The air was perceived as less heavy and less dry, especially when humidification was added to the supply air. The improvements in the workers' reports on the environment could not be attributed to placebo effects. Generally, the hygienic measurements were improved or unchanged after the change in ventilation system. Thus, displacement ventilation improved environmental conditions in this study. When adding humidification, this improvement was further sustained.

Key words Placebo effect, Interview, Health effects, Air quality, Thermal comfort, Textile industry.

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Introduction

Workrooms must be ventilated mainly for two reasons: firstly, to provide clean breathing air, i.e. to remove air pollution and add fresh air; and secondly, to ensure a pleasant thermal environment. Industrial companies spend large sums on mechanical ventilation. In Denmark alone, yearly investments are around US 50 million.

The ventilation of workrooms is designed according to various principles. In industry, dilution ventilation is frequently used. With this type of ventilation, air is supplied through jets at ceiling level, whereby secondary recirculating airflows are formed. Ideally, the mixing process creates a uniform distribution of temperature and air pollutants in the room. The efficiency of dilution ventilation in supplying clean air to the workers' breathing zone has been questioned (Skåret and Mathisen, 1985). In recent years, displacement ventilation has become increasingly popular, and in Scandinavia its market share is now around 50% (Svensson, 1989). With displacement ventilation, a non-uniform distribution of temperature and air pollutants is aimed at, so that the air in the workers' breathing zone is cleaner and cooler than in the upper parts of the room. Cool air is supplied at low velocity near the floor, and is heated by heat sources in the room, forming convective air currents in which contaminants are entrained. The heated air is exhausted at ceiling level.

Laboratory data indicate that displacement ventilation is superior to dilution ventilation in improving air quality without violating thermal comfort requirements (Sandberg, 1981; Breum, 1992; Wyon and Sandberg, 1990). Test data from laboratories may not be valid in practice, but consistent measurements have been reported from actual buildings (Breum et al., 1989; Breum and Skotte, 1992). So far, no data are available on dilution versus displacement ventilation in terms of the employees' perceptions of the air quality and the thermal environment (indoor climate).

The present study collected data on the indoor cli-

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mate in a sewing plant before and after change of the ventilation from dilution to displacement.

The main objective of the study was to evaluate the effect of the changes, both how they were perceived by the employees and how they were measured. A secondary aim was to evaluate the effect of adding humidification to the displacement ventilation.

The indoor climate was evaluated by hygienic measurements of air pollution, temperature, air velocity, etc., and by interviewing the employees about perceived thermal comfort, air quality and irritative symptoms.

It was hypothesized that the change from dilution to displacement would provide better air quality and better temperature in the room but also more draught. The addition of humidification was hypothesized to intensify the feeling of better air quality, especially less dry air.

Material and Methods

The design was an intervention study over three periods during November 1991 – April 1992. Before the study started, the employees were informed at a meeting that the ventilation system of the plant would be rebuilt, and they were asked to participate in the interviews. No details were given about the rebuilding or the expected consequences.

In the *first study period*, dilution ventilation was used. Fresh air was supplied at a constant rate by 14 diffusers at ceiling level. The heated and contaminated air was exhausted at the machines and at ceiling level.

The employees were interviewed about their perceptions of the indoor climate, their symptoms during the preceding three months and on the day of the interview, and about their health in general. Hygienic measurements were made (see below).

The ventilation system was then changed to the displacement principle. The diffusers at the ceiling were removed, and 9 diffusers were installed near the floor. No other changes were made to the ventilation system. The rebuilding of the ventilation system was designed by a publicly available computer program (Laurikainen, 1991). However, the rebuilding resulted in an unintended 13–17% reduction in the overall airflow.

Second period. Ten weeks after the change, the second interview was carried out and it included the same questions as the first, except that only symptoms on the interview day were ascertained since a three-month reference period would include the day of the first interview. The same hygienic measurements were taken as in the first period.

Thereafter, while maintaining the displacement principle, humidification was added to the supply air so that the relative humidity was kept at 50%.

Third period. After two months with humidification, the third interview took place. It included the same questions as the second interview and the same hygienic measurements were taken.

The humidification was then turned off and displacement ventilation without humidification was kept for the remaining study period.

The Plant

The study was undertaken in a plant in which uniforms and waterproof clothes were sewn. The workroom had 70 closely placed sewing machines. The fabrics were a mixture of 50% cotton/50% polyester for uniforms, and PVC fabrics for waterproof clothes. At all machines, there were local exhaust hoods. The floor area was 600 m^2 and the volume of the room was 2300 m^3. The production conditions were stable in all 3 periods.

The Study Population

During the study period, the workforce of the plant comprised 44–45 persons. In the study periods there was little turnover; 40 employees were available for all three interviews. None declined to participate. The majority were seamstresses; only 2–3 employees in each period had other tasks. Ninety-eight percent were women, the mean age being 40 years. The analysis is restricted to include the 40 persons employed at the plant during all three periods.

The Interview, the Questions and the Indexes

Personal interviews were made at the plant in a room next to the workroom. A structured questionnaire was used which included, among others, questions about temperature, draught and dry and heavy air, and symptoms relevant for indoor climate monitoring in the textile industry (Kristensen, 1978). The questions were adapted from a Nordic questionnaire on work environment and health (Ørhede, 1994).

The question about temperature had 7 alternatives from +3="much too warm" to −3="much too cold". In the analysis, four alternatives, including the answers "much too warm", "too warm", "too cold" and "much too cold", were combined into a category named "uncomfortable temperature", and the remaining three alternatives, "comfortably warm", "comfortable" and "comfortably cold" were combined into a category called "comfortable temperature".

Table 1 Replies to the questions concerning perception of indoor climate (in percent)

	Dilution ventilation (low humidity) Period 1	Displacement ventilation (low humidity) Period 2	Displacement ventilation (high humidity) Period 3
Temperature			
Pleasant	60	70	85
Unpleasant	40	30	15
Draught	43	35	25
Dry air	75	63	38
Heavy air	65	38	23
Number of persons	40	40	40

The questions on dry and heavy air had 6 alternatives from "all of the time" to "no". These alternatives were dichotomized to "Yes" and "No" with the cut-point at the 4th alternative: ">1/4 of the time". This cut-point was found to be adequate in former studies (Ørhede, 1988). The question on draught had only "yes" and "no" alternatives.

An overall "indoor-climate" index was computed by adding the values of the dichotomized alternatives of the four questions on indoor climate with low values indicating the best indoor climate.

All symptom questions had "Yes/no" alternatives, and likewise an index of the four symptom questions was computed.

Hygienic Measurements

Indoor climate measurements were made at workstations considered representative of the activity and technical installations. With the assistance of 8 employees working full shift at selected workstations, personal samples were obtained on breathing zone air quality. Thermal parameters at the workstations were obtained at three levels above the floor (0.1, 0.6, 1.1 m) twice a day (morning and afternoon). The location of the workstations and technical details concerning the sampling techniques and laboratory analyses are given elsewhere (Breum and Ørhede, 1994). The hygienic measurements included technical ventilation parameters, temperature, humidity, concentration of formaldehyde, dust, and particle and fibre counts.

Statistical Methods

Cross-tabulations and pairwise comparisons were made of the questionnaire data from one period to another.

The alternatives for answers were dichotomized and P-values for the paired data were computed with McNemar's test in SPSS. McNemar's pairwise test was chosen as one of the questions asked (draught) had only two alternatives.

To compare the "overall indoor climate" indexes and the "overall symptom" indexes, Wilcoxon matched-pairs signed-ranks test in the SPSS-program was used.

Mean values of hygienic measurement data were used for pairwise comparison of the study periods. A detailed pairwise comparison is given elsewhere (Breum and Ørhede, 1994).

Results

Interview

Before the change to displacement ventilation, 40% of the employees reported the temperature to be unpleasant which means either too hot or too cold (Table 1). After the change, a substantially smaller proportion was dissatisfied with the temperature. In particular, the proportion reporting "too hot" declined even though the measured temperature rose from 21.9° in the first period to 23.3° in the second period.

Draught complaints decreased from 43% of all employees in the first period to 25% in the third, with the second period intermediate.

The perception of dry air decreased slightly with the introduction of displacement ventilation without humidification. With the addition of humidification this tendency became more pronounced.

Complaints about heavy air showed similar decreases; whereas in the first period 65% of the employees experienced the air as heavy, this proportion

Table 2 Pairwise comparison of the indoor climate questions in period 1 vs 2, 2 vs 3, and 1 vs 3[1]. P-values from McNemar's test

Indoor climate	Period 1 vs 2	Period 2 vs 3	Period 1 vs 3
Temperature	0.42	0.15	0.01
Draught	0.65	0.39	0.09
Dry air	0.18	0.02	0.00
Heavy air	0.03	0.11	0.00
Number of persons	40	40	40

[1] Period 1: Dilution ventilation (low humidity)
Period 2: Displacement ventilation (low humidity)
Period 3: Displacement ventilation (high humidity)

Table 3 Comparison of the overall indoor climate index in period 1 vs 2, 2 vs 3, and 1 vs 3[1]. P-values from Wilcoxon's matched-pairs signed-ranked test

	Period 1 vs 2	Period 2 vs 3	Period 1 vs 3
Indoor climate index	0.02	0.00	0.00
Number of persons	40	40	40

[1] Period 1: Dilution ventilation (low humidity)
Period 2: Displacement ventilation (low humidity)
Period 3: Displacement ventilation (high humidity)

Table 5 Comparison of the overall symptom index in period 1 v 2, 2 vs 3, and 1 vs 3[1]. P-values from Wilcoxon's matched-pai signed-ranked test

	Period 1 vs 2	Period 2 vs 3	Period 1 vs 3
Symptom index	0.16	0.74	0.28
Number of persons	40	40	40

[1] Period 1: Dilution ventilation (low humidity)
Period 2: Displacement ventilation (low humidity)
Period 3: Displacement ventilation (high humidity)

decreased to 38% in the second period, and to 23% in the third period.

To supplement the prevalence data, pairwise comparisons of the data were made. Individual changes in the perception of the indoor climate could thus be observed.

When changing the ventilation principle from dilution to displacement, only the perception of heavy air changed significantly (Table 2). For the other indoor climate variables the changes were minor. When adding humidification, a significant proportion of the employees felt the air to be less dry. The perception of the changes in the indoor climate was checked by the "overall indoor climate" index. The perception of the indoor climate was significantly improved from period 1 to period 2 (Table 3) when considering the overall indoor climate. When humidification was added, the perception of the indoor climate further improved significantly.

Reported Health Complaints

The prevalences on the interview day of itching eyes, dry mouth and sneezing decreased slightly during the intervention period whereas the prevalence of headache was unchanged (Table 4).

The comparisons of the "overall symptom" index for all 3 periods did not show any significant changes in the occurrence of symptoms from one period to the other (Table 5).

Hygienic Measurements

The air change rate for the room as a whole decrease by 13–17% with the introduction of the displacemer ventilation principle. In spite of this, the air change rat at the workstations increased by 2–13% (Table 6). Th improvement was statistically significant ($p=0.05$) fc period 1 as opposed to period 2.

The operative temperature increased 0.8–1.4°C, an the temperature gradient increased 0.5°C, but was sti within standards for comfort (<3°C/m).

The mean air velocity decreased but the turbulenc intensity was unaffected. Total dust decreased by a fac tor of 3–4, but apparently this was due to decreases i the non-respirable fractions, whereas respirable fibre as well as non-fibres increased by a factor of 1.4–4.7 especially in the third period. Formaldehyde concen trations increased 50% in the third period.

Discussion

The overall perceived thermal comfort was improve by changing the ventilation principle from dilution t displacement. The air was perceived to be less heav and less dry, especially when adding humidificatior The overall airflow was reduced but the local ai change increased, and most of the hygienic measure ments were unchanged or better in the second perio compared to the first. It is recognized that persona clothing is important for perceived thermal comfor

Table 4 Reported health complaints on the day of the interview (in percent)

	Dilution ventilation (low humidity) Period 1	Displacement ventilation (low humidity) Period 2	Displacement ventilation (high humidity) Period 3
Itching eyes	20	18	20
Dry mouth	50	45	43
Sneezing	30	13	20
Headache	5	8	5
Number of persons	40	40	40

Table 6 Hygienic measurements (mean values)

Level	Measurement	Dilution ventilation (low humidity) Period 1	Displacement ventilation (low humidity) Period 2	Displacement ventilation (high humidity) Period 3
Room	Air humidity (%)	35 A**	29 A	49 B
	Air change rate (h^{-1})	6.0 A	5.2 B	5.0B
Workstation	Local air change rate (h^{-1})	6.1 A	6.9 B	6.2 A
	Operative temperature (°C)	21.9 A	23.3 B	22.7 C
	Vertical temp. gradient (°C/m)	0.7 A	1.2 B	1.2 B
	Air velocity (m/s)	0.14 A	0.11 B	0.11 B
	Turbulence intensity (%)	52 A	62 A	60 A
	Total dust (mg/m^3)	0.12 A	0.04 B	0.03 B
	Respirable dust (mg/m^3)	0.05	NA*	NA*
	Non-fibres,non-respirable (particles/cm^3)	0.0086 A	0.0033 B	0.0032 B
	Non-fibres, respirable (particles/cm^3)	0.64 A	0.63 A	0.89 B
	Fibres, non-respirable (particles/cm^3)	0.0020 A	0.0013 B	0.0014 B
	Fibres, respirable (particles/cm^3)	0.13 A	0.23 B	0.61 C
	Formaldehyde (mg/m^3)	0.021 A	0.022 A	0.031 B

* Not available
** Within a row, data assigned identical letters were not statistically different at a 5% level of significance

(Fanger, 1973). However, data on personal clothing were not collected in this study. There was a time span between the changes of ventilation and the interviews. Throughout this period it was assumed that the respondents adjusted their clothing to the temperature level in the room.

Formaldehyde and respirable particles were correlated with the rise in air humidity in the third period. This was not reflected in any rise in the employees' complaints about the indoor climate, probably because formaldehyde and fibre concentrations were still low. In a study of formaldehyde release from cotton fabrics, a positive correlation was found between formaldehyde release and air humidity and temperature (Reinhardt and Kottes Andrews, 1986). Electrostatic forces may bind dust particles to fabrics. When air humidity rises, the electric forces decrease, and dust may be released. This has been shown to take place in carpets (Kivistö and Hakulinen, 1981).

The employees were not informed about the specific changes in the ventilation system. In general, no attenuation of effects concerning the perception of the indoor climate was apparent from the second to the third period. On the contrary, all improvements being observed from the first to the second period were sustained from the second to the third period.

Finally, the prevalence of health complaints did not change nearly as much as did the complaints about the indoor climate, and the frequency of headaches did not decrease at all. These findings seem to rule out any strong placebo effect.

The experience of heavy or stuffy air has been found to be influenced by the temperature, the air humidity and the physical load (Berglund and Cain, 1989). In our study, the addition of humidification was not followed by any increase in complaints about heavy air; on the contrary, parallel declines in complaints about dry air and heavy air were observed. The physical load and the temperature did not change substantially during the study period.

Since displacement ventilation tends to induce higher air velocities at floor level than does dilution ventilation, draught is a potential comfort problem. Similarly, displacement ventilation tends to entail higher temperature gradients, which can give rise to discomfort. The study showed that none of these ill effects occurred. On the contrary, the perception of draught significantly improved from period 1 to period 2, and also the perception of the temperature generally improved. This did not occur at the cost of lower ventilation efficiency with regard to air pollutants. Also in this respect the displacement ventilation was more efficient, in that the measured air pollution parameters were unchanged or improved.

The displacement principle is not a panacea. Theoretically, it is advantageous since it introduces fresh air near the breathing zone of the employees. In practice, air turbulence created by machines and people in the workroom may interfere with convective air currents and thereby reduce the efficiency of the displacement ventilation (Nickel, 1990; Sandberg and Blomquist, 1989). However, this intervention study showed that displacement ventilation has a potential for improving environmental conditions in industry. The study did not indicate any strong placebo effects in the interview data.

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