Title
Laboratory studies of the effect of air movement on thermal comfort: a comparison and discussion of methods

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LABORATORY STUDIES OF THE EFFECT OF AIR MOVEMENT ON THERMAL COMFORT: A COMPARISON AND DISCUSSION OF METHODS

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ABSTRACT

This paper compares and contrasts methods used in laboratory studies of thermal comfort that focus on the effect of air movement. In laboratory studies, subjects typically wear standardized or similar clothing, are prescreened for healthy body temperature, are restricted in activity, and are exposed to a set of environmental variables that remain constant for a specific period of time. Three broad methodological categories are compared: experiments in which subjects have control of (1) air velocity or (2) air temperature or (3) neither. Specific experimental practices that may confound results are discussed.

INTRODUCTION

Studies of thermal comfort in laboratories benefit from carefully controlled conditions, replicability of conditions for different subjects, and the possibility of very detailed measurement strategies. Important pitfalls of laboratory studies have been discussed in detail by McIntyre (1982); however, the laboratory remains a powerful tool with which to look at the effects of specific variables generally uncontrolled in the field. One important comfort variable that has been the focus of many laboratory studies is air movement. This paper compares methods used in 20 studies and suggests improvements for consideration in planning future work.

Basic protocols for the laboratory study of thermal comfort follow a typical pattern. Subjects arrive and are screened for healthy body temperature and no recent alchohol use. Generally, the subjects are given instructions concerning thermal sensation and/or thermal preference scales and then enter a controlled-environment chamber. Frequently, but not always, the subjects are allowed to reach a steady-state condition (thermally "neutral") before the experiment begins. They are then exposed to a set of environmental variables that remain constant for a specific period of time or are systematically varied by the subject or the experimenter. At the end of the exposure time, the subject is asked to respond to questions regarding his or her subjective thermal state. Then, either the experiment is over or one of the constant environmental parameters is altered (usually air temperature or air velocity) and the next exposure period begins. Experimental arrangements vary from a simple oscillating fan to a matrix of ceiling fans to complicated ductwork that delivers air at specific areas of the body.

The studies considered in this paper can be roughly divided into three major types (see Table 1) that reflect the experimental hypothesis being tested and the statistics required to confirm it. These are (1) experiments in which the subject has control of the air velocity at a fixed temperature, (2) experiments in which the subject has control of the air temperature at a fixed air velocity, and (3) experiments in which the subject has control of neither air temperature nor air velocity. Within these types, there are a multitude of variations that focus on different aspects of the interaction between the subjects and air. A few examples of possible variations include changing the direction of the airflow with respect to the subject; varying the physical properties (turbulence, wave number, etc.) of the flow; choosing a specific temperature, humidity, angle of incidence, metabolic rate, or clothing range; and directing the flow on a particular part of the body.

BACKGROUND

With the advent and widespread distribution of air-conditioning systems in the first half of the century, the problem of how to deliver cool air to work spaces received increasing scrutiny. Before this question could be adequately addressed, however, the issue of what particular thermal conditions were appropriate for human occupancy needed attention. Since members of the American Society of Heating and Ventilating Engineers (ASHVE) were engaged in day-to-day designing of systems for air cooling and delivery, the society began to focus attention and energy on determining suitable indoor thermal environments. This effort was spurred by complaints received from the users of existing systems that drafts were the most frequent cause for HVAC-related criticism (Houghten et al. 1938).

Detailed work on the effect of air movement on thermal comfort began in the early 1920s with the work of F.C. Houghten, director of the ASHVE Laboratory at the Pittsburgh Experiment Station of the U.S. Bureau of Mines. Houghten initiated a series of experiments testing the effects of air motion over a range of temperatures. Results from U.S. laboratories were incorporated into the ASHVE standard, while results from European laboratories were incorporated into the Deutsches Institut fur Normung (DIN 1946) standard. The DIN and ASHVE standards did not agree well, as the ASHVE standard allowed much more air movement at a given temperature based on Houghten's results (McIntyre 1979). More recently, the ASHRAE

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TABLE 1
Description of Studies

First Author	Expt. Type	Measurements	Temp. Range	Air Vel. Range	Met,Clo	Country	Year	# of Subjects	Comments
Berglund	3	AT,AV,SD,MRT,RA	18.5-23.0	.05-.5	sed,.86	US	1987	50	horiz. fans
Burton	1	AT,AV,FS	26.3-29.1	.1-1.7	sed,.3-.4	AUS	1975	6	ceiling fans
Fanger	3	AT,AV,SD	20-26	.05-.4	sed,.57-.92	DK	1986	100	back of neck
Fanger	3	AT,AV,SD	23	.05-.4	sed,.72-.77	DK	1988	50	back of neck
Fanger	2	AT,AV,SD,TSK,TR,WL	24-28.3	.8	sed,.6	DK	1972	4	varying directions
Fanger	3	AT,AV,SD	19.3-27.3	.07-.58	sed.,.7	DK	1977	16/10	back of neck
Houghten	3	AT,AV,TSK	21.1-35	0-.55	sed,?(~1.1)	US	1938	10	back of neck
Houghten	3	AT,AV	28.6-32.9	.76-2.54	1.2,?(~.3)	US	1924	3	high RH
Jones	3	AT,AV	10-26	.2-1.32	2.3,.65-1.09	US	1986	16	high met
Konz	3	AT,AV	25.6-30	.3-1.2	sed,.6	US	1983	8/16	oscillating vs. fixed fan
Kubota	3	AT,AV	26-34	.1-.24	sed,.6	J	1979	5/45	preheated
McIntyre	1	AT,AV,SD,FS,TSK	22-30	0-2	sed,.38-.48	UK	1978	11	thermal acceptability
McIntyre	2	AT,AV,TSK,TCK	22-30	.15-.7	sed,NA	UK	1979	91/20/5	cool air jet on cheek
Rohles	3	AT,AV,SD	24-29	.06-1.02	sed,.5	US	1983	256	pre-heated
Rohles	3	AT,AV	21.1	.08-.28	sed,1.7	US	1983	72	ceiling fans
Rohles	3	AT,AV,SD,TSK	22.2-29.6	0-1	sed,.6	US	1974	90	3X3 factorial design
Scheatzle	3	AT,AV,SD	25-31	.13-1.63	sed,.52	US	1986	96	pre-heat,low RH
Tanabe	3	AT,AV,TAR,TSK	27.8-31.3	.05-1.52	sed,.5	J	1986	64	randomized exposures
Tanabe	3	AT,AV,TAR,TSK	27.9-31.5	.5-2	sed,.5	J	1989	64	sinusiodal variations
Wu	3	AT,AV	31-33	.2-.81	sed,.4-.5	US	1989	93	pre-heat,low RH

Type 1 = subject has control of air velocity
Type 2 = subject has control of air temperature
Type 3 = subject has control of neither air temperature nor air velocity
AT = air temperature
MRT = mean radiant temperature
TSK = skin temperature
TAR = armpit temperature
TR = rectal temperature
TCK = cheek temperature
RA = radiant asymmetry
WL = weight loss
AV = air velocity
SD = standard deviation of air velocity
FS = fan speed
sed = sedentary, not reported in met units. Subjects were generally occupied with specific tasks, which varied from experiment to experiment, so no generalization of the met value of sedentary activity would be totally accurate.
US = United States
AUS = Australia
DK = Denmark
J = Japan
UK = United Kingdom

All temperature units are given in degrees Celsius. All velocities are given in meters per second (m/s). Metabolic rates are given in met units (1 met = 58.2 W/m^2). Clothing insulation values are given in clo units.

standard (ASHRAE 1981) has followed the International Standards Organization standard (ISO 1984) in terms of more stringent air movement restrictions (McIntyre 1979). Since Houghten's work in the 1920s, laboratory work in thermal comfort related to air movement has been concentrated in a few specialized research centers around the world.

MEASUREMENTS

Laboratory methods utilize a wide array of possible physical and subjective measures. The basic measurements needed in experiments involving airflow comfort are air temperature, air velocity, and some subjective measure of the thermal state of the subject. Several studies also collected extensive skin and core temperature data directly. Some studies concentrated on a portion of the comfort zone, while others attempted to measure throughout the entire zone. Some focused specifically on lower or higher velocity effects. Measurements of air temperature were typically made with thermocouples, while air velocities were measured at first with Kata thermometers and later with hot wire/bulb anemometers. Subjective measures included thermal sensation, thermal preference, ability to sense air motion, pleasantness or unpleasantness of the air motion, and presence of or lack of a draft. The interval for physical measurements on the body was typically every 10 minutes, while physical environmental measurements varied from many times per second to every 10 minutes. In the early phases of the subject's exposure to the test conditions, some

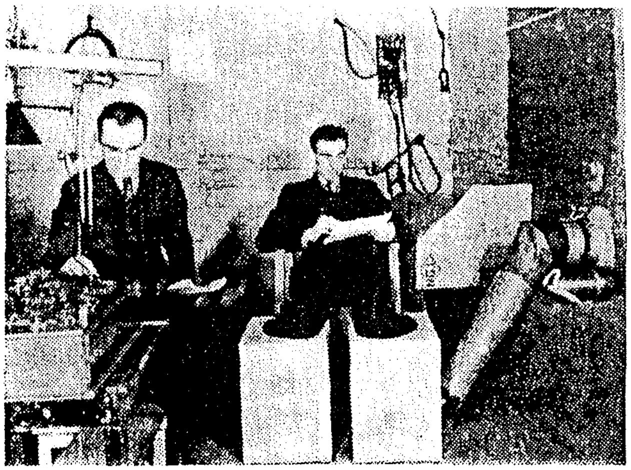

Figure 1 *Setup for determining ankle temperature and feeling of draft (Houghten et al. 1938)*

experimenters surveyed the subjects as often as every 2 minutes, while more typical intervals ranged from 15 minutes to half an hour. Sample size varied appropriately with experimental design—factorial designs having as few as 2 subjects (but usually 4 or 5) and randomized block or repeated-measures designs typically having 50 to 100 subjects.

About half the studies included an acclimation period after the subject's arrival but before exposure to the test conditions. During the acclimation period, either the subject was allowed to adjust clothing until thermally neutral or the subject was exposed to conditions representing "neutral" appropriate to his or her clothing level (determined mathematically or empirically) for a sufficient period to reach steady state. For those experiments that did not include an acclimation period, some experimenters recorded the subject's initial thermal sensation as a "starting point," which was not necessarily neutral.

DESCRIPTION OF STUDIES

Early Work at the ASHVE Laboratory

Houghten ventured into air movement and thermal comfort work by quantitatively examining the cooling effects of air motion at different temperatures. The experiment (Houghten and Yaglou 1924) was done using a pair of side-by-side "wind tunnels" with the "judges stripped to the waist" alternately moving from one to the other ("type 3"). At the end of one wind tunnel was a matrix of propeller fans generating more than 500 fpm (2.54 m/s) of air movement. The other wind tunnel was simply a box without fans that provided the still air condition. Both tunnels were set to a given temperature and the judges were asked to move back and forth between the two tunnels and compare their relative warmth. The experiment consisted of gradually increasing the temperature in the fan tunnel (initially "colder") and recording judgments as the relative warmth of the fan tunnel increased. The work was done at fairly extreme conditions of temperature and velocity and was directed mainly at industrial working conditions, for example, mines and paper mills, rather than offices or homes. Equivalent temperature as a function of air temperature for a given air movement was derived.

Houghten et al. (1938) said, "The problem of determining what combinations of temperature and movement of air constitute drafts was recently assigned to the Research Laboratory by the ASHVE technical advisory committee OH-22 consisting of [list of people]." Houghten's challenge was to create a standard from scratch. From the complaints of drafts in many commercial structures, the need clearly existed. In one extreme case, the question of an air-conditioning installation was put to the occupants for a vote and was voted down handily due to previous bad experiences with air conditioning in other spaces (Houghten et al. 1938). Specifically, the issue was draft discomfort in commercial spaces, such as offices, stores, and transit stations, and it set the stage for the next 50 years of research.

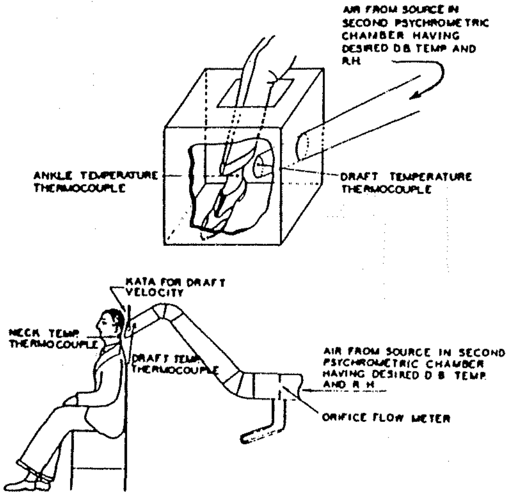

Figure 2 *Test arrangement for determining the effect of drafts on the neck (Houghten et al. 1938)*

Houghten's 1938 experiment ("type 3") focused specifically on drafts experienced at the back of the neck and the ankles. Elaborate ductwork was constructed within the chamber to deliver air directly to the back of the subject's neck (Figures 1 and 2). Two large boxes with holes in the tops for the subject's legs served to shield the ankles from all air motion except that provided through the sides of the box. Skin temperature at the neck or ankles was measured for 20 minutes, then the air was turned on and skin temperature was monitored for 30 to 50 minutes longer. Subjects voted on a seven-point (cold-hot) scale with votes one and two indicating a draft was experienced. Great care was exercised to ensure that the thermocouples were placed with the proper pressure against the skin. If the pressure was too light, the measurement would be influenced by air temperature, and if the pressure was too great, it would be influenced by core temperature. The experiment was repeated over a range of ambient temperatures and velocities. Draft limits were proposed that would ensure that 90% of persons exposed to certain temperature/velocity combinations would not feel a draft.

The Kansas State University Studies

In the late 1950s, ASHVE became ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers), and the ASHRAE laboratory was moved to Kansas State University (KSU). The ASHRAE laboratory fell under the administration of the Institute for Environmental Research, directed in turn by Ralph Nevins, Fred Rohles, and currently, Byron Jones.

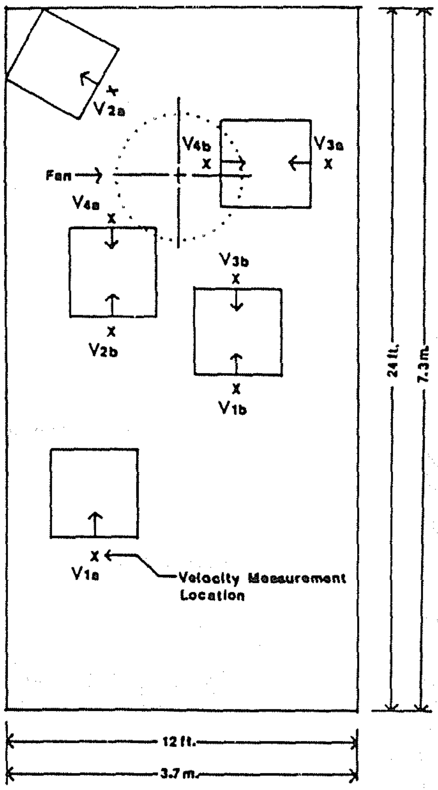

Figure 3 *Orientation of the subjects with respect to the fan (Rohles et al. 1983)*

Rohles completed his first experiment involving air movement and thermal comfort of humans (Rohles et al. 1974) coincident with the revision in 1974 of ASHRAE *Standard 55, Thermal Environmental Conditions for Human Occupancy* (ASHRAE 1981). It was one of the first of a series of "type 3" experiments performed during this general period at several different laboratories. For a 3 by 3 factorial design with repeated measures, Rohles exposed 90 subjects in groups of five to one of nine experimental combinations of air temperature and air velocity. Air motion was provided uniformly to the space through a perforated ceiling. Subjects voted after one hour and every half-hour thereafter for a total of three hours. Rohles's important results include finding a significant adaptation to test conditions during the exposure period, no sex differences, strong correlations between skin temperature and thermal sensation, and that convective heat transfer is very important in determining airflow affective states. He recommended an extended summer comfort zone using 157 fpm (.8 m/s) as the limit for air movement.

The next two airflow-related comfort studies at this facility involved local fans. Ceiling fans and oscillating fans have received increased attention as a possible supplement for air conditioning as energy prices have risen. The first study (Rohles et al. 1983) was motivated by the question of whether the 157 fpm (.8 m/s) limit was still applicable under the fairly turbulent flow of a ceiling fan. In this "type 3" experiment, eight subjects at a time moved from station to station in a room with a large fan experiencing different velocities at different stations (Figure 3). Four temperatures bracketing the upper edge of the summer comfort zone were tested for three hours, and for the first hour, the fan was off, exposing the subjects to still air conditions. Rohles et al. found subjects considered air

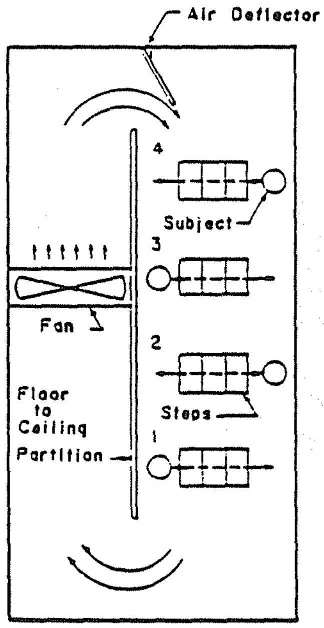

Figure 4 *Test chamber layout (top view) (Jones et al. 1986)*

movement pleasant at levels beyond what was previously considered reasonable (up to 196 fpm [1 m/s] at 85°F [29.5°C]), and they considered the turbulence of the flow a beneficial aspect.

The second fan study (Konz et al. 1983) compared fixed fans with oscillating fans and explored the effect of angle in two "type 3" experiments. In the first experiment, the protocol and temperatures was very similar to Rohles et al. above. Oscillating fans were preferred over fixed fans. In the second experiment, the subjects were exposed to air movement from a small axial fan directed at different angles to the front of the body. Angle was not significant.

A subsequent study (Jones et al. 1986) focused on airflow comfort at increased metabolic rates (2.3 met) for two clothing levels. Subjects walked up a small flight of stairs every 15 seconds and stood quietly in between (Figure 4). A large range of air temperatures was used in the test, and each subject was exposed to one combination of air velocity, air temperature, and clothing for two hours. Subjects voted just prior to the test and every half-hour thereafter. Similar levels of comfort were obtained for lower temperature/lower velocity combinations and higher temperature/higher velocity combinations at each clothing level.

Technical University of Denmark

In 1970, P.O. Fanger published his landmark book, *Thermal Comfort*, presenting a detailed laboratory validation of his thermal comfort equation. Although some of the data used in validating the comfort equation were collected at KSU, Fanger's Laboratory of Heating and Air Conditioning at the Technical University of Denmark has produced a large and comprehensive body of laboratory work in thermal comfort using college-age subjects in Denmark. He tested the effect on thermal comfort of a wide range of variables including age, sex, menstrual cycle, national origin, etc. A detailed description of the original laboratory validation is omitted from this paper because it does not focus on air movement in particular. However, since the protocol for all of Professor Fanger's experiments follows

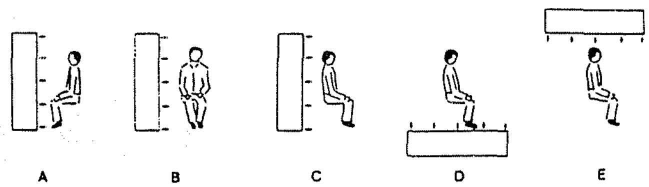

Figure 5 *The five different directions of the velocity to which the subjects were exposed (Fanger et al. 1974)*

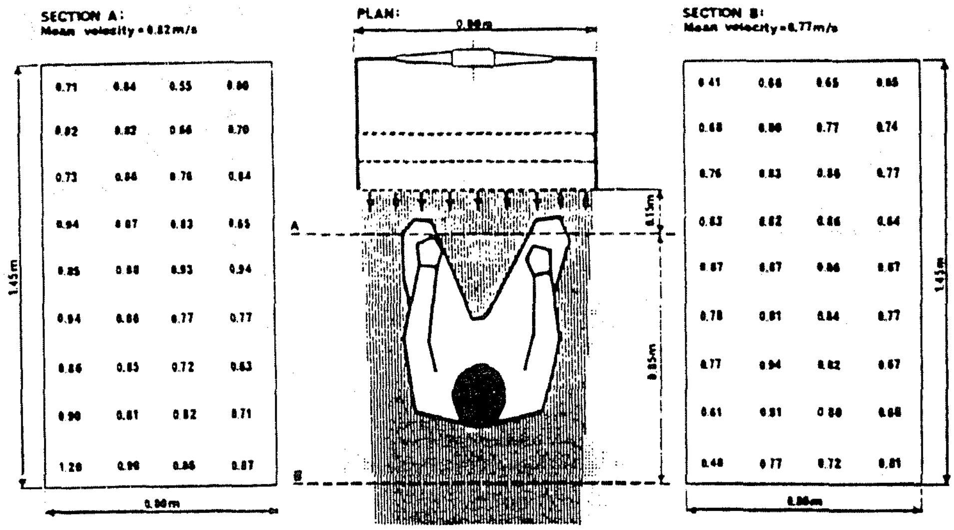

Figure 6 *Experimental setup when a subject was exposed to a uniform velocity from in front. The subject was sitting in the core of the jet, where the velocity was reasonably uniform. The velocity distributions in two sections are shown (m/s) (Fanger et al. 1974).*

similar lines, it is worth a brief outline. Subjects report to the site well in advance of the experiment and are interviewed in a "neutral temperature staging area." Subjects are asked if (during the past 24 hours) they have slept well, eaten normal meals, consumed no alcohol, and had no fever. If all questions are answered affirmatively, the physiological measurement apparatus is attached, and the subject enters the chamber, which is preset to the initial conditions to be tested. Most of the studies fall under the description of "type 2."

In the area of airflow studies, Fanger has also made a significant contribution. Fanger et al. (1974) looks at the effect of airflow from different directions. Subjects were exposed to a specific air velocity from a specific direction (Figures 5 and 6) while adjusting the ambient temperature to continuously remain in a state of optimal comfort ("type 2"). Every attempt was made to keep the airflow as uniform as possible to avoid confounding the results with the effects of turbulence. Angle was not a factor. Two important results from this work were the findings that (1) a thermally comfortable subject has a skin temperature independent of air velocity and (2) the quantitative influence of air velocity is in good agreement with the comfort equation.

Fanger and Pedersen (1977) first exposed subjects to well-defined turbulent flow. They looked at a range of frequencies of variation to determine which frequencies caused a sensation of draft. The 10 most draft-sensitive subjects were pre-selected from an initial pool of 100. Each subject was exposed to 16 conditions in 16 different one-hour exposures. Airflow was directed at the back of the neck and the ankles (Figure 7). It was determined that turbulent flow is more uncomfortable than uniform flow with the same mean velocity and that frequencies in the range of .3 to .5 Hz are more uncomfortable than other frequencies. Draft limits on mean velocities are presented.

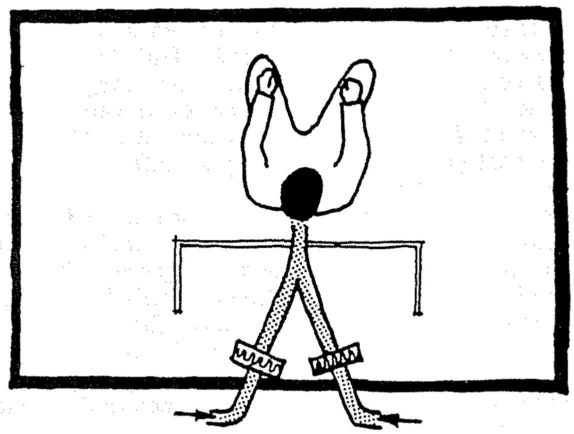

Figure 7 *Experimental setup for a subject being exposed to a constant or fluctuating airflow directed toward the back of the neck (Fanger and Pedersen 1977)*

Fanger and Christensen (1986) is a study in which the laboratory attempts to mimic conditions found in the field in order to do a repeated measures design. After Fanger and Pederson (1977), a study was done (Thorshauge 1982) that examined existing spaces in the field specifically with regard to air velocity fluctuations. This body of knowledge has been enlarged considerably with the recent publication of Hanzawa et al. (1987) and Melikov et al. (1988). Conditions found in the field guided the design of Fanger

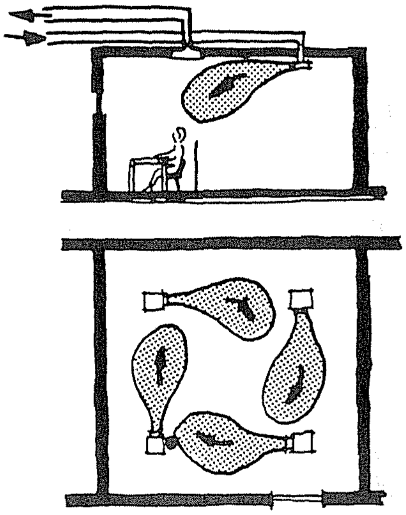

Figure 8 *A subject in the draft chamber with the velocity sensor behind the neck, with the airflow from the diffusers indicated and the air-conditioning system shown in the control room (Fanger and Christensen 1986)*

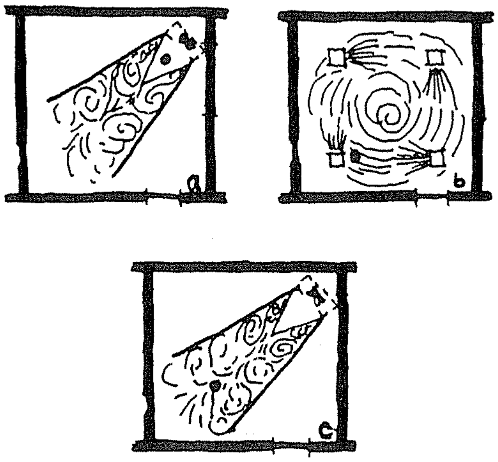

Figure 9 *The experimental setup in the draft chamber when a subject was exposed to (a) low turbulent, (b) medium turbulent, and (c) high turbulent airflow (Fanger et al. 1988)*

and Christensen (1986). Subjects were initially allowed to adjust their clothing until they felt neutral. During this period, the air velocity was kept constant and then was subsequently lowered and raised in steps every 15 minutes while no clothing adjustment was allowed. To mimic situations found in the field yet measure the sensitivity of the back of the neck, a horizontal diffuser was placed on the ceiling and directed slightly downward at an angle to the ceiling. The subject sat at a table facing away from the diffuser (Figure 8) and was not allowed to wear clothing that covered the back of the neck. Turbulence intensity varied nonlinearly with air velocity and ranged between 30% and 60% but was not a controlled variable in the experiment. The study produced a draft chart that predicts the percentage of people feeling a draft at a given air velocity and air temperature.

A subsequent Danish study (Fanger et al. 1988) focuses on turbulence intensity as a controlled variable. For easy comparison, the same protocol as Fanger and Christensen (1986) is used with the exception that turbulence intensity is varied instead of air temperature. The same stepping sequence of velocities was used, but the air was provided using an "air box" placed behind the subject (Figure 9). They found increased discomfort with increased turbulence and present a modified draft risk chart for inclusion in future comfort standards.

ECRC at Capenhurst (United Kingdom)

Two important studies were done in the late 1970s by McIntyre of the Electricity Council Research Centre at Capenhurst in the United Kingdom. While previous studies were aimed at determining the "comfortableness" of higher air velocities at higher air temperatures, McIntyre's first "type 1" experiment (McIntyre 1978) focuses on the "acceptability" of higher air velocities at higher temperatures. Subjects were exposed to a specific air temperature and were asked to adjust the air velocity and vote at 15-minute intervals. Air motion was provided using a hidden ceiling fan (Figure 10) with a transformer at the subject's disposal. The air motion could be adjusted whenever the subject wished within the minimum interval. In addition to

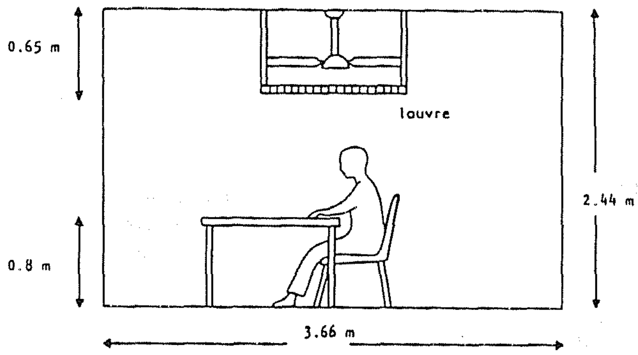

Figure 10 *Section of chamber (McIntyre 1978)*

the usual subjective scales of comfort, a magnitude estimation of the strength of the air movement was requested. Important findings from this study include: (1) subjects chose fans speeds that were lower than what was required to maintain neutrality; (2) air movement can compensate for air temperature up to 82.5°F (28°C)—above this level, the necessary air speed for comfort produces too much disturbance; and (3) subjective evaluation of the strength of the air speed varies with the square of the velocity.

McIntyre's second experiment (McIntyre 1979) is a "type 3" study looking specifically at drafts on the face. He directed a jet of air at the cheek of the subject from 0.3 m away. Performed in three phases, each phase combines different jet temperatures, air velocities, and exposure times. Two major differences between this study and others are the extra variables of "lower than room temperature air" directed at the subject and short exposure times. In addition to thermal sensation, questions about perceived strength of the airflow, affectivity, and acceptability of the conditions for office work were asked. Important results from this study include: (1) at the same air temperature, subjects who felt cool found the air movement unpleasant, while subjects who felt warm found the air movement pleasant; (2) initial cool sensations from draft conditions lessened over time, i.e., the subjects adapted; and (3) small changes in air speed can result in large changes in sensation.

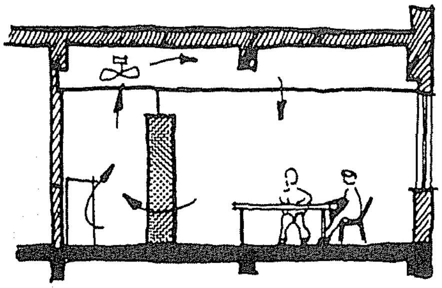

Figure 11 *Test chamber with slots mounted on the ceiling (Kubota 1988)*

Japan

During the last decade in Japan, several experiments looked specifically at the ability of air motion to compensate for higher summer temperatures. Three of these studies are discussed here. In the first, a "type 3" (Kubota 1988), subjects were exposed to airflow from ceiling diffusers at various temperatures (Figure 11). Subjective questions included judgments of wind strength, disturbance, and thermal sensation. All subjects found the air motion desirable at all temperatures studied, with the exception of one subject who "received the air flow behind his neck."

The second Japanese study, a "type 3" (Tanabe and Kimura 1987), included tests at high relative humidity. Air temperature and relative humidity were held constant for each three-hour exposure period. During the first hour, air movement was held constant and during the next 100 minutes it was changed every 20 minutes. The five specific velocities were presented in random order for each test. For the final 20 minutes, a "type 1" strategy was adopted to find if the subjects preferred the air velocity for the given air temperature and relative humidity combination. Tanabe and Kimura found subjects regularly preferred air movement above 196 fpm (1 m/s) and very few regarded the high air movement as unpleasant under the conditions studied, even though it was received from behind (Figure 12).

Using a similar protocol to their 1987 study, Tanabe and Kimura (1989) looked at the effect of low-period variations in air velocity in a "type 3" experiment. Subjects were exposed to air velocities that varied between about 100 fpm (.5 m/s) and about 400 fpm (2 m/s), with seven different patterns of variation including sinusoidal (with periods ranging from 10 seconds to 60 seconds), random, constant, and pulse. Sinusoidally fluctuating air movement was found to have more perceived cooling effect than random, constant, or pulse air movement as well as more effect on mean skin temperature.

Arizona State University

The methods used in Rohles et al. (1983) were repeated at Arizona State University in two experiments using fans. The first (Scheatzle et al. 1989) extends the ceiling fan experiment to lower and higher relative humidities. They found the upper limit of acceptability for air motion (as proposed by Rohles) could be raised for lower humidities but must be lowered for higher humidities. The second study (Wu 1989) uses an oscillating axial fan instead of a ceiling fan and covers the same extended humidity range. Wu found the oscillating fan extended the acceptable temperature range even farther.

J.B. Pierce Foundation (New Haven, Connecticut)

The J.B. Pierce Foundation has been involved in thermal comfort modeling and laboratory studies for many years. One recent study (Berglund and Fobelets 1987) looks at the combined effects of air motion and radiant asymmetry for the first time. Subjects were exposed to 32 different thermal environments, 16 at a neutral operative temperature and 16 at an operative temperature 5.5°F (3°C) lower than neutral. The conditions included zero radiant asymmetry. Groups of two to four subjects were exposed to neutral conditions for one hour. If the mean thermal sensation was not zero after one hour, the air temperature was altered appropriately. For the second hour, the subjects were exposed to one of the 16 possible neutral minus 3 conditions. Important results from this study include: (1) neutral operative temperature, air velocity acceptability, and draft perception are independent of radiant asymmetry; (2) thermal acceptability at neutral conditions is unaffected by air velocity up to 50 fpm (.25 m/s) but deteriorates above that level; and (3) draft perception can be represented by a linear function of air velocity and temperature.

ANALYSES

This section summarizes typical data analysis methods used in the studies presented in the previous section. The earlier studies (Houghten and Yaglou 1924; Houghten et al. 1938) presented results in detailed graphical form. Fits of lines to data points are empirical and do not involve regression. Most of the studies completed within the past 20 years include some form of an analysis of variance (ANOVA). Typically, subjects or "subject exposures" are divided into two or more groups and an ANOVA is used to determine if there is a significant difference between groups. However, given more than two groups, a simple ANOVA will not determine which groups are different from the others, only that a difference exists. To answer this question, multiple-stage tests are used that operate on subgroups of the whole. Duncan's multiple-range test is frequently used, although its increased power is coupled to a higher error rate than, for example, repeated t tests (SAS 1988).

Where subjective measures are modeled as functions of environmental variables, regression is used. The two major types of regression include ordinary least-squares regression (OLS) for continuous response measures and logistic regres-

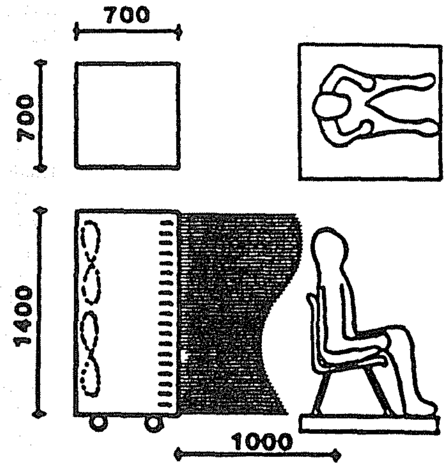

Figure 12 *Wind box (Tanabe and Kimura 1986)*

sion (which includes logit and probit analysis) for discrete response measures. In cases where large amounts of subjective data were collected, factor analysis helped to reveal groups of terms that could be combined into a single predictor variable (e.g., Konz et al. 1983). One particularly revealing analytical method was used by McIntyre (1979) to determine a threshold air velocity for acceptability. He separated his subjects (all at the same air temperature) into warm, neutral, and cool groups by preference vote and found significant differences in the affective ratings of air velocity above 69 fpm (.35 m/s) but not below.

Another class of data analysis techniques involves model generation and validation. In model generation, either specific coefficients are found for a theoretical model developed from first principles (Fanger et al. 1988; Berglund and Fobelets 1987) or a stepwise OLS multiple regression is done to find the "best" linear model.

DISCUSSION

Experimental Design Considerations

A number of the studies exhibit some potentially important limitations in experimental design. Five experimental design approaches that could bias the results obtained are discussed below. In some cases, the researchers acknowledged shortcomings of the method used and discussed potential impacts on the results.

1) Not acclimating subjects before the experiment.

If subjects are not acclimated or brought to neutral before data collection begins, the results may be biased by the conditions the subject experienced in the hour before the experiment began. Almost all the studies had at least a brief period before the subject entered the chamber during which the experimental procedure was explained and oral temperature was taken. Often, the "staging area" was kept at what would be a neutral temperature under Fanger's comfort equation. In a few carefully conducted studies, subjects were brought to neutral in the chamber well before subjective data collection began. Burton et al. (1975), Konz et al. (1983), and Scheatzle et al. (1989) are striking counterexamples of this procedure. Subjects appeared at the laboratory and were ushered directly into the chamber for data collection. The extent to which this method might influence experimental results is not specifically known, and it would depend on the subject's thermal state and environmental surroundings prior to beginning the experiment.

2) Pre-heating subjects as part of the first "phase."

A few studies focused specifically on air motion at higher air temperatures. Without exception, these studies began with a zero-velocity "control" period where the subject was exposed to a high temperature without air movement for up to one hour. Naturally, after a period of time without air movement, the subject's core temperature would rise and sweating would begin. Even fairly high levels of air movement will improve comfort for these subjects after "pre-heating," and the experiments show that they prefer much higher velocities at these temperatures than was previously expected. This raises the important question of whether "no air movement," as opposed to "neutral sensation," is an appropriate control condition for experiments at the upper boundaries of the comfort zone. Studies that fall into this category include Kubota (1988), Rohles et al. (1983), Scheatzle et al. (1989), and Wu (1989).

3) Sequencing air velocities to average out to neutral.

Some experimenters exposed subjects to a step-wise sequence of velocities below what would be needed to keep them neutral and then to a sequence of velocities above what would be needed to keep them neutral. The claim is the two effects balance each other out over the entire time period. It seems likely that this method might actually narrow the range of comfortable velocities. The feeling produced by each more extreme velocity may be amplified by the fact that the subject is pre-heated or pre-cooled by the previous exposure. For example, a 15-minute exposure to a 50 fpm (.25 m/s) velocity might be more readily judged uncomfortable if the previous 15 minutes were at 40 fpm (.2 m/s) rather than 20 fpm (.1 m/s). Studies that fall into this category include Fanger and Christensen (1986) and Fanger et al. (1988).

4) Randomizing sequential exposures to remove the effects of the sequence.

Some studies claimed to have removed the effects of variable sequencing by randomizing the exposure to that variable. For example, if five exposures to specific velocities are planned for the session, the order of exposure is randomized and the claim is then made that each is an independent observation. Physiologically, this may not be the case. The subject's vote may be influenced by the previous exposure, resulting in nonindependent tests. Studies that fall into this category include Tanabe and Kimura (1987), Rohles et al. (1982, 1983), Konz et al. (1983), Scheatzle et al. (1989), and Wu (1989).

5) Not distinguishing between local cooling and whole-body cooling effects.

Some experimenters present results based on local cooling using air jets in close proximity to particular body areas. There are two possible problems when comparing these approaches with other work where the whole body is cooled. First, thermal sensations for a particular air velocity/air temperature combination are different when exposure is confined to a small area rather than the exposing the body as a whole (Houghten et al. 1938). Second, air ducted to the body will disturb the boundary layer at the skin (but just at that area, e.g., the back of the neck), producing a possibly more noticeable effect than would a similar exposure to the whole body (McIntyre 1979). Studies that fall into this category include Houghten et al. (1938), Fanger and Pedersen (1977), Fanger and Christensen (1986), and McIntyre (1979). The issue of how to interpret and compare results between local cooling and whole-body cooling experiments is probably the major cause of difference in opinion regarding the influence of air velocity.

Psychological Considerations

The effect of psychological variables on thermal comfort perception is often acknowledged but is rarely discussed in detail or controlled for in experiments. Examples of confounding variables include the colors and textures of the laboratory chamber, lighting, unnaturally rapid temperature or velocity changes, lack of windows, fan noise, seeing the fan move, proximity of other subjects, having to wear a uniform, and having to wear physiologically intrusive sensing equipment (such as skin or rectal temperature probes).

Several situations where psychological effects may influence results turn up repeatedly. An abrupt transition, such as moving from a still air condition to a "randomly chosen" 295 fpm (1.5 m/s) condition as a fan is turned on, may feel unnatural and therefore may be judged abnormally. If changes in fan speed produce noticeable changes in the ambient noise level, the subject may establish noise/comfort relationships and return to previously chosen "comfortable" noise levels without going through the intended judgment. Similarly, if the subjects can see the fan moving, they may form blade-speed/coolness relationships and "feel" cooler if they see the fan blades begin to blur. About half of the experiments required subjects to wear a standard uniform, and half allowed them to wear their own clothing either with or without certain restrictions. In experiments where personal clothing was allowed with restrictions (e.g., light summer clothing), the standard deviation (in clo) between subjects was generally quite low. Finally, perhaps the most influential psychological variable might be the presence of sensors on and in the body. Skin temperature measurements are frequently taken and usually include a number of different sites. Rectal temperature measurements are a proven method of accurately measuring core temperature; however, some subjects may be disturbed by the presence of the probe. Despite the intrusive nature of these sensors, no mention is made of the possible effect on judgments of "comfortableness." Even a question such as "How comfortable do you feel thermally?" may be confounded.

Several studies (McIntyre 1978, 1979; Rohles 1965; Rohles et al. 1983; Konz 1983) attempt to characterize the psychological aspects of air movement and the thermal environment itself, if not of the laboratory setting. The two most common methods are paired comparisons and magnitude estimation. Both methods are widely used and widely accepted in the field of quantitative psychology. Paired comparisons require a list of adjective pairs that are bipolar in nature (good-bad, pleasant-unpleasant, drafty-stuffy, etc.). A judgment is made on a numerical scale (the ends of which correspond to the adjectives) as to which adjective best describes what the subject is experiencing. Magnitude estimation involves repeated judgments of the same stimuli but at different magnitudes, e.g., different fan strengths, supplied in a random order to determine the coefficients of the stimulus-response function. A power function ($R = aS^b$) is usually postulated as appropriate for human sensory processes of magnitude estimation, but rarely do the coefficients reflect the actual physical processes involved. In one case, considered by the experimenter to be "extremely fortuitous," magnitude estimations of wind strength were related to exactly the square of the actual velocity (physical wind pressure also varies as velocity squared).

General

Why are studies of the influence of air movement on thermal comfort done? Primarily for developing standards such as ASHRAE 55-81 and ISO 7730. Yet the studies discussed in this paper, when considered as a whole, present a plethora of conflicting suggestions and results. This section examines some of the findings in light of the experimental considerations to suggest reasons for some of the contradictions.

One possible problem arises from a comparison of studies where subjects began at "neutral" with studies where they didn't. Subjects in the latter uniformly preferred higher air velocities up to the point where disturbance effects became important. Similarly, comparing results from studies where subjects were exposed to a sequence of velocities with results from studies where only a single condition was tested may be inappropriate. A velocity exposure period that follows a previous period at conditions that produce discomfort is more likely to result in discomfort than a single exposure. Both examples above relate to temporal issues: what is the subject's thermal state at time t_0? And what is it at time $t_1 > t_0$? How long does it take for the body to thermally "forget" a previous condition? A few minutes? A few hours? A day? A season?

Another issue not often discussed but implicitly built into most of the experimental designs is the question of local discomfort vs. whole-body discomfort. For example, ceiling fans, diffusers, or slotted ceilings produce air currents in the room as a whole, whereas oscillating desktop fans and directed air jets produce local cooling effects often confined to a particular area of the body. Consider a hypothetical study where a random sample of subjects experience "whole-body" cooling for a certain period under specific conditions of air temperature and air velocity. Suppose 90% of those surveyed vote that they feel "comfortable" and the experimenter concludes that 90% of all humans will vote "comfortable" under those conditions of temperature and velocity. In another study, randomly selected subjects experience the same temperature and air velocity conditions as in the previous experiment, but the air is delivered through a duct that terminates several inches from the back of a subject's neck. This time, 90% of the subjects vote that they are "uncomfortable," and the experimenter concludes that 90% of all humans will vote "uncomfortable" under those conditions of temperature and velocity. How do we reconcile these two studies, both of which have been conducted under rigorous laboratory conditions? They really are asking different questions. The first is concerned with what is acceptable in terms of ambient conditions, while the second is interested in finding the limit of acceptability for local cooling.

CONCLUSIONS

Comparing the methods used in previous studies of the effect of air movement on thermal comfort suggests some guidelines for obtaining reliable data.

1. Either bring the subject back to neutral after each exposure or keep the subject at neutral the whole time.
2. When keeping the subject at neutral, vary only a single variable and wait until the subject has again reached neutral using his/her personally adjustable variable before changing the controlled variable.
3. If specific body areas are being tested for sensitivity, results and recommendations should be presented in terms of those particular areas.

This review of previous work was inspired in part by current discussions regarding the revision of ASHRAE Standard 55-81 (ASHRAE 1989), the thermal comfort standard. The standard includes an extended summer comfort zone allowing increased air movement at higher temperatures. Some of the studies reviewed in this paper, e.g., Rohles et al. (1982) and Scheatzle et al. (1989), support the current air movement limits or would extend them, while other studies, e.g., Fanger and Christensen (1986) and Fanger et al. (1988), would restrict them considerably if applied throughout the occupied zone. Differences in methods between these groups of studies inhibit the effective synthesis of a standard from the results. On one hand, increased air movement and increased turbulence can increase comfort, while, on the other hand, increased air movement and increased turbulence under conditions of local cooling can increase the likelihood of uncomfortable drafts. A standard incorporating general air movement limits, higher temperature limits, and draft limits for different situations would address the issue but may be difficult to apply in practice. Finally, another important issue for future research and standard development is the level of control provided to subjects in the laboratory and office workers in the field. It seems likely that an externally imposed draft might be perceived more negatively than an individually controlled "draft" even though identical environmental conditions were being experienced in each case.

Taken collectively, the studies reviewed in this paper do not provide strong support for developing a specific air movement standard after the model of ASHRAE 55-81. Since ASHRAE Standard 55 influences the environmental engineering of 250 million square feet per year of newly built office space in the United States alone, further work must be done to establish air movement limits, as they are an essential component of the standard. This suggests experimentation examining the influence of air movement on thermal comfort (aimed specifically at refining the ASHRAE standard) is an appropriate topic for ASHRAE-funded research.

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DISCUSSION

Tetsumi Horikoshi, Associate Professor, Nagoya Institute of Technology, Nagoya, Japan: We usually use mean velocity to express the air movement. There are many characteristics of air movement, e.g., direction, frequency, turbulence, etc. It is difficult to compare the data (velocity) by many different investigators. How can we evaluate or indicate these characteristics of air movement synthetically?

M.E. Fountain: Yes, it is difficult and perhaps inappropriate to compare experiments where characteristics of air motion are measured in different ways and with different levels of detail. Since our ability to measure the physical environment in detail has increased over time, it is important to compare groups of experiments using the subset of parameters measured in all. Otherwise, we run the risk of continually abandoning previous work that may be meaningful.

Harrison D. Goodman, Senior Vice-President, Joseph R. Loring & Associates Inc., New York, NY: Why was the Fanger format not used?

At the low end of air motion in the occupied space, a small difference in room sensible temperature appears to make a considerable difference in the comfort level, according to the Fanger chart. Does the ASHRAE format indicate the same result?

What instrument was used to measure room air motion to obtain the best results? Whatever is used should be recommended to the AABC and NEBB for actual investigation of on-site balancing problems with thermal comfort.

Fountain: The presentation of Figure 3 in the proposed revision of ASHRAE Standard 55-81 follows the format of Figure 3 in the current Standard 55-81, which is not in the Fanger format. Regarding the comparison of the Fanger chart and the "ASHRAE format," I don't believe there is a discrepancy. Regarding instrumentation, I cannot name any particular manufacturer here but, with the possibility of turbulence intensity limits being incorporated into Standard 55-81, a device that has a fast response time (on the order of 0.1 s) is a necessity.