# PERCEIVED AIR QUALITY AND THE THERMAL ENVIRONMENT

4207

**L.G. Berglund** **W.S. Cain**

## ABSTRACT

*Occupants' perceptions of air freshness, stuffiness, and acceptability are predictably influenced by the thermal parameters of the environment. This conclusion was derived from the subjective responses of 20 subjects studied at three temperatures, three humidities, and three activity or metabolic rates. Air was perceived to be fresher and less stuffy with decreasing temperature and humidity. The effect of temperature was linear and stronger than humidity. The effect of humidity on freshness, stuffiness, and acceptability of air quality was smaller in the dew point range of 35° to 52°F (2° to 11°C) than in the range from 52° to 68°F (11° to 20°C). Air quality was typically judged not very acceptable when relative humidity exceeded 50%. The perception of the freshness, staleness, and stuffiness proved independent of metabolic rate in the activity range from sitting quietly to continuous walking. However, the acceptability of the air decreased when the subjects felt warmer than neutral and when their skin felt damp or wetter, both of which are affected by metabolic activity.*

## INTRODUCTION

The perceived quality of the air in a building depends upon a combination of the chemical and physical properties of the air. For the person fresh from another space, chemical properties will predominate. Specifically, the person's judgment of acceptability will correlate strongly with level of odor (Cain et al. 1983). A place with a high level of occupancy odor, for example, will be judged unacceptable, even though the visitor to the space may not consciously focus on odor (Cain 1979). The air quality may just seem poor.

For the person who has occupied a space for a while, the chemical properties of the atmosphere will generally seem less salient than its physical properties. That is, odor will have less relevance than temperature, humidity, and air motion. Higher than desirable temperatures, high humidity, and low air motion may create unacceptable feelings of stuffiness and closeness. The introduction of fresh, outside air may alleviate such feelings insofar as it reduces temperature and humidity. On the other hand, cooler and drier air may suffice even without introduction of fresh air. Hence, the need for fresh air can rest largely on the illusion that cooler and drier air is somehow freer of contaminants.

Recent investigations of ventilation requirements for human comfort have focused more on the chemical parameters of the atmosphere (e.g., occupancy odor, environmental tobacco smoke, formaldehyde) than on physical parameters and, accordingly, more on the judgments of visitors fresh from another space than occupants of the space. In actual field circumstances, however, judgments of poor air quality will most often arise from occupants.

The present investigation examines the perception of air quality for various combinations of physical parameters. It addresses such issues as the relative importance of temperature vs. humidity on perceived air freshness. In its focus on the occupant, it has something in common with the classic investigation of the New York State Commission on Ventilation, 1913–1922 (Winslow 1922). The present results, as well as those of that earlier study, suggest the need to understand the combined effect of both physical and chemical factors on perceived air quality. The results reported here formed part of a larger investigation (Berglund 1989) on human responses to temperatures and humidities of air-conditioned environments in the summer.

## EXPERIMENTAL PROGRAM

The experiments were conducted in a 17.5 ft by 20.5 ft by 8 ft chamber (Kjerulf-Jensen et al. 1975) that provides uniform conditions of temperature and humidity with an air speed of 10 fpm (0.05 m/s). Human responses were obtained at conditions that bracketed the ASHRAE summer comfort zone. Specifically, test temperatures equaled 70°, 75°, and 81°F (20°, 24°, and 27°C) (air temperature = mean radiant temperature) with humidity levels defined by dew point temperatures of 36°, 52°, and 68°F (2°, 11°, and 20°C). Humidification was achieved by injection of low-pressure steam made from untreated tap water. The ventilation rate of the chamber, measured via decay of $CO_2$ under actual test conditions, averaged 157 ± 18 cfm, with no significant variation with temperature or humidity.

Twenty test subjects (10 men and 10 women) with diverse socio-economic status participated. Ages of the subjects ranged from 18 to 62 with an average of 35 years.

Occupants of commercial spaces, such as offices and stores, typically exist at various levels of activity from sitting quietly to continuous walking. Increased activity results in increased physiological effort, metabolic heat, and perspiration, all of which may affect sensations of comfort and air quality. The study accordingly assessed perceptions and physiological responses at three activity states from sedentary (1 met) to continuous walking (3 met), where 1 met = 58.3 W/$m^2$, the nominal energy level of a resting person. The intermediate level (2 met) was accomplished through a repetitive routine of 5 min walking and 5 min standing.

Each of the 20 subjects participated in 27 different hour-long test conditions defined by the combination of the three temperatures, three humidities, and three metabolic rates. Such a design offered considerable sensitivity to small differences in responses.

The subjects wore their own summer clothing (slacks, long- or short-sleeve shirts). The insulation level of their attire was evaluated each day using the checklist method (ASHRAE 1981). It averaged 0.56 ± .04 clo. For reference, a winter business suit has a value of about 1 clo.

Twenty-five percent of the subjects (five) were instrumented to measure internal and skin temperatures, heart rate, and skin wettedness. The temperatures were measured

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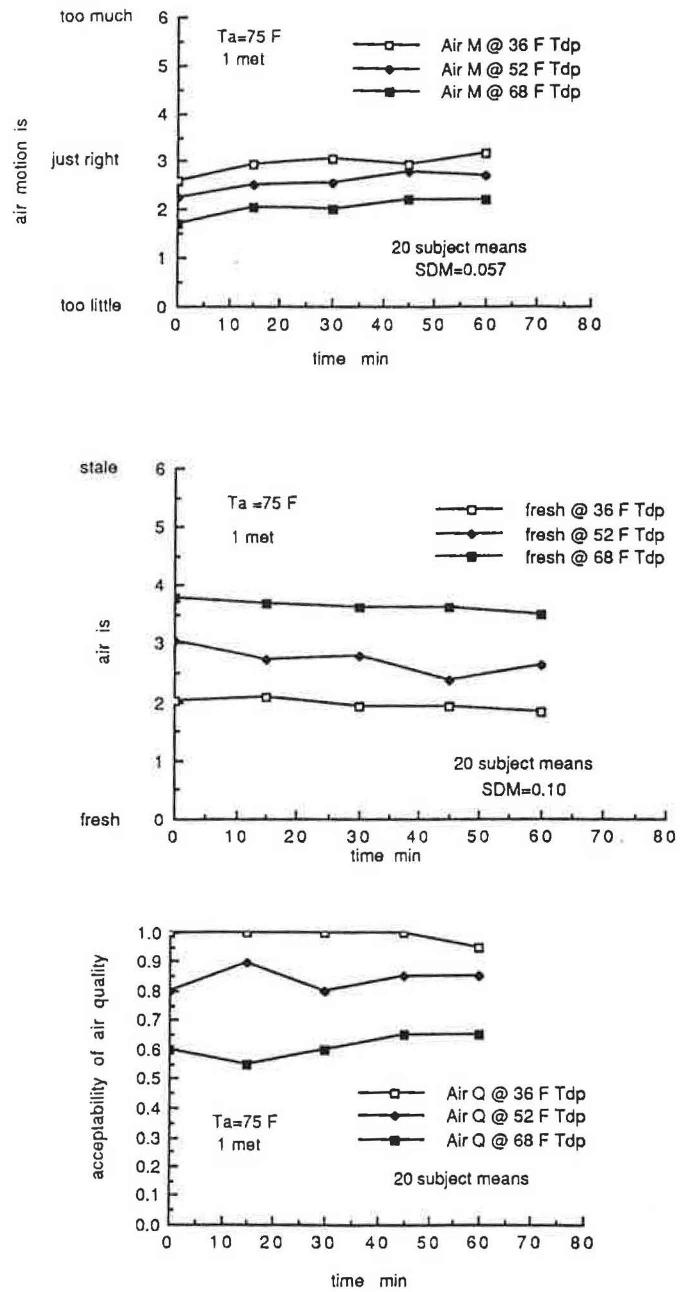


*Figure 1 Perceived air motion, freshness, and acceptability over time*

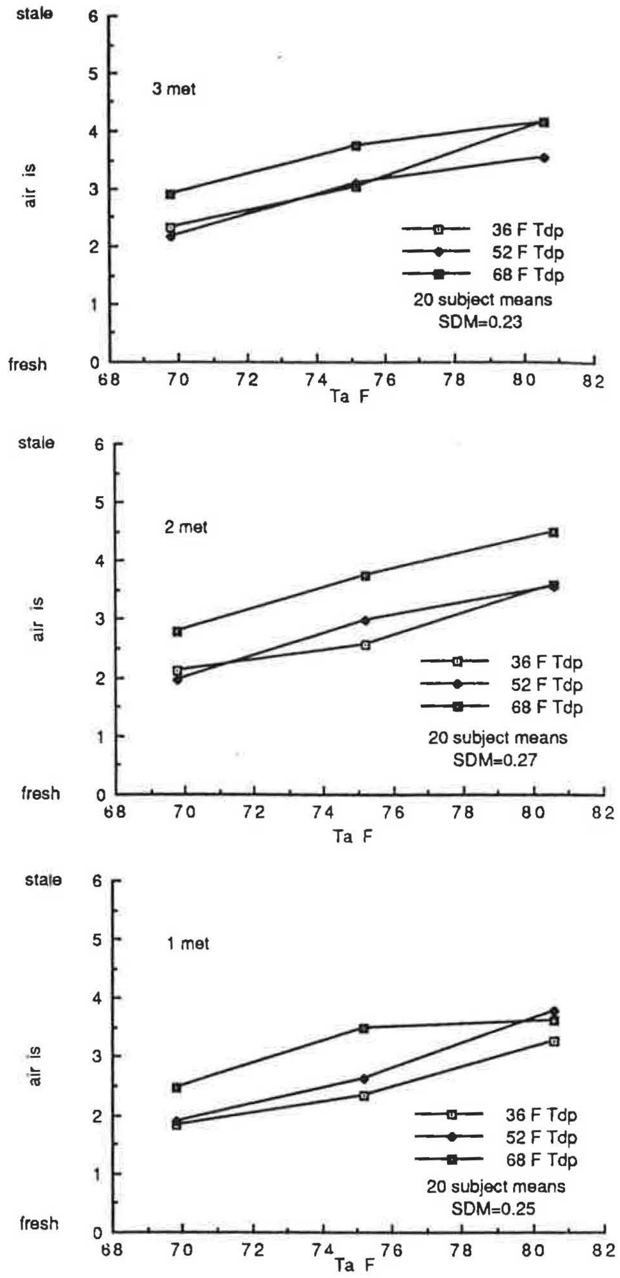


*Figure 2 Perception of air's freshness at 1, 2, and 3 met*

via thermocouples read by an on-line computer. Internal temperature was measured in the esophagus at the level of the heart. Skin temperatures were measured on the face, hand, upper and lower arm, chest, back, thigh, and calf. Skin wettedness was calculated from humidity measurements made under the clothing. Miniature dew point sensors on the back, chest, arm, thigh, and calf measured humidity 2 mm above the skin. Local dew point and skin temperatures, together with the ambient humidity, were combined to determine the local skin wettedness ($w$)—defined as the ratio of local evaporation rate ($E$) to the maximum evaporation rate ($Emax$) that would occur when the skin at that point is completely covered with water. Maximum evaporation occurs when the measured vapor pressure ($Pm$) just above the skin equals the saturation vapor pressure ($Pssk$) for water at skin temperature. At submaximal evaporation rates the skin is not completely covered with water and the measured dew point temperature is less than the temperature of the skin. Assuming the mass transfer characteristics through the clothing and boundary layers are the same for maximal and submaximal evaporation, skin wettedness by definition ($w = E/Emax$) becomes the ratio of the vapor pressure differences for the two cases:

$$w = (Pm - Pa)/(Pssk - Pa),$$

where $Pa$ represents ambient vapor pressure. The mean skin wettedness under clothing and the mean skin temperature comprise the area-weighted averages of the local values.

The subjects were usually tested in groups of five except for the instrumented subjects, who were tested individually on a treadmill. The others could either walk about the test chamber or use the treadmill for the walking. Tests lasted one hour for the uninstrumented subjects and a bit longer for the instrumented subjects.

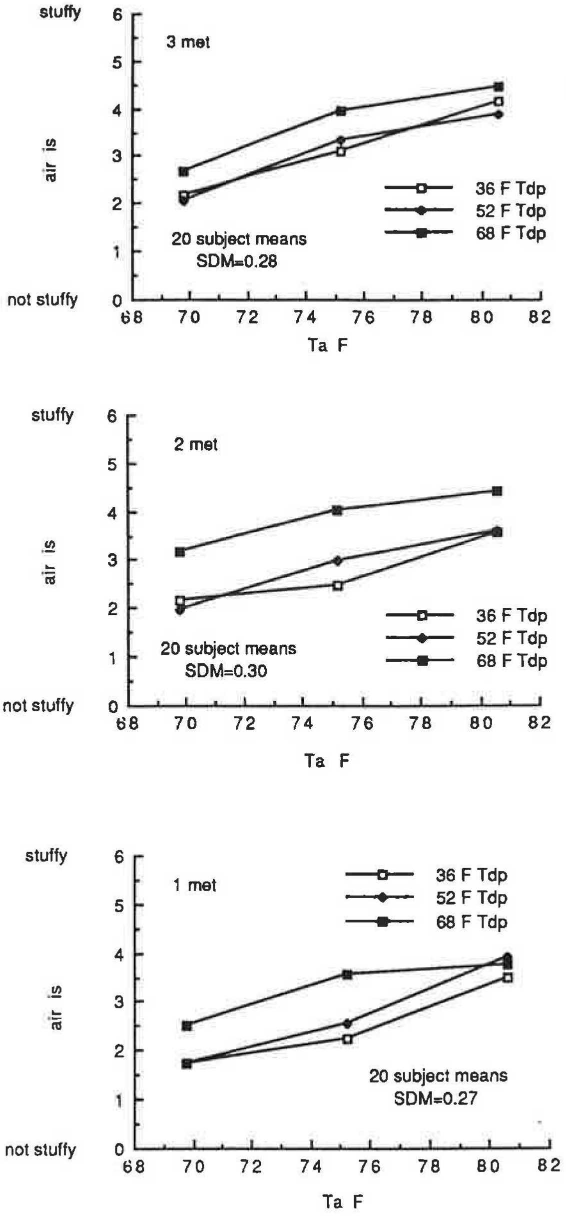


*Figure 3 Stuffiness of the air as judged by 20 subjects at three levels of activity*

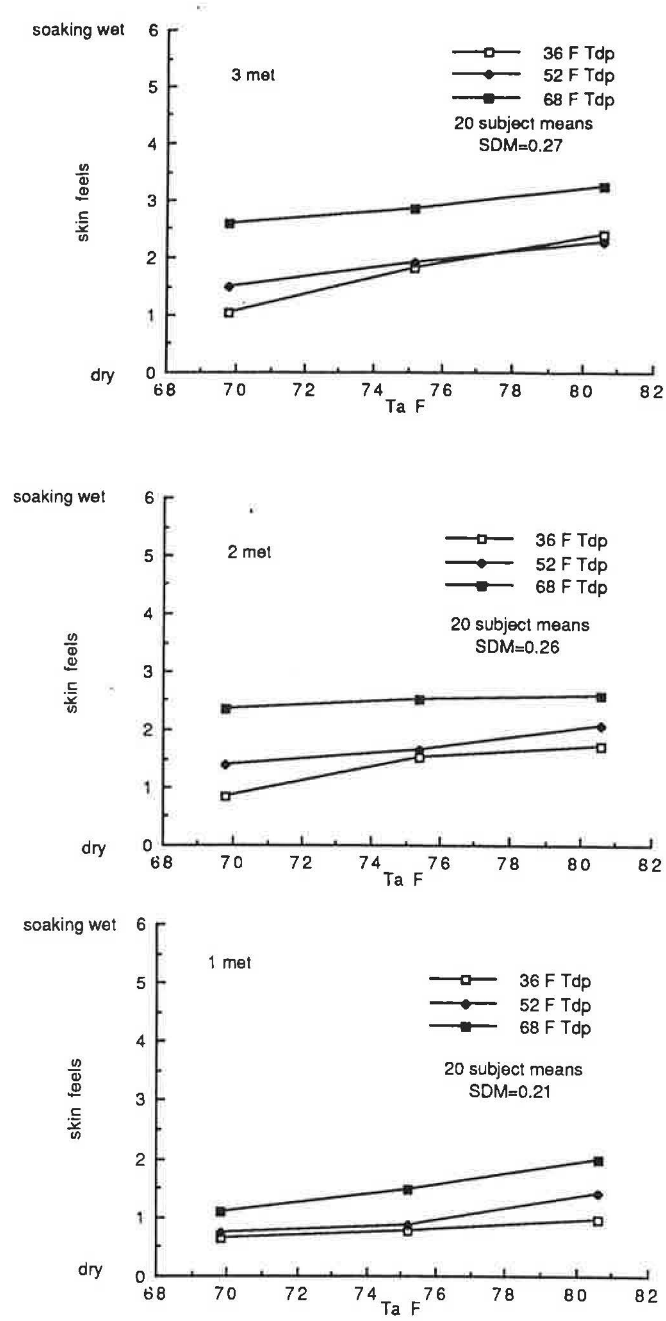


*Figure 4 Perceived skin wettedness at three levels of activity*

Instrumented subjects had their rate of oxygen consumption measured twice per test with the open-loop method. The overall average metabolic rates for the activities calculated from these measurements were:

| | |
|---|---|
| Sitting | 0.94 met |
| Intermittent walking | 1.95 met |
| Continuous walking | 2.82 met |

Energy production during intermittent walking equaled about twice that of sitting and the heat produced by continuous walking equaled about three times that of sitting. All of the metabolic energy of these experiments ended up as heat since the subjects did no net thermodynamically useful work.

Participants gave subjective responses immediately upon entering the chamber and every 15 min thereafter using a questionnaire. Three of the questions concerned air quality directly (freshness, stuffiness, and acceptability), whereas four concerned air quality only indirectly (skin moisture, humidity, air motion, and thermal sensation). The subjects marked a line to indicate how they felt at that moment. For the air freshness scale, the line was bounded by "fresh" at one end and "stale" at the other. For stuffiness, the line was bounded by "stuffy" and "not stuffy"; for humidity, by "very dry" and "very humid"; for skin wettedness or skin moisture, by "dry" and "soaking wet"; and for air motion, by "too much" and "too little." The thermal sensation scale comprised the nine-point ASHRAE scale from "very cold" to "very hot." For the question of acceptability, the subjects judged whether or not the air quality was acceptable, under instructions that an unacceptable condition would evoke a behavioral action to improve the climate and/or reduce discomfort, e.g., open a window, turn on a fan, change the thermostat setting, complain, or leave.

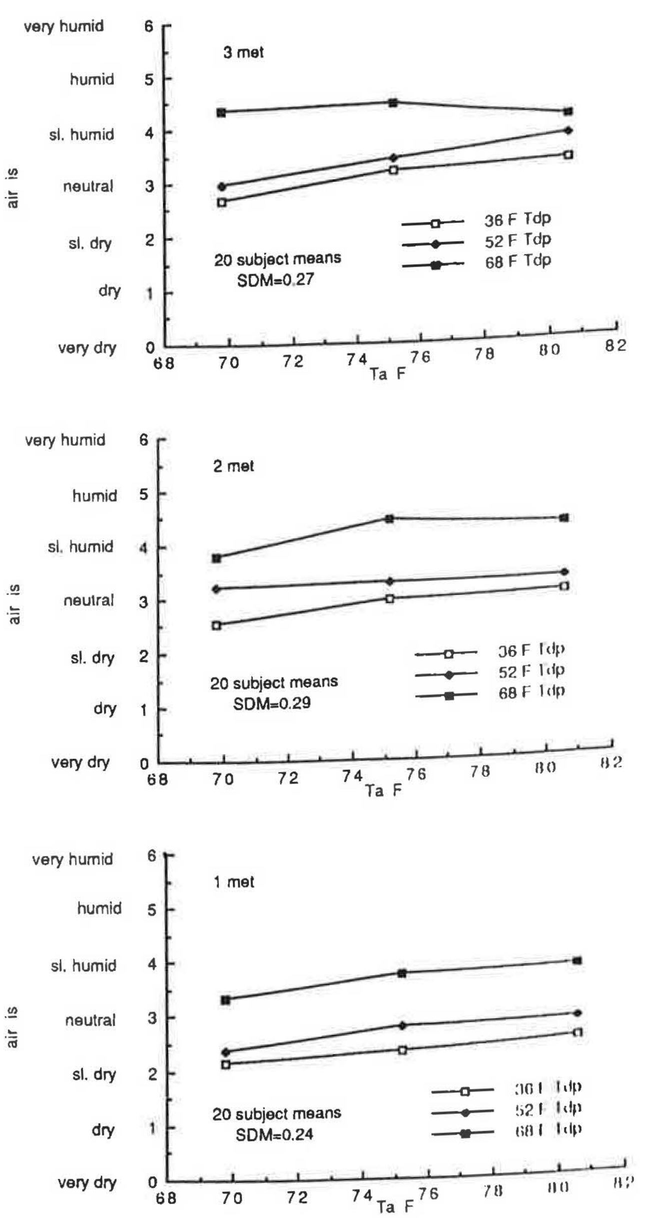


*Figure 5 Perceived humidity level of ambient environment at three activity levels*

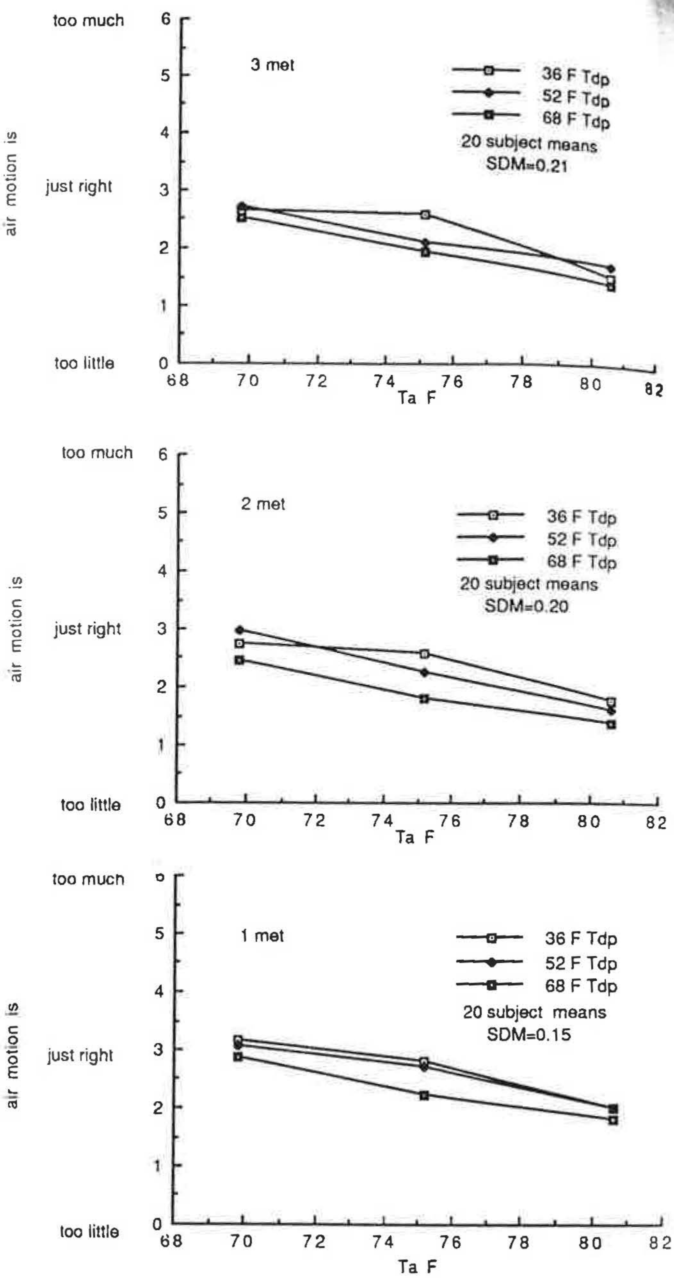


*Figure 6 Adequacy of the air motion at three levels of activity*

## RESULTS

### Responses Over Time

Figure 1 depicts the perception of air motion, freshness, and acceptability over time for the sedentary case at 75°F. Perceived air motion increased slightly over time at all three dew points. At all points in time, however, air motion appeared slower at the higher humidities. Perceived air freshness and acceptability proved even more stable with time. Higher humidity, however, made the air appear less fresh and less acceptable. A slightly greater time dependence arose with thermal sensation and perceived skin wettedness, both of which reached fairly stable levels by 45 min. The physiological measurements of internal and skin temperature and skin moisture reached steady levels within 30 min. In Figure 1 and those that follow, the data points indicated are the means of 20 subjects. The average standard deviation of the means (SDM) is also indicated where applicable.

### Steady-State Responses

Since the data changed little with time, particularly after 30 min, we will focus hereafter on steady-state values. The figures that follow contain responses given at the end of the testing and figures are arranged to show a given response at all three activity levels.

The subjects perceived the air as less fresh, i.e., more stale, at higher temperatures and dew points (Figure 2). The effect of temperature was more pronounced than that of humidity. The responses were, however, less consistently related to activity.

Stuffiness (Figure 3) was rated similarly to freshness-staleness, i.e., stuffiness increased with increasing temperature and humidity. Activity had only a slight effect on the perception. The correlation between perceived freshness-staleness and stuffiness equaled 0.98. For all practical purposes, the judgment of one attribute seems interchangeable with that of the other.

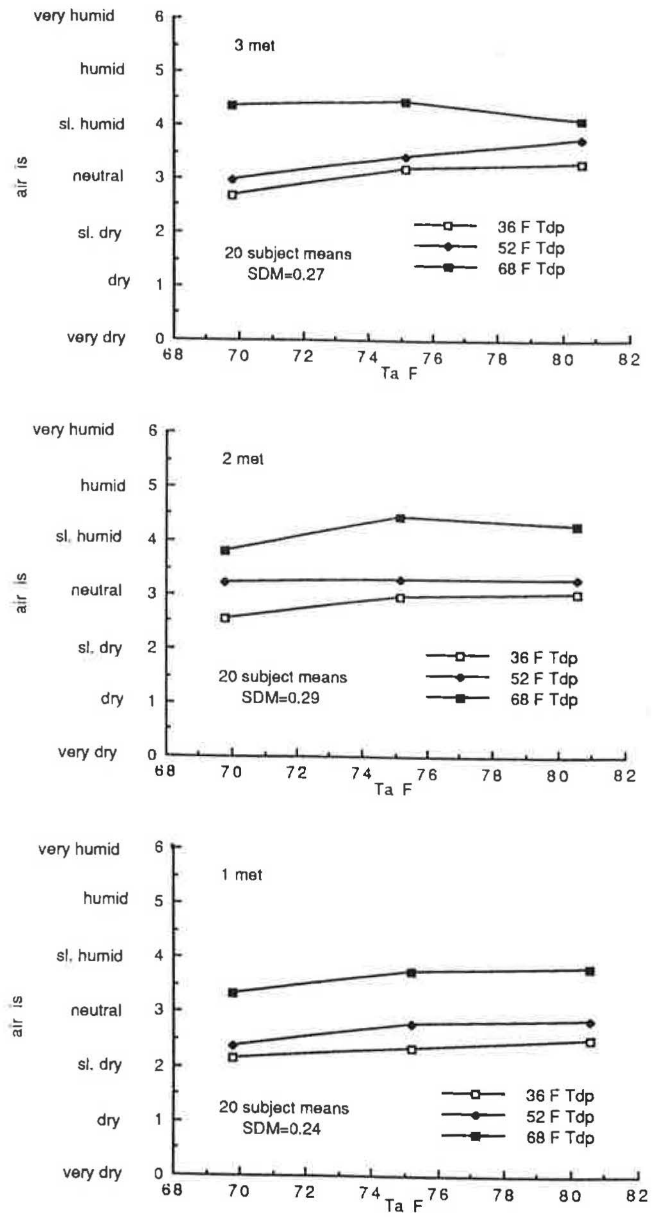


*Figure 5* *Perceived humidity level of ambient environment at three activity levels*

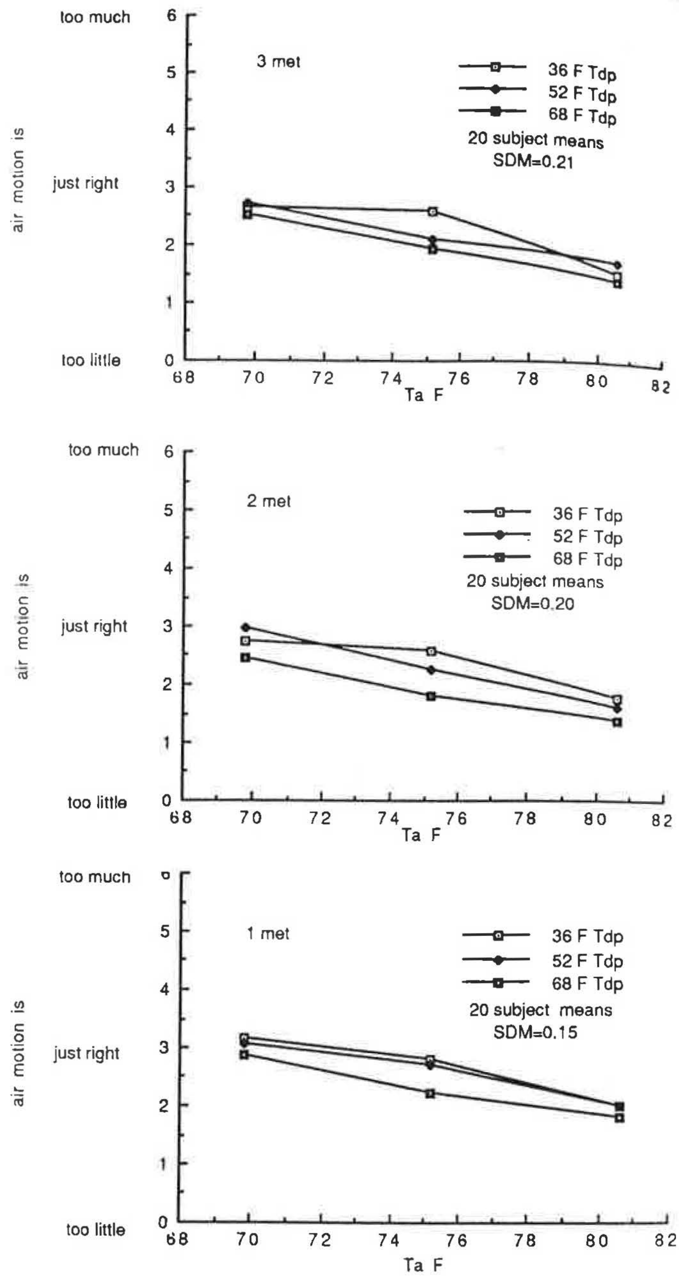


*Figure 6* *Adequacy of the air motion at three levels of activity*

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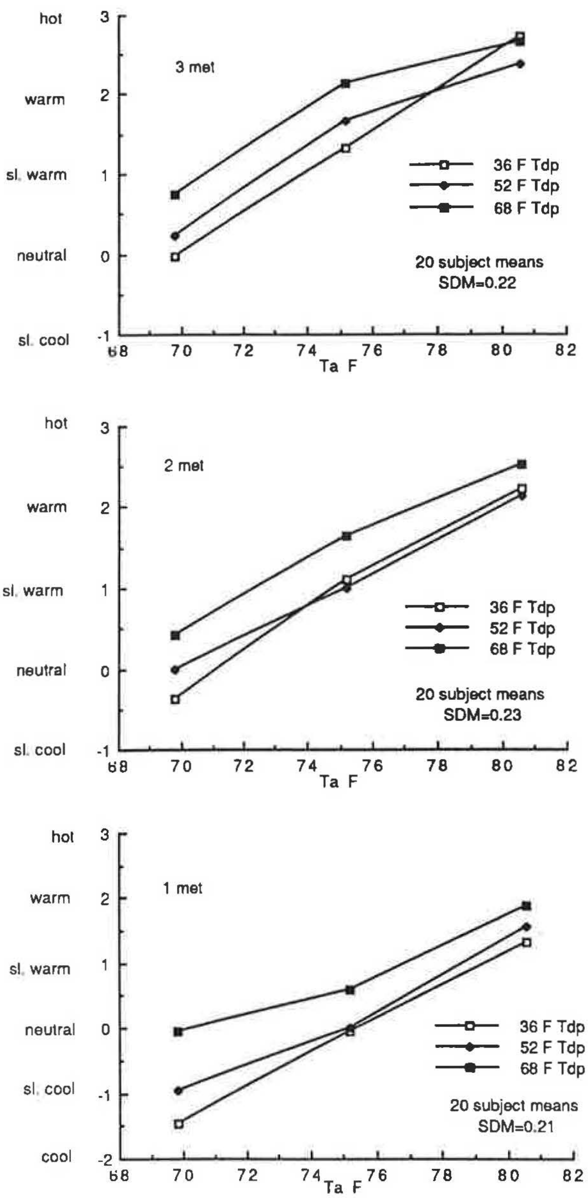


***Figure 7*** *Thermal sensations after one hour at three activity levels*

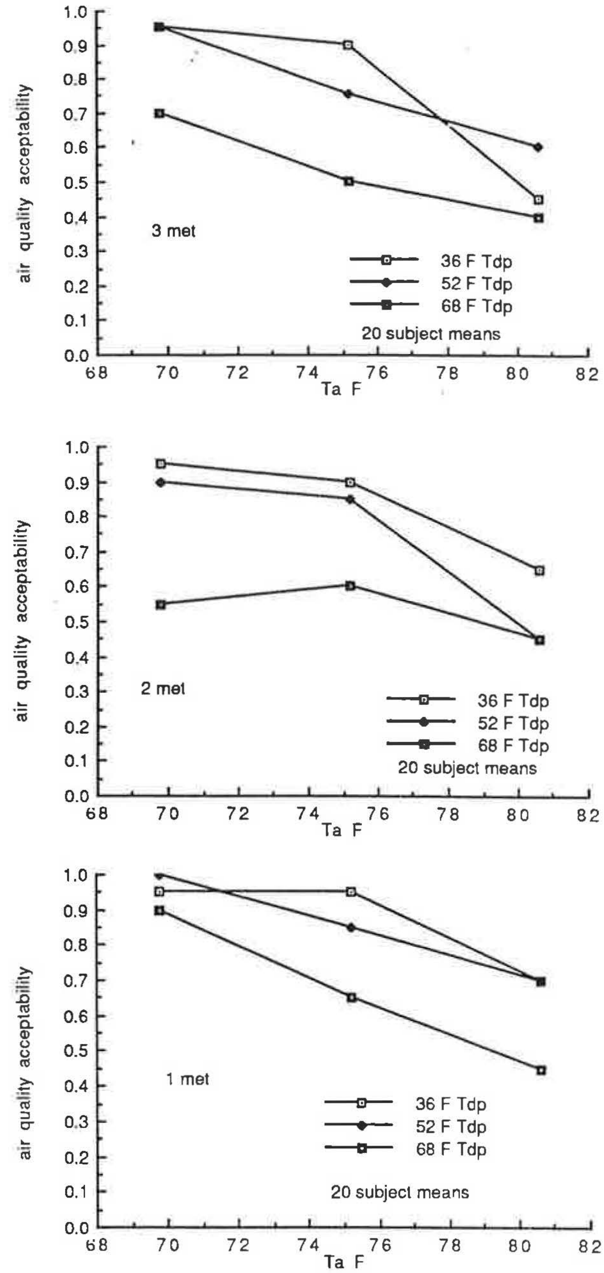


***Figure 8*** *Acceptance of air quality at 1, 2, and 3 met*

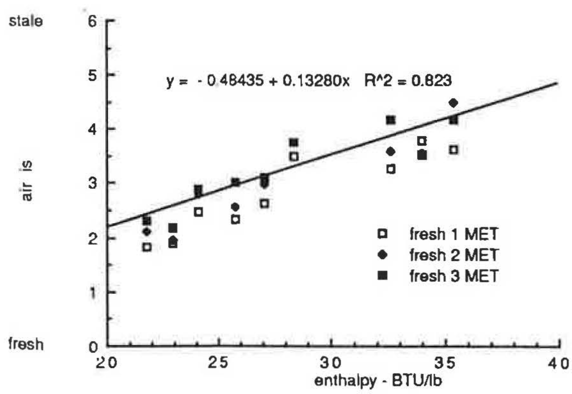


***Figure 9*** *Perceived freshness related to the enthalpy of the environment*

The skin felt wetter with increasing temperature, humidity, and activity (Figure 4). This perception of skin moisture may have affected acceptability and freshness perceptions, though by what means is uncertain. The correlation of perceived to measured skin moisture equaled 0.92.

Judgments about the humidity were consistent with actual conditions, though compressed in comparison to the range of humidities explored (Figure 5). Ambient temperature had a minor influence on humidity assessments. Activity level had a greater influence, probably because of increased perspiration and wettedness at higher activity levels. Subjects judged the air more humid with increased activity.

The constant 10 fpm (0.05 m/s) air motion of the test room was judged to be less adequate with increasing temperature, humidity, and activity (Figure 6). The effect was more pronounced for temperature than for humidity and activity, though still relatively minor.

Mean steady-state thermal sensations for the three levels of activity appear in Figure 7. At a given temperature, subjects felt warmer at the higher activity levels. The response to temperature was quite linear and the response to humidity was uniform among the activities. Decreasing the humidity at a given temperature caused the subjects to feel cooler. However, the perceived difference between the 52° and 36°F dew point conditions was small.

The question of the acceptability of air quality may be the most important from a design or operator's point of view. It was strongly affected by humidity, as shown in Figure 8. The 68°F dew point condition (RH > 65%) was particularly associated with unacceptable air quality judgments. Recall that the subjects could answer the acceptability question only with yes or no. They were instructed that an unacceptable environment is one that would evoke a behavioral action to improve the situation.

## DISCUSSION

The subjective responses of the participants in the present study changed very little over time. For most attributes, the initial and final responses were the same or nearly so, particularly for those sensations related to air quality. The participants immediately perceived the air as less stale, less stuffy, and more acceptable at drier and cooler conditions. The immediateness of their impressions, though somewhat obscure in origin, is intriguing.

The environmental chamber had little background odor and, therefore, any such odor seems an unlikely source of the initial impression of staleness/stuffiness. The chamber contained essentially no active odor sources, except for the occupants themselves, and had the relatively high ventilation rate of at least 30 cfm occupant. Such a ventilation rate would typically prevent more than a trivial buildup of odors over time and would, in any case, allow for fresh starting conditions. It seems more likely that the occupants decided upon relative staleness/stuffiness on the basis of immediate impressions of temperature and humidity. Whether persons with less experience than those studied here would show such keen discrimination remains to be seen.

Air temperature had a somewhat more potent influence on perceived air quality than did humidity. On average, a 1°F change in air temperature had the same effect on staleness as a 6°F change in dew point temperature. The ability of the present subjects to assess humidity reliably nevertheless holds interest. They proved as consistent when sedentary as when active and as consistent at the lowest as at the highest temperature. For both perceived humidity and perceived staleness/stuffiness, the increase in dew point from 52°F to 68°F proved more salient than the increase from 36°F to 52°F.

Staleness ($S$) can be related to air temperature ($T$), dew point ($DP$), and metabolism ($M$) by the regression equation:

$$S = 0.141\ T + 0.0211\ DP + 0.2095\ M - 9.066$$

$$(r^2 = 0.95)$$

where $T$ and $DP$ are in °F, $M$ is in mets, and $S$ is a 0–6 scale with 6 representing "stale" and 0 "fresh." Staleness can also be related to temperature and humidity, as in Figure 9, where the thermodynamic property enthalpy represents the energy content of the air-water vapor mixture (Btu/lb dry air). In that case, enthalpy accounted for 82% of the variance in judgments of freshness-staleness.

The present investigation reinforces the notion that the comfort of occupants in buildings will depend upon almost all perceptible influences. Temperature and humidity will influence thermal comfort, but they will also influence perception of the chemical quality of the air. The concentration of contaminants will also influence judgments of air quality, but in some instances may actually prove secondary to temperature and humidity. In order to understand how the confluence of physical and chemical properties will jointly determine comfort, it will be necessary to study them jointly.

## ACKNOWLEDGMENT

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## REFERENCES

ASHRAE. 1981. *ANSI/ASHRAE Standard 55-1981*, "Thermal environmental conditions for human occupancy." Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Berglund, L.G. 1989. "Comfort criteria in a low-humidity environment." RP2732-10. Palo Alto, CA: Electric Power Research Institute.

Cain, W.S. 1979. "Ventilation and odor control: prospects for energy savings." *ASHRAE Transactions*, Vol. 85, Part 1, pp. 784–792.

Cain, W.S.; Leaderer, R.P.; Isseroff, R.; Berglund, L.G.; Huey, R.J.; Lipsitt, E.R.; and Perlman, D. 1983. "Ventilation requirements in buildings—1. Control of occupancy odor and tobacco smoke odor." *Atmospheric Environment*, Vol. 17, No. 6, pp. 1183–1197.

Kjerulf-Jensen, P.; Nishi, Y.; Graichen, H.; and Rascati, R. 1975. "A test chamber design for investigating man's thermal comfort and physiological response." *ASHRAE Transactions*, Vol. 81, Part 1, pp. 73–82.

## DISCUSSION

**Carl N. Lawson,** LRW Engineers Inc., Tampa, FL: In the studies with people, was there any consideration for effective temperature or black globe temperature? If so, what were the results? Was there any significant difference between male and female subjects?

**L.G. Berglund,** John B. Pierce Foundation Laboratory and Yale University, New Haven, CT: The test chamber's design provides very uniform thermal conditions. That is, the air, wall, ceiling, and floor temperatures are very nearly equal. Therefore, for the unoccupied chamber the temperature of a black globe would coincide with the air temperature. When occupied, radiation from the people could raise the black globe temperature slightly (.2° to .5°F) above air temperature, though this was not specifically measured during these tests.

The ASHRAE effective temperatures (ET*) for the sedentary subjects corresponding to the three temperatures and humidities of the tests were:

| Ta °F | Tdp °F | ET* °F | Ta °F | Tdp °F | ET* °F | Ta °F | Tdp °F | ET* °F |
|---|---|---|---|---|---|---|---|---|
| 69.8 | 36 | 69.4 | 75.2 | 36 | 74.7 | 80.6 | 36 | 79.5 |
| 69.8 | 52 | 69.8 | 75.2 | 52 | 75.1 | 80.6 | 52 | 80.1 |
| 69.8 | 68 | 70.6 | 75.2 | 68 | 75.9 | 80.6 | 68 | 81.5 |

The data have not been analyzed for response differences between the men and women.

**Birgitta Berglund,** Department of Psychology, University of Stockholm, Sweden: I noticed that the responses on your perceived scales, e.g., stale-freshness, were given only for a narrow range (2 or 3 units). Do you have some information on how large your intraindividual variance is in relation to the interindividual variance? This is of importance when you should evaluate perceived scales obtained later for real environments. It will influence the resolution of the scales and thus the possibility to generalize the results. In the real environment there will be many confounding factors that will influence the variance of perceptual scales. Thank you for an interesting paper.

**Berglund:** Yes, the perceived freshness of the air on a scale of 6 units was about 1.5 units fresher at 70 °F than at 81 °F and a dew point change from 68 °F to 36 °F improved freshness by about .7 units. We have not completed the analysis of variance of the data, so the between- and within-subject variance is not yet available. However, the figures in the paper do give the average standard deviations of the means. For the freshness data, it was 0.25 when the subjects were sedentary, and 0.23 when they walked continuously.

**James E. Woods,** Honeywell Indoor Air Quality, Golden Valley, MN: Congratulations on an important new set of data presented. Would you please comment on the potential differences of bioeffluents that may have been generated by the subjects' sweating at 36 ° and 68 °F? Could the odors from sweating influence the perceived air quality? In your analysis, will you be able to control for this potential confounding effect?

**Berglund:** In general, one would expect the generation of bioeffluents to increase with skin moisture from perspiration. The perceived and measured skin moisture of the subjects increased with ambient humidity. Measured skin wettedness under clothing was about 15% higher at the 68 °F dew point humidity than at the 36 °F dew point condition. Further, skin wettedness increased about 10% per Met unit of activity at each environmental condition. The subjects were in each test environment for one hour. If their skin was clean at the onset they may not have had sufficient time to generate any noticeable gaseous bioeffluents from their skin during the test periods. Since the judgment of air quality and the perception of air freshness at the end of each test was nearly unchanged from that at the beginning, it appears that body odor did not contribute to the air quality judgments made by the subjects during these tests. Also, the perceived freshness decreased only slightly with increasing activity.