

Drafts in Cold Environments

—The Significance of Air Temperature and Direction—

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Abstract: This paper concerns the influence of air temperature and of the direction of drafts on subjective and physiological responses. In three experimental series 58 healthy persons (50 men, 8 women, 20–29 yrs) were exposed to drafts in overall 446 experimental sessions. Drafts were applied either horizontally or vertically with mean air velocities of 0.1 to 0.3 m/s and a turbulence intensity of 50%. Air temperature was varied between 11 and 23°C and metabolic rates between <70 and 156 W/m². These parameters were kept constant during the single one-hour sessions. The subjects were dressed for thermal neutrality. Draft-induced annoyance was registered every 5 minutes using a list of prescribed body parts and skin temperature was measured at the forearm and at the neck. Subjective and physiological responses were systematically related to air temperature. Draft-induced general annoyance, draft-induced local annoyance (neck, forearm) and the drop of the corresponding skin temperature were inversely related to air temperature. Concerning the direction horizontal drafts seem to cause somewhat stronger reactions. The predictive model developed by Toftum¹ underestimates the percentage of persons annoyed. A modified version increases the predictive power significantly².

Key words: Drafts, Annoyance, Air temperature, Direction, Draft rating

Introduction

Various field studies revealed that drafts are more frequently stated and more often evaluated as annoying the lower the air temperatures are, particularly at stationary workplaces and the percentages of workers concerned vary between 60% and 100%^{3–5}. There is even some evidence—yet to be proved—that daily exposure to drafts in cold environments contributes to the genesis and manifestation of several diseases. An extended study, where the climate and the professional activities were ascertained in detail, revealed a strong statistical association between the occurrence of drafts at the workplace and the prevalence of common colds, rheumatic and bronchitic complaints as well

as the signs and symptoms of the white finger disease³.

The influence of air temperature on the effects of drafts was experimentally studied by Toftum and Nielsen⁶ who found an inverse relation between air temperature and draft-induced dissatisfaction for the bare hands but not for the head region which was the main criterion in their study. This is presumably related to the fact that their subjects wore high collars and long sleeves, which often does not meet the situation at real workplaces where the forearms are bare as for instance in the meat processing industry. The experimental design was again not realistic as air speeds were stepwise increased every 15 minutes from 0 to 0.4 m/s, whereas workers are exposed to defined drafts throughout their entire shifts.

Moderate cold at many workplaces is often achieved by cooling devices where the outlets are installed in the ceiling.

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Thus, the workers are not only exposed to horizontal drafts as caused by leak doors and windows but also by vertically or diagonally directed airflows which are often supposed to cause stronger effects particularly at the neck that is commonly supposed to be sensitive to drafts.

The present paper aims at the determination of the influence of air temperature and of the direction of airflow on subjective and physiological responses to drafts. It bases on the analysis of 3 experimental series where the real situation at the workplace was simulated as far as possible.

Materials and Methods

The general experimental procedure was the same in the present 3 studies.

Subjects: Fifty men and eight women with a good physical condition participated in the experiments. Their data are listed in Table 1, separately for the 3 studies.

Technical equipment: The experiments were executed in a climatic chamber (area $7 \times 3 \text{ m}^2$), which operates like a wind tunnel. Turbulence were produced by 4 ventilators where the on/off-times and the number of revolutions per minute were randomly varied by a computer program. Radiation temperature was equal to air temperature, humidity was not controlled and varied between 40 and 70%.

General procedure: After the fixation of the thermistors

for the registration of skin temperatures the subjects sat first 20 minutes in a neutral and rather windstill climate (t_a : 21–23°C, \bar{v}_a : <0.05 m/s, RH: 40–60%). They then moved into the climatic chamber where recording was resumed 5 minutes later and continued for another 55 or 60 minutes throughout the exposure to drafts.

In the neutral climate, the subjects completed a questionnaire which concerned actual health state, tiredness, previous sleep duration, alcohol and drug consumption, general thermal sensation (cold-cool-slightly cool-neutral-slightly warm-warm-hot), and thermal preference (whether the actual climate was comfortable or if a higher or lower temperature was preferred (ISO 10551⁷⁾)).

Thereafter, identical questionnaires were completed every 5 minutes throughout the sessions. They started with the assessment of general thermal sensation and thermal preference and were followed by a list of body sites. Eight sites were regarded in all 3 studies (forehead, neck, both forearms, legs, ankles). Separately for each of these locations the subjects answered in the affirmative or in the negative whether they felt airflows, whether they were annoyed by drafts or by the sensation of local cold. The paper-and-pencil method was used in the neutral climate and in Study 2 during the stay in the climatic chamber. In Studies 1 and 3 the subjects were then asked by the experimenter via an intercom system to avoid an interruption of the physical work. Skin temperatures

Table 1. Data of the subjects involved in the 3 studies

		mean \pm s.d.	min – max	mean \pm s.d.	min – max	mean \pm s.d.	min – max
Study 1		30 subjects		15 men (11, 15, 19°C)		15 men (11, 15, 23°C)	
age	[years]	23.9 \pm 2.5	20 – 29	23.3 \pm 2.4	20 – 28	24.5 \pm 2.4	21 – 29
height	[cm]	181.5 \pm 7.1	157 – 196	182.1 \pm 8.9	157 – 196	180.9 \pm 4.8	175 – 189
weight	[kg]	75.9 \pm 10.4	48 – 99	77.0 \pm 12.6	48 – 99	74.9 \pm 8.0	64 – 91
A_{DU}	[m ²]	2.0 \pm 0.2	1.5 – 2.2	2.0 \pm 0.2	1.5 – 2.2	1.9 \pm 0.1	1.8 – 2.2
VO_{2max}	[l/min]	3.4 \pm 0.7	2.0 – 4.5	3.3 \pm 0.7	2.0 – 4.5	3.5 \pm 0.7	2.3 – 4.5
VO_{2max}	[ml/min kg]	45.1 \pm 8.8	24.8 – 61.6	43.6 \pm 8.0	24.8 – 56.6	46.6 \pm 9.6	31.8 – 61.6
Study 2		16 subjects		8 women		8 men	
age	[years]	24.1 \pm 2.5	21 – 29	23.0 \pm 2.6	21 – 29	25.3 \pm 1.8	23 – 29
height	[cm]	176.1 \pm 8.6	164 – 190	169.5 \pm 5.2	164 – 180	182.8 \pm 5.5	173 – 190
weight	[kg]	69.9 \pm 11.3	57 – 95	61.6 \pm 3.2	57 – 65	78.1 \pm 10.3	65 – 95
A_{DU}	[m ²]	1.9 \pm 0.2	1.7 – 2.2	1.7 \pm 0.1	1.7 – 1.8	2.0 \pm 0.1	1.8 – 2.2
Study 3		12 male subjects					
age	[years]	25.5 \pm 1.4	23 – 28				
height	[cm]	183.7 \pm 4.4	175 – 190				
weight	[kg]	81.1 \pm 6.3	67 – 91				
A_{DU}	[m ²]	2.0 \pm 0.1	1.9 – 2.2				

A_{DU} : Body surface.

at the neck and at the left forearm were continuously registered with thermistors (YSI 427, Yellow Springs).

Clothing: The IREQ-model (ISO/TR 11079⁸⁾) and the PMV-model (ISO 7730⁹⁾) were used to calculate the clothing insulation required for thermal neutrality in air temperatures of 15°C and less IREQ_{neutral} or 19°C and more (PMV) and usual clothing habits at work were taken into account as well. As the arms and the neck are most sensitive both these sites were not covered by clothing¹⁰⁾. The clothing ensembles worn in the different thermal conditions are listed in Table 2.

Break-off criteria: The detailed experimental protocols were submitted to the ethic committee. This external committee is responsible for the approval of any experiment planned and executed in the Institute for Occupational Health. These comprise physiological, psychological, and toxicological experiments. The committee approved the experiments but prescribed for Studies 1 and 3 a break-off in case that heart rates exceed 150 beats per minute (which happened in none of the overall 318 experimental sessions). Informed consent was obtained from each subject.

Study 1: concerning the effects of air temperature (velocity and workload)

Thirty healthy men (20–29 yrs, Table 1) took part in the experiments. Mean air velocity, air temperature, and workload were varied in 3 steps each. To limit the number of sessions for the individual, a fractional factorial 3³-design was applied meaning that the 27 possible combinations were

distributed over ever 3 subjects and that each person took part in 9 randomly arranged sessions.

In the climatic chamber the subjects operated an arm ergometer during 50 minutes while adopting a standing posture. The workloads corresponded to measured metabolic rates of 104, 128, and 156 W/m². Horizontal airflows with mean velocities of 0.1, 0.2, and 0.3 m/s and a turbulence intensity of about 50% were directed towards the left dorsolateral body sites. All subjects worked in air temperatures of 11°C and 15°C; the 3rd step was splitted and ever fifteen subjects worked in 19°C or in 23°C, respectively, so that finally 36 different conditions were studied.

Study 2: concerning the effects of air temperature, horizontal and vertical airflows

Sixteen healthy persons (8 women, 8 men, 21–29 yrs, Table 1) took part in 8 randomly arranged experiments. In ever four sessions they were exposed to horizontal or to vertical airflows with air temperatures of 11, 15, 19 and 23°C, respectively. Mean air velocity was adjusted to 0.3 m/s and turbulence intensity to 50%. A stationary work with low metabolic rate was simulated applying a two-dimensional compensatory tracking test¹¹⁾. Using a standing chair the subjects stood 1.5 m in front of a 17-inch monitor which was adjusted to the head level and served to present the task which was controlled by a joy stick. The test was executed every 5 minutes before the questioning. It lasted 2.5 minutes and its purpose was to keep the subjects in a defined posture.

Table 2. Clothing ensembles in the various conditions of the 3 studies

Air temperature [°C]	11				15				19				23			
Workload [Watt/m ²]	70	104	128	156	70	104	128	156	70	104	128	156	70	104	128	156
Estimated insulation [clo]	1.5	1.5	1.0	0.6	1.2	1.1	0.7	0.5	0.6	0.6	0.4	0.4	0.5	0.4	0.4	0.4
Cotton socks			x	x			x		x	x	x	x	x	x	x	x
Terry socks	x	x			x	x		x								
Gym shoes	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Pants, short legs	x		x	x	x		x	x	x	x	x	x	x	x	x	x
Pants, long legs	x	x			x	x										
Undershirt, no sleeves							x	x							x	
T-shirt, short sleeves	x		x		x	x		x	x		x	x	x	x	x	x
Sweat-shirt	x	x									x	x				
Cotton shirt, half sleeves			x	x		x	x		x	x						
Flannel shirt, half sleeves	x	x			x											
Padded vest			x			x										
Jogging jacket	x	x			x											
Jeans			x	x		x	x	x	x	x	x	x	x	x	x	x
Jogging trousers	x	x			x											

As the range of air velocities applied was negligible for insulation, mean velocities were set to 0.2 m/s.

Study 3: concerning the effects of horizontal vs vertical airflows in moderate cold

Twelve healthy young men (Table 1) took part in 4 randomly arranged sessions. Airflows with mean velocities of 0.2 or 0.3 m/s and a turbulence intensity of 50% were directed either horizontally towards the dorsolateral body sites or vertically towards the person. Air temperature was adjusted to 11°C. In the climatic chamber the subjects executed while standing a defined dynamic work with an arm ergometer. Workload was equivalent to a metabolic rate of 128 W/m² (procedure see Study 1).

Statistics

Due to the different experimental designs, statistical analyses were executed separately for the 3 studies. Calculations were restricted to the determination of the influence of air temperature and direction on the effects of drafts. Other parameters that were varied in the 3 studies, e.g. air velocity in Study 1 and 3 and workload in Study 1 were not considered. The calculations were done across these conditions which was possible as they were evenly distributed over the experiments.

Statistical analyses refer mainly to the percentages of persons who stated for at least one body site that they were annoyed by drafts (draft-induced general annoyance).

Draft-induced local annoyance and its relation to the corresponding drop of skin temperature (the difference between the average values of the last minute in the neutral climate and the last 5 minutes of exposure) were considered for the left forearm and for the neck.

Concerning the effects of air temperature and direction of airflows generalized linear models were calculated for the questionnaire that was completed after the steady state was unequivocally reached, namely in the 45th minute in Studies 1 and 3 and in the 60th minute in Study 2. The steady state is concerned as an essential prerequisite for the reliable evaluation of the effects of drafts.

Results

The courses of subjective responses during exposure

Figure 1 presents the percentages of affirmative votes for draft-induced general annoyance and averaged thermal sensation during exposure, separately for Studies 1 and 2 and for the 4 air temperatures. Where annoyance reached a steady state soon within the first 10 minutes in Study 1, the number of affirmative votes increased further in Study 2 and reached the steady state not before 40 to 50 minutes

after exposure onset.

Concerning averaged general thermal sensation the subjects felt - apart from an air temperature of 23°C—cooler than in the neutral climate immediately after they entered the climatic chamber. This effect was strongly related to air temperature in both studies. Whereas thermal sensation became gradually warmer (less cool) within the following 20 minutes in Study 1 the subjects in Study 2 felt gradually cooler.

The influence of air temperature

Figure 2 presents the percentages of persons who revealed draft-induced general annoyance as well as averaged thermal sensation. The p-values as determined with the analysis of variance for the influence of air temperature are included as well. Figure 3 shows the percentages of persons who stated draft-induced local annoyance for the neck and for the forearm along with the corresponding drops of skin temperature and the p-values for the influence of air temperature. These figures reveal that draft-induced general annoyance is considerably more often in Study 2 and that the subjects felt much cooler than in Study 1. The same was true for draft-induced local annoyance which was again larger in study 2 whereas the drop of the corresponding skin temperatures was almost the same in both studies.

Subjective and physiological responses were systematically related to air temperature in both studies. The percentage of draft-induced general annoyance in Study 1 where the subjects performed a muscular armwork increased from 4% to 36% when air temperature decreased from 23°C to 11°C. This was similar in Study 2 except that annoyance was considerably more frequent; in 23°C the percentage was 16%, in 11°C already 72%.

General thermal sensation in Study 1 altered systematically from 'slightly warm' in 23°C to 'slightly cool' in 11°C. At the same time, averaged general thermal sensation in Study 2 altered gradually from almost 'neutral' to 'cool'.

Draft-induced local annoyance as reported for the neck and for the forearm and the drop of the corresponding skin temperature were again inversely related to air temperature. The lower the air temperature the more frequent was draft-induced local annoyance and the larger was the drop of skin temperature. The drop was considerably larger at the forearm than at the neck in both studies ($\approx 8^\circ\text{C}$ vs $\approx 3^\circ\text{C}$ at 11°C).

The influence of the direction

Table 3 presents the percentage of persons annoyed by drafts and averaged thermal sensation at the end of exposure,

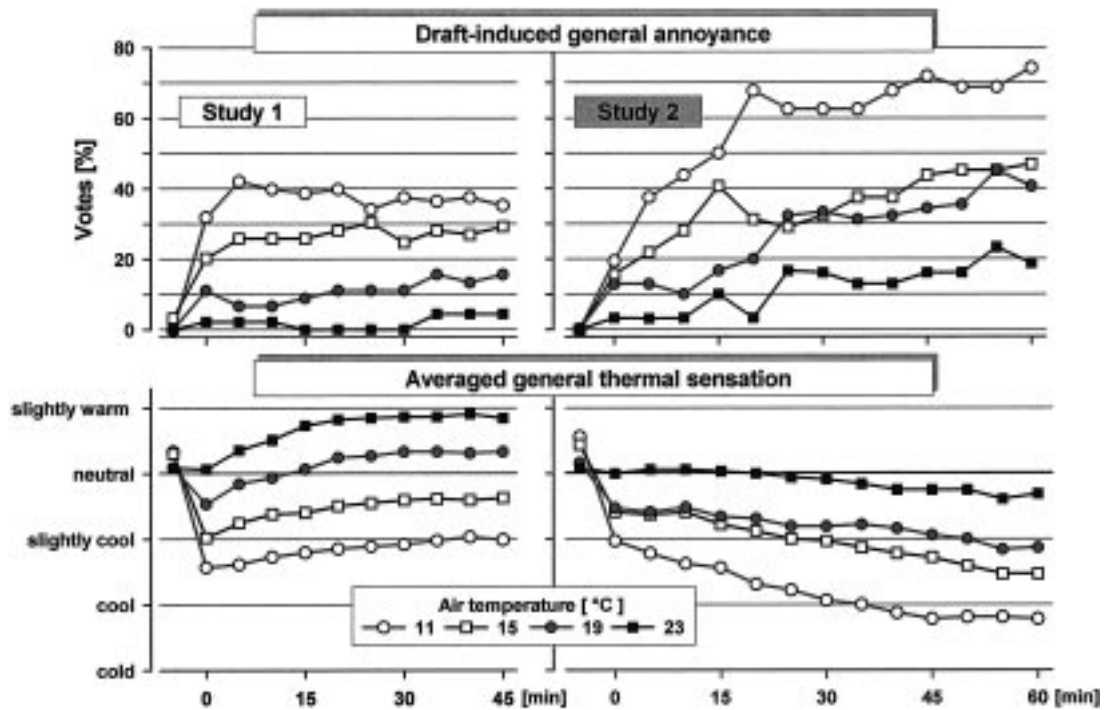


Fig. 1. Courses of the percentages of persons who were annoyed by drafts during exposure related to air temperature in 2 studies (Study 1: 30 young men, 20–29 yrs, Study 2: 8 women, 8 men, 21–29 yrs).

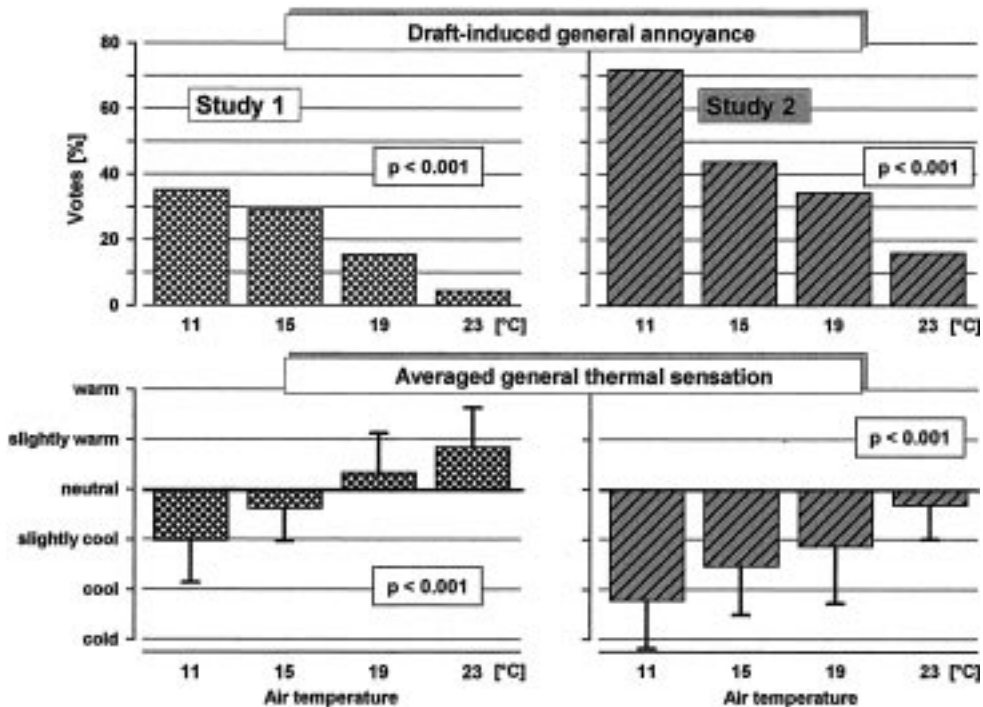


Fig. 2. Percentages of persons with draft-induced general annoyance and averaged general thermal sensation at the end of a 60 minutes exposure related to air temperature (Study 1: 30 young men, 20–29 yrs, Study 2: 8 women, 8 men, 21–29 yrs).

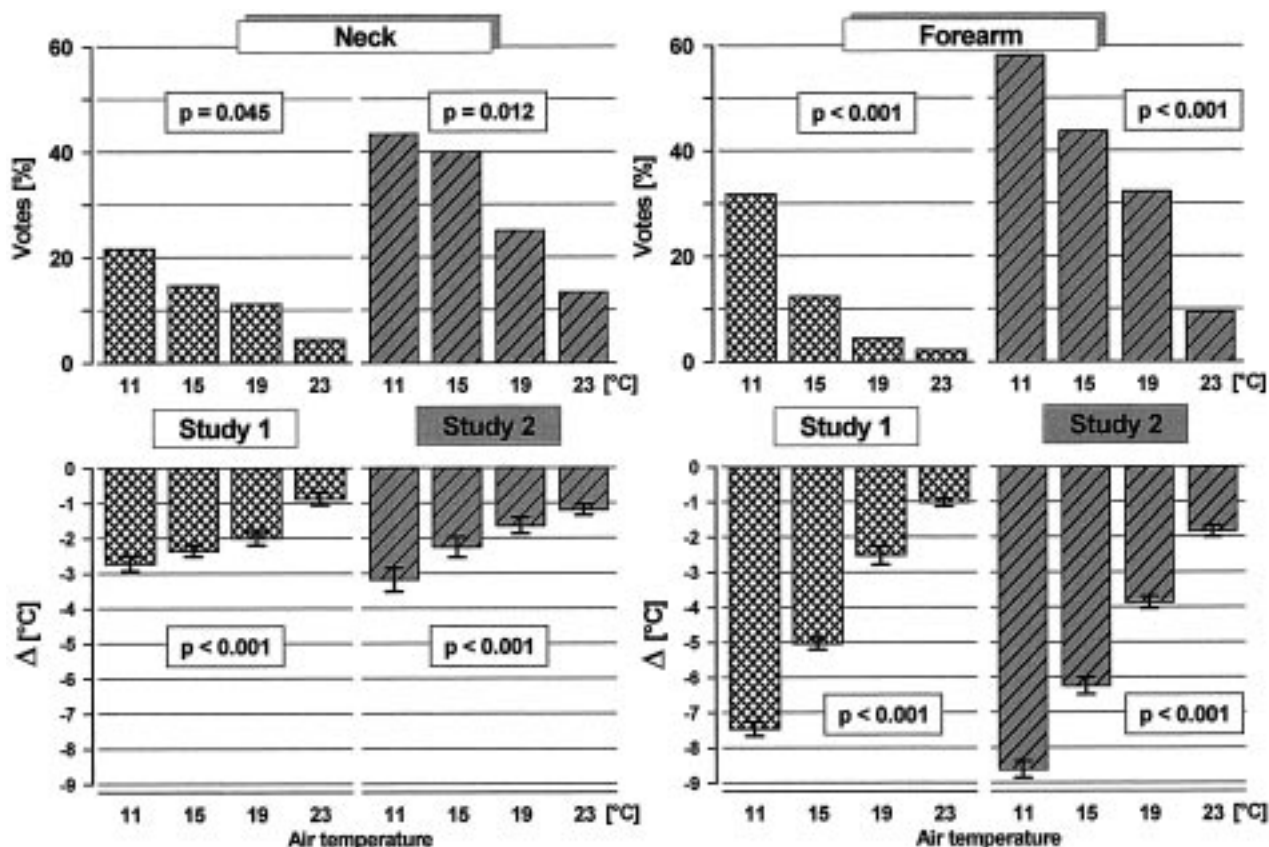


Fig. 3. Percentages of persons with draft-induced local annoyance as stated for the neck and for the forearm and the corresponding drop of skin temperature at the end of a 60 minutes exposure to draft related to air temperature (Study 1: 30 young men, 20–29 yrs, Study 2: 8 women, 8 men, 21–29 yrs).

Table 3. Draft-induced general annoyance and averaged general thermal sensation related to the direction of drafts in 2 studies

Direction	Draft-induced general annoyance		Averaged general thermal sensation	
	Study 2	Study 3	Study 2	Study 3
horizontal	54%	54%	- 1.3	- 1.3
vertical	36%	63%	- 1.4	- 1.3
p-value	<0.01	>0.05	1.000	0.503

separately for the 2 directions of drafts and for Studies 2 and 3 together with the p-values calculated with the analysis of variance. Figure 4 shows—again separately for both studies and directions—draft-induced local annoyance as stated for the neck and for the forearm together with the drop of skin temperature at the respective site.

As compared to vertical airflows horizontal drafts caused a significantly higher percentage of persons feeling annoyed in general only in Study 2, whereas averaged general thermal

sensation was not affected by the direction of drafts (Table 3). Concerning draft-induced local annoyance the only difference concerned a twice as high frequency with horizontal as compared to vertical airflows that affected the neck. The drop of skin temperature was not consistent with the subjective response. Horizontal drafts were associated with a numerically unimportant but larger drop at the neck in both studies, where vertical drafts in Study 2 were accompanied by a larger drop at the forearm and no difference occurred for that site in Study 3.

Discussion

Methodological aspects

Methodological studies were executed prior to these experiments to identify the most sensitive body parts and to elaborate a questionnaire by which misinterpretations of local cold are avoided.

Concerning sensitivity, ventral and dorsal body sites were

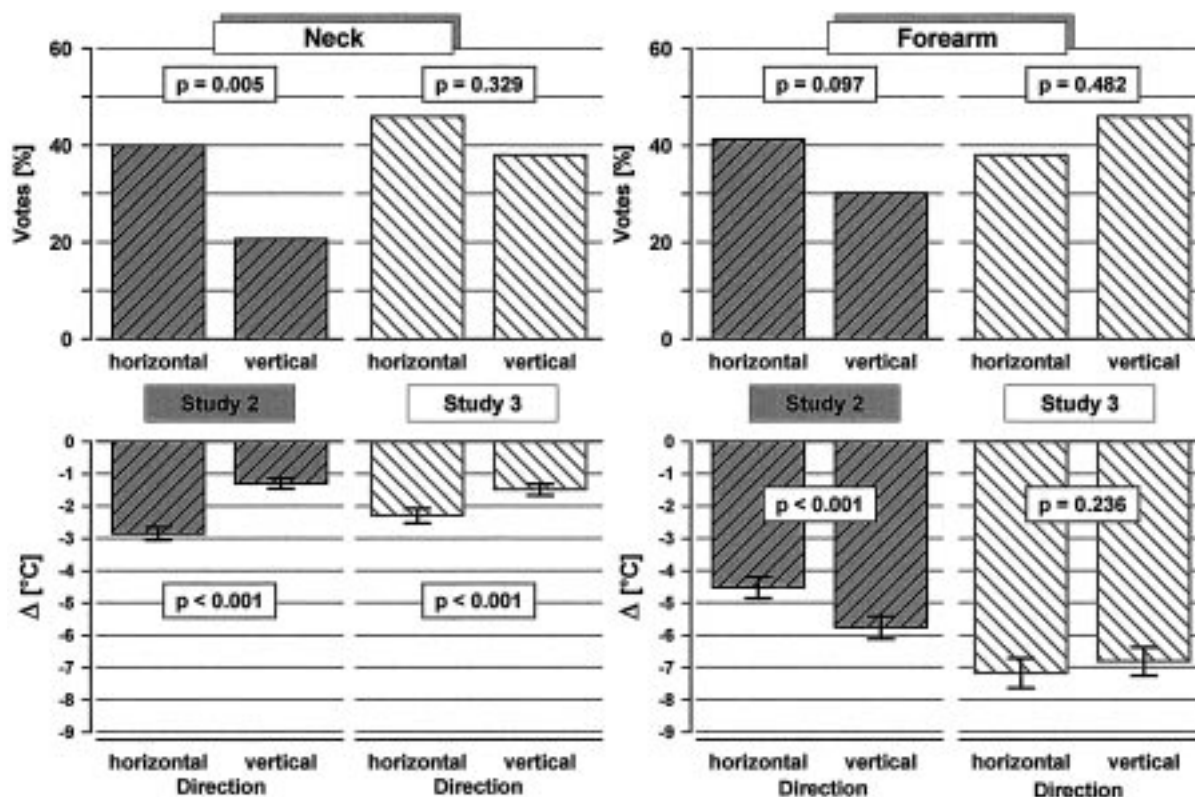


Fig. 4. Percentages of persons with draft-induced general annoyance and averaged general thermal sensation (standard deviation only in one direction) at the end of a 60 minutes exposure related to horizontal and to vertical airflows (Study 2: 8 women, 8 men, 21–29 yrs, Study 3: 12 young men, 23–28 yrs).

only affected if the drafts were accordingly directed. Perception thresholds were lowest for the ventral areas but drafts were then scarcely annoying. Among the dorsal sites high frequencies of affirmative votes were determined only for the neck. The extremities were affected by drafts from whatever direction and the arms revealed to be most sensitive.

Consequently, horizontal drafts in our studies were ever directed towards the dorsolateral body sites and neither the forearms nor the neck were covered by clothing (though overall insulation provided thermal neutrality).

Local cold due to whatever reason is usually related to drafts, even in windstillness. To avoid these misinterpretations the subjects answered every 5 minutes in the affirmative or in the negative, separately for various body sites whether they had perceived airflows, whether they were annoyed by drafts or by the sensation of local cold. Thus, they were forced to concern the cause of their sensations and this proved to be effective. None of the subjects neither in the prestudies nor in the control sessions of any experimental series executed in our lab ever had stated

to be affected by drafts in a rather windstill environment ($\bar{v}_a < 0.05$ m/s) whereas Fanger and Christensen¹²⁾ reported that some of their subjects have stated drafts at velocities of 0.04 m/s and less.

Courses of draft-induced general annoyance and general thermal sensation

In Study 1 draft-induced general annoyance was stated soon after the onset of exposure and the steady state whereafter the number of affirmative votes did not increase further, was reached within 10 minutes (Fig. 1) and this course was also found in Study 3. In Study 2, however, annoyance increased gradually during the first 40 to 50 minutes and this course was observed in any of our former experiments where sedentary subjects were exposed to drafts¹⁰⁾. At the end of exposure the percentage of persons annoyed by drafts was almost twice as high in Study 2 as compared to Study 1. The different courses are most likely related to the higher metabolic rate due to the muscular arm work in Studies 1 and 3, whereas the metabolic rate in Study 2 as well as in

our previous studies did not exceed 70 W/m^2 . The course of annoyance is probably mediated by general thermal sensation. In Studies 1 and 3 the subjects felt cooler immediately after the entrance into the climatic chamber but sensation then altered gradually towards neutral in the following 20 minutes whereas the subjects in Study 2 as well as in our previous studies felt gradually more often cooler during time. With increasing metabolic heat production enforced convective heat dissipation becomes probably less annoying.

Air temperature

The results of both Studies 1 and 2 verify the hypothesis that draft-induced general and local annoyance increases and that general thermal sensation becomes gradually cooler and skin temperature drops accordingly more with decreasing air temperature. This is in accordance with the observations of other authors who studied the temperature range of 18 up to 30°C ¹²⁻¹⁵. Similar effects were observed if the temperature of drafts were selectively lowered as compared to the room temperature^{14, 16-18}.

Similar conditions as in Study 1 were applied by Toftum and Nielsen⁶ where ten males operated an arm ergometer with metabolic rates of 104 and 129 W/m^2 while exposed to drafts with stepwise increasing velocity (every 15 min by 0.1 m/s from 0 to 0.4 m/s). However, no relation was found between air temperature and draft-induced annoyance which the authors explained by the fact that their subjects were ever dressed for thermal neutrality. Suitable clothing was also applied in the present study but the forearm and the neck were never covered by clothing. The greater unclothed skin area caused probably the excitation of a larger number of cold receptors, more impulses to reach the cortex and to evoke stronger reactions¹⁹. This is supported by Pedersen¹⁴, whose subjects wore clothing ensembles with insulation of 0.1 or 0.6 clo. For both these situations Pedersen determined first the individually preferred air temperature, which he then adjusted in the main experiments. Despite thermal neutrality in both situations the subjects reacted more to drafts if they wore clothing insulation of 0.1 clo i.e. if a greater skin area remained uncovered.

Direction of airflow

In real spaces horizontally directed drafts are mainly caused by (partly) open doors or leak windows, where vertically or diagonally (from above) directed drafts prevail in those spaces where the climate is controlled by air conditioning devices where the outlets are installed in the ceiling. Vertical air

streams are commonly considered as most annoying. Despite this, previous experiments concerned mainly the effects of horizontal drafts, which were directed towards the dorsal body sites^{12, 14, 20, 21}. Concerning horizontal drafts, pretests have shown that the reactions are largest if drafts are directed towards the dorsolateral body parts and thus affect the sensitive sites, namely the arms and the neck. This situation was compared with exposure to vertical drafts. The results revealed that drafts from both directions are almost equally annoying where horizontally directed drafts might be somewhat worse (Fig. 4). This is in accordance with a study of Mayer and Schwab²¹ who investigated the reactions of 25 women and 25 men (18–65 yrs). They directed horizontal drafts towards the ventral and the dorsal body sites and applied downwardly and upwardly directed vertical airflows. No effect was reported by Fanger *et al.*²² who applied air movements with a velocity of 0.8 m/s in 5 directions (vertical from above and beneath, horizontal from the front, the back and the side). Preferred air temperature did not depend on the direction of drafts. So, in view of preventive consequences, it is justified to restrict experimental observations to horizontal drafts.

The drop of skin temperature for the evaluation of drafts

The drop of skin temperature was not systematically related to annoyance. This contradicts the report of Houghten *et al.*¹⁶ who determined a decrease of thermal comfort at the neck and at the ankle as soon as skin temperatures decreased by 3°C at whatever site. But the present results are supported by Toftum¹ and by Pedersen¹⁴ who also could not determine a correlation between subjective and physiological responses. In addition, Nielsen and Nielsen²³ stated that ‘thermal sensation from local body areas, generally, did not correlate well with the skin temperature in the same area. The correlation for uncovered areas were especially low’.

The analysis of the data from 6 experimental studies executed in our institute revealed that not only the extent but also the courses of skin temperature vary extremely with the various body sites. It was therefore impossible to develop an evaluation criterion, i.e. a global measure for skin temperature as it was possible for the subjective response (draft-induced general annoyance, i.e. annoyance stated for at least one body site). An impressive example for the discrepancy between subjective and physiological responses gives Fig. 3. Though the extent of the drops were almost the same in two different studies, draft-induced local annoyance as stated for the same sites was significantly different. So, skin temperature is regarded rather as a

moderator variable than a causal factor for the perception and evaluation of drafts and not suitable for the evaluation of drafts.

Prediction of draft-induced general annoyance

Fanger *et al.*²⁰⁾ developed a mathematical model that predicts the percentage of persons dissatisfied by drafts (PD) and which is supposed to be valid for sedentary persons, drafts with mean air velocities up to 0.4 m/s, turbulence intensities up to 70%, and air temperatures from 20 to 26°C (ISO 7730⁹⁾). As this model underestimated the effects for persons who operated an arm ergometer in air temperatures of 11°C to 20°C, Toftum¹⁾ extended the model with concern to workload and to the variation of mean skin temperature (t_{sk}) due to air temperature and workload. The resulting model was applied to the 40 thermal conditions concerned in the present

$$PD = (t_{sk} - t_a) \cdot (\bar{v}_a - 0.05)^{0.6223} \cdot (3.143 + 0.37 \cdot \bar{v}_a \cdot Tu) \cdot [1 - 0.013 \cdot (M - W - 70)],$$

where t_a = air temperature [°C], \bar{v}_a = mean air velocity [m/s], Tu = turbulence intensity [%], M = mean metabolic rate [W/m²], and W = external work [W/m²] paper. The results are plotted in Fig. 5a against the observed percentages of persons annoyed and reveal again an underestimation. This is probably related to the experimental design Toftum¹⁾ has applied, in particular to the stepwise increase of air velocity (every 15 minutes by 0.1 m/s from almost 0 to 0.4 m/s) which does not meet the real situation where the workers are exposed to defined drafts during their whole shifts. Second, Toftum's subjects had worn long sleeves and high collars which is again not realistic for many workplaces even in moderately cold. Third, the workload in his study was varied in a smaller range. Fourth turbulence intensities were much lower (10 to 40%) than at real workplaces and fifth Toftum interrupted the work at the arm ergometer ever after 4 minutes so that the subjects could complete the questionnaire in the fifth minute.

It becomes apparent from Fig. 5a that the deviations concern particularly higher workloads. Griefahn *et al.*^{2, 24)} who have observed altogether 107 persons in a greater range of conditions corrected the Toftum-model accordingly. As shown in Fig. 5b the predictive power of the modified model is significantly better than that of

$$PD = (t_{sk} - t_a) \cdot (\bar{v}_a - 0.05)^{0.62} \cdot (3.14 + 0.37 \cdot \bar{v}_a \cdot Tu) \cdot [1 - 0.0061 \cdot (M - W - 70)]$$

the equation provided by Toftum²⁾. Due to the underlying

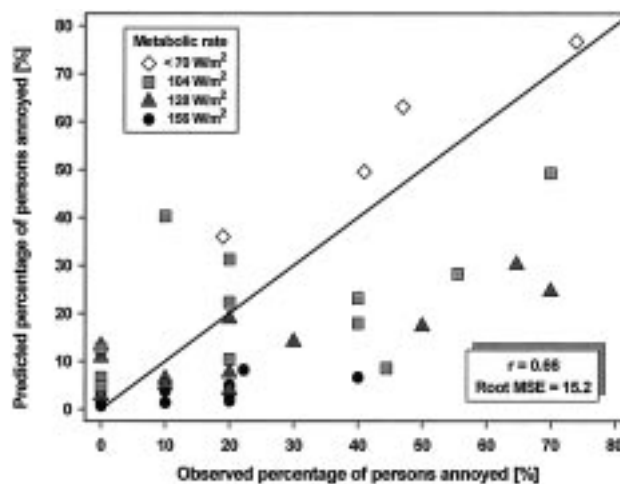


Fig. 5a. Draught-induced general annoyance at the end of a 60 minutes exposure to draft as predicted with the draught-rating equation developed by Toftum [1994] versus the actually observed percentages.

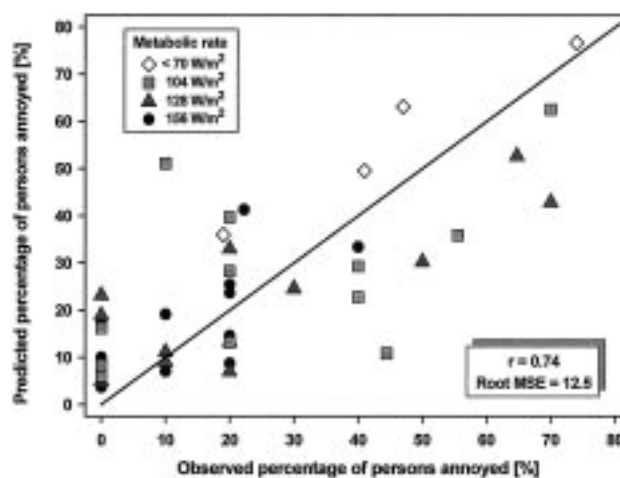


Fig. 5b. Draught-induced general annoyance at the end of a 60 minutes exposure to draft as predicted with the modified Toftum-model [Griefahn *et al.* 1999] versus the actually observed percentages.

experiments the modified model applies for the same ranges as the Toftum-model concerning mean air velocity and turbulence intensity but for broader ranges concerning air temperature and workload (namely t_a : 11–23°C and M : <70–156 W/m²).

Conclusions

Three studies were analyzed to determine the effects of drafts, in particular the influence of air temperatures and

horizontal versus vertical airflows. The experiments concerned the real situation at the workplace as far as possible. The physical parameters of drafts, i.e. mean air velocity, turbulence intensity, the air temperature and workload were kept constant during the single sessions and the subjects were dressed for thermal neutrality. Draft-induced annoyance was rated every 5 minutes using a list of prescribed body parts and skin temperature was measured throughout the sessions at the forearm and at the neck.

The percentage of draft-induced general annoyance and draft-induced local annoyance as reported for the neck and for the forearm and the drop of the corresponding skin temperature were—as hypothesized—inversely related to air temperature. Concerning the direction of drafts there was no clear effect though horizontal drafts seem to cause somewhat stronger effects. In view of preventive measures against the impact of drafts it is therefore justified to deduce recommendations from experiments executed with horizontal airflows. The model for the prediction of the percentage of annoyed persons that was developed by Toftum¹⁾ on the basis of the draft rating model proposed in ISO 7730⁹⁾ for persons working in moderate cold revealed an underestimation. A modified version proposed by Griefahn *et al.*²⁾ provides a better prediction. Due to the underlying experiments the modified model applies for the same ranges as the Toftum-model concerning mean air velocity and turbulence intensity but for broader ranges concerning air temperature and workload (namely t_a : 11–23°C and M: <70–156 W/m²). It is therefore suggested to replace the Toftum-model and the draft rating model in ISO 7730⁹⁾.

Acknowledgement

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References

- 1) Toftum J (1994) Trækgener i det industrielle arbejdsmiljø. Licentiatafhandling, laboratoriet for varme- og klimateknik. Danmarks Tekniske Universitet.
- 2) Griefahn B, Künemund C, Gehring U (1999) Wirkung und Bewertung von Zugluft am Arbeitsplatz. In: Arbeitsphysiologie heute. eds. by Bolt HM, Griefahn B, Heuer H, Laurig W, Bd 1, 30–45, IfADo Dortmund.
- 3) Griefahn B (1995) Arbeit in mäßiger Kälte. Schriftenreihe der Bundesanstalt für Arbeitsschutz, Fb 716, Wirtschaftsverlag NW, Bremerhaven.
- 4) Mäkinen H (1992) Variation in the protection against cold in the food industry. In: Proceedings of the Fifth Int Conf on Environmental Ergonomics. eds. by Lotens WA, Havenith G, Maastricht/The Netherlands, Nov 2–6 1992, 194–5. TNO-Institute for Perception, Soesterberg.
- 5) Toftum J (1994) A field study of draught complaints in the industrial work environment. In: Proceedings of the Sixth International Conference on Environmental Ergonomics. eds. by Frim J, Ducharme MB, Tikuisis P, Scientific Information Center, Defence & Civil Institute of Environmental Medicine. 252–3, North York Ontario, Canada.
- 6) Toftum J, Nielsen R (1996) Impact of metabolic rate on human response to air movements during work in cool environments. *Int J Indust Ergonomics* **18**, 307–16.
- 7) ISO 10551 (1995) Ergonomics of the thermal environment—Assessment of the influence of the thermal environment using subjective judgement scales. ISO Geneva.
- 8) ISO/TR 11079 (1993) Evaluation of cold environments—Determination of required clothing insulation (IREQ). ISO Geneva.
- 9) ISO 7730 (1994) Moderate thermal environments—Determination of the PMV and PPD indices and specification of the conditions for thermal comfort. ISO Geneva.
- 10) Griefahn B (1999) Bewertung von Zugluft am Arbeitsplatz. Schriftenreihe der Bundesanstalt für Arbeitsschutz und Arbeitsmedizin. Fb 828, Wirtschaftsverlag NW, Bremerhaven.
- 11) AGARD Advisory Group for Aerospace Research and Development (1989) Human performance assessment methods (AgardDograph No 308). Neuilly sur Seine: AGARD.
- 12) Fanger PO, Christensen NK (1986) Perception of draught in ventilated spaces. *Ergonomics* **29**, 215–35.
- 13) Rohles FH, Woods JE, Nevins RG (1974) The effects of air movement and temperature on the thermal sensations of sedentary men. *ASHRAE Transactions* **80**, 101–19.
- 14) Pedersen CJK (1977) Komfortkrav til luftbevægelser i rum. Licentiatafhandling, laboratoriet for varme-og klimateknik. Danmarks Tekniske Højskole.
- 15) Fanger PO, Pedersen CJK (1977) Discomfort due to air velocities in spaces. I.I.F.-I.I.R.-Commissions B1, B2 and E1, Belgrade.

- 16) Houghten FC, Gutberlet C, Witkowski E (1938) Draft temperatures and velocities in relation to skin temperature and feeling of warmth. *ASHRAE Transactions* **44**, 289–308.
- 17) Fishman DS (1978) Subjective effects of air movement around the feet. *CIBS Symposium: Man Environment and Buildings*, Sept 1978.
- 18) McIntyre DA (1979) The effect of air movement on thermal comfort and sensation. *Proceedings from the first International Indoor Climate Symposium*, 541–60, Copenhagen.
- 19) McIntyre DA (1980) *Indoor climate*. London: Applied Science.
- 20) Fanger PO, Melikov AK, Hanzawa H, Ring J (1988) Air turbulence and sensation of draught. *Energy and Buildings* **12**, 21–39.
- 21) Mayer E, Schwab R (1990) Untersuchung der physikalischen Ursachen von Zugluft. *Gesundheits-Ingenieur- gi* **111**, 17–30.
- 22) Fanger PO, Ostergaard J, Olesen S, Lund Madsen Th (1975) The effect on man's comfort of a uniform air flow from different directions. *ASHRAE Transactions* **80**, 142–57.
- 23) Nielsen R, Nielsen B (1984) Influence of skin temperature distribution on thermal sensation in a cool environment. *Eur J Appl Physiol* **53**, 225–30.
- 24) Griefahn B, Gehring U, Künemund C (in press) Empfindung und Bewertung von Zugluft. *Z Arb wiss.*