Title

A field measurement system for the study of thermal comfort

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A FIELD MEASUREMENT SYSTEM FOR THE STUDY OF THERMAL COMFORT

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ABSTRACT

This paper describes the instrumentation and measurement protocol used in ASHRAE research project RP-462, a field study of environmental conditions and occupant comfort in 10 office buildings located in the San Francisco Bay region. During this study, we made a total of 2342 visits to 304 participants during two seasons, collecting a full set of physical measurements and subjective responses at each visit. In this paper we describe the design of equipment and techniques for gathering physical measurements with the detail and accuracy required by both ASHRAE Standard 55-81 (ASHRAE 1981) and ISO Standard 7726 (ISO 1985). In addition, the project developed a laptop microcomputer-based thermal assessment survey that collected a substantial subjective data set in machine-readable form. These components performed reliably during nine months of field use, providing a detailed description of the monitored workstation environments with a concurrent portrait of subjective occupant response. The system is recommended for further use.

INTRODUCTION

The design of pleasant and efficient working environments is becoming an increasingly complex task. Our "post-industrial" economy features a major expansion in the white-collar workforce, radical changes in the technology of the office workplace, and growing concern about the efficiency of office workers. With these changes, contemporary designers face new challenges that will directly affect the design of building comfort systems.

The scale of the office arena is immense; consider the following statistics describing the United States office enterprise (Roark and Dowell 1986): in 1985, our office inventory totaled 4 billion ft^2 of interior space with a yearly expansion of 250 million ft^2. These offices provided the work setting for two-thirds of all U.S. employees, who in turn spent a cumulative 100 billion hours per year working inside the buildings we design. In this vast interior landscape, the quality of the physical environment can have profound effects on a worker's sense of health and well-being, as well as subtle but significant effects on worker productivity. Current practices in office design raise important questions regarding the needs of individual building occupants. For example, does the objective of providing a constant, uniform interior environment respond to the needs of workers with different comfort preferences, clothing styles, and environmental sensitivities? Does today's application of centralized controls for thermal and lighting systems allow workers adequate control to respond to their own hour-to-hour or day-to-day environmental preferences? To what extent does the proliferation of desktop computers, acting as localized heat sources, contribute to variations in comfort between adjacent workstations?

ASHRAE provides standards for maintaining comfortable interior environments and in providing this service affects the experiential reality of each year's 100 billion hours of office occupancy. The current comfort standard, ASHRAE 55-81 (ASHRAE 1981), is primarily based on the results of laboratory studies in which sedentary people were exposed to uniform thermal environments and comfort was equated with neutrality or the lack of thermal sensation. While laboratory-based studies of comfort allow experimental precision, it is uncertain whether the standards that they engendered are optimal for real buildings. For in real buildings, conditions are both dynamic and familiar; occupants face well-known settings and pursue customary tasks. In addition, it is uncertain whether the college students often employed in short-term laboratory studies are accurate representations of the general office population. There are also numerous functional and aesthetic attributes of the office environment that may influence the worker's thermal response differently from that of the laboratory subject. One method for assessing the appropriateness of existing laboratory-based comfort standards would be to conduct a field study of building occupants' responses to their normal office environments.

The instrumentation system presented in this paper was developed for ASHRAE research project RP-462 (Schiller et al. 1988b), a field study of thermal environments and occupant comfort in existing office buildings. We visited 10 San Francisco Bay area office buildings during the winter and summer seasons of 1987, making a total of 2342 visits to 304 participants and collecting a full range of physical measurements and occupant responses characterizing the physical environment. The occupants were volunteers, surveyed during their normal work activities. The objectives of this study included:

1. The development of a detailed data base on

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the thermal environment and subjective responses of occupants in representative Bay Area office buildings.

2. The documentation of comfort conditions in the monitored office environments including their degree of compliance with ASHRAE (1981) and ISO (1984).

3. The analysis of the compiled data to identify relationships between physical, psychological, and demographic parameters. We derived comfort parameters from the monitored data, calculated commonly used temperature indices, and applied statistical analysis to identify significant correlations between thermal conditions and subjective responses.

4. The development of instrumentation, measurement procedures, and occupant survey techniques to assess thermal comfort.

Work on the first three objectives has been described in previous papers (Schiller et al. 1988; Schiller 1989). This paper describes the field methods and the system developed for collecting comfort-related data in the field. Following a summary review of previous field studies, we provide a detailed description of the systems used for field measurements, including specifics on transducers, data acquisition equipment, and data management techniques. The paper also includes a description of the system in use and sample data from the study.

PREVIOUS FIELD STUDIES

Thermal comfort is defined by ASHRAE (1981) and ISO (1984) as "that condition of mind which expresses satisfaction with the thermal environment." Just as we understand the experimental advantages for investigating the effects of physical-environmental factors in laboratory studies, we must also acknowledge the important role played by nonphysical, or psychological, parameters in the definition of comfort. In an effort to provide a practical, real-world context for the abundance of laboratory-based thermal comfort research, several notable field studies have been carried out and are briefly discussed below.

Humphreys (1976) provided a worldwide summary of more than 30 field studies performed over many years. In his paper, Humphreys compared the field study results with predictions from the PMV heat-balance model (Fanger 1970) based on laboratory research. This comparison identified important differences between field and laboratory results, including (1) an increased adaptability of people to variations in their thermal environment compared to the model predictions—in fact, a majority of the field study results found that the optimum temperature was lower than the laboratory-based preferred temperature—and (2) a dependence of thermal response on acclimatization to outdoor and indoor temperatures during the preceding weeks, which is not accounted for by the PMV model. Several significant and more recent field studies have noted similar differences between field and laboratory results (Fishman and Pimbert 1978; Howell and Kennedy 1979; Auliciems and Dedear 1984; Dedear and Auliciems 1985; Schiller et al. 1988). In the great majority of field studies performed prior to 1984, it is unusual to find studies that characterize the thermal environments with more than a single set of basic sensors positioned at one location near the monitored workstation, and in some cases environmental variables are merely assumed or estimated. Typical field instrumentation permitted the average building thermal conditions to be tested for general compliance with the ASHRAE and ISO standards but was insufficient to verify all specifications required for thermal comfort. With regard to the Fishman and Pimbert study (1978), McIntyre (1980) pointed out that, unlike laboratory test subjects, real-world people do not wear standard clothing and are generally free to adjust their insulation level in response to changes in their thermal environment. However, during their one-year field study, Fishman and Pimbert found that their test subjects were more (not less) sensitive to uncomfortable conditions compared to laboratory-based predictions.

Just as the level of thermal instrumentation has varied from study to study, so has the detail with which psychological assessments have been carried out. The field work of Howell and Kennedy (1979) and Howell and Stramler (1981) demonstrated the relative importance of psychological vs. physical variables in determining perceived thermal comfort. Cena et al. (1986) attribute the differences between measured results and PMV model predictions to a psychological adjustment made by their elderly test subjects. Still other field studies have concluded that the measured comfort conditions were in general agreement with the recommendations of ASHRAE (1981) (Gagge and Nevins 1976; Lammers et al. 1978). During recent years, several large office building occupant studies have virtually dropped all physical measurements and used survey methods alone to address a range of environmental parameters—thermal comfort, air quality, acoustics, visual comfort, spatial comfort, and functional and aesthetic aspects of the space—which are critically related to occupant comfort, satisfaction, and productivity (Harris 1980; Brill 1984; Woods et al. 1987; Dillon and Vischer 1987; and Baillie et al. 1987).

The variation of conclusions from previous field studies is due in part to the inherent difficulties of performing well-controlled measurements in the field and the significant variations among the studies in the level of detail with which both the thermal environment and the subjective state of mind of the respondent have been assessed. Many of the earlier studies avoided measuring air velocity altogether because of the cumbersome Kata thermometer, the only available low-speed anemometer at that time (Dedear and Auliciems 1985). Recent evidence, however, suggests that air movement (magnitude and variability) is perhaps the most significant of the fundamental comfort parameters in its potential influence on occupant response (Purcell and Thorne 1987). Clothing levels and metabolic rates of previous field study respondents have also been assessed by methods ranging from an estimated constant value to individual checklists. The most common psychological assessment methods have made use of a simple seven-point ASHRAE or Bedford scale, while a few more thorough investigations have contained additional survey questions aimed at determining the effects of alternative psychological variables on perceived comfort. In many cases, simplified data constructs have limited the potential usefulness of field data in comfort analysis.

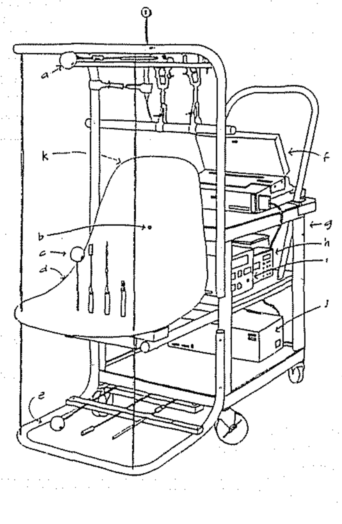
ASHRAE (1981) and ISO (1984, 1985) provide the protocols for determining the combination of environmental (temperature, radiation, humidity, and air movement) and personal (clothing and activity) factors that provide conditions for thermal comfort in the built environment. The detail of physical measurements in many previous field studies is below the requirements specified by these standards, requirements necessary to test for compliance with recommended values for average and dynamic conditions, as well as local nonuniformities. One of the major objectives of ASHRAE research project RP-462 (Schiller et al. 1988) was, in fact, to determine whether current comfort standards were being met in the 10 monitored buildings.

MEASUREMENT SYSTEM DESIGN

In the context of our field study's objectives and the measurement specifications of ASHRAE (1981) and ISO (1985), we developed a series of requirements for our own field measurement system. Our design of a measurement strategy for both physical and subjective variables was based on the following criteria:

- The system(s) must be capable of collecting concurrent physical data (air temperature, dew point temperature, globe temperature, radiant asymmetry, air velocity, and illuminance) from an array of transducers placed to represent the immediate environment of our seated subjects. In addition, the system should be capable of recording a wide range of subjective responses and questionnaire answers with direct input from the building occupants.
- The survey process, including subjective responses and physical measurements, should be completed in approximately 10 minutes per workstation visit.
- The physical measurement transducers and their interrogation must meet the ASHRAE (1981) and ISO (1985) standards for accuracy and response time.
- Physical measurements should be made as close as possible to the exact physical position of the subject completing the subjective questionnaire and as soon as possible after completion of the questionnaire.
- All physical and subjective data should be collected in machine-readable form. Compiling data in digital files during the collection process eliminates keypunch errors and expedites daily summary sheets for error checking.
- The instrumentation package should be mobile and portable with battery power for the system(s) capable of a full day's operation without recharge.
- The data acquisition systems should provide a real-time display of measured values for error-checking purposes. These values should be hidden from the sight of test subjects to avoid bias in their answers to subjective questions.
- The data-gathering process should include a continuous temporal record of physical variables in a fixed location to monitor transient effects.
- The field equipment should be automated to the extent that student assistants with modest training could contribute to the daily data collection effort.
- The entire instrumentation package (including transducers, data acquisition systems, and computers) should not exceed a budget of approximately $25,000.

To meet these criteria, a measurement strategy was developed that combined four separate data acquisition systems running simultaneously. The data collected by each system was time stamped at collection and then combined during the data analysis phase to assemble a complete profile of physical and subjective variables. Detailed measurements of individual workstations were made with a mobile instrumentation cart (see Figure 1) that housed three systems: a laptop computer-based survey system for subjective assessment, a packaged indoor environment measurement system for the mid-level (0.6 m) physical measurements, and a microdatalogger-based measurement system for all additional physical measurements. The fourth system was a fixed-position, microdatalogger-based equipment group that collected time-series data to provide a temporal record of the building's interior conditions. The next section, describing the transducers in detail, is followed



A: Sensors at 1.1 meter height (Dry Bulb Temperature, Air Velocity, Globe Temperature, Plane Radiant Temperature, Illuminance)

B: Surface temperature sensor (behind chair)

C: Sensors at 0.6 meter height (Dry Bulb Temperature, Air Velocity, Globe Temperature, Dewpoint Temperature)

D: Chair (molded fiberglass without feet)

E: Sensors at 0.1 meter height (Dry Bulb Temperature. Air Velocity, Globe Temperature)

F: Laptop computer (polling sensors at 0.6 meters))

G: Accesories bag (pencils, extra survey forms, cassette tapes, replacement cables, basic tools)

H: Portable datalogger with cassette tape (polling sensors at 0.1 and 1.1 meters)

I: Multiplexer and signal conditioning box (interfaces sensors at 0.6 meters with laptop computer)

J: Two twelve-volt batteries (powering all systems on the cart)

K: Space for survey laptop (sits on cart while traveling between workstations)

***Figure 1** Mobile measurement chart*

by a complete description of the four measurement systems.

TRANSDUCERS

ASHRAE (1981) and ISO (1985) specify minimum response time and required accuracy levels for sensors used in the measurement of environmental variables. Additional project-specific criteria for transducer selection included reliability, physical integrity, and an overall response time appropriate for the five-minute length of workstation measurements. Table 1 provides a description of the primary transducers used in our study (see Figure 2). These include transducers for the environmental variables listed below:

Height Above Floor	*Point-in-time measurements at each workstation (via mobile instrumentation cart)*	*Time series measurements at a single representative location*
0.1 m	air temperature air velocity globe temperature	
0.6 m	air temperature air velocity globe temperature dew-point temperature chair surface temperature	air temperature
1.1 m	air temperature air velocity globe temperature radiant asymmetry illuminance	air temperature air velocity globe temperature illuminance
1.7 m		air temperature

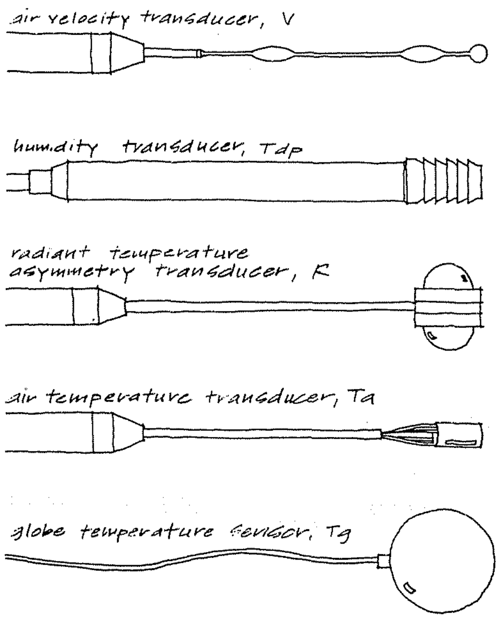


Figure 2 *Transducer profiles*

Air Temperature

Air temperature was measured with either a platinum RTD, a thermistor, or a thermocouple depending on the location of the measurement. In each case, the sensing element was shielded from radiation by a cylindrical metal screen. A platinum RTD measured air temperature at the 0.6 m height on the mobile cart, and type-T copper-constantan thermocouples were used at the 0.1 m and 1.1 m heights. High-precision thermistors were used in the stationary system.

Air Velocity

The air velocity transducers, used on the mobile cart and the stationary system, were omnidirectional anemometers based on the constant temperature principle. An elliptical-element anemometer was used for the 0.6 m height on the mobile cart, while the remaining anemometers featured a spherical sensing element. The anemometer elements are maintained at a constant temperature by an electrical heating element that compensates for heat lost to the surrounding airstream. The amount of current required to keep an element at a constant temperature is related to the amount of air flowing past the element per unit time (and is easily measured). Both types of sensors were optimized for the low air velocities commonly found in indoor environments and featured compensation for ambient temperature.

Dew Point Temperature

The transducers used in this project had relatively fast sampling rates with the exception of the dew point sensor, which took a single measurement every two minutes. This was considered acceptable, as dew point temperature is a relatively stable variable. In the sensor, a small conical mirror is cooled until atmospheric water condenses on it. A light-emitting diode (LED) and a photosensitive transistor (receiver) are located above the mirror. When condensation occurs, the receiver detects light scattered by the dew. The temperature of the mirror at that time is measured and recorded as the dew point temperature.

Plane Radiant Temperature and Radiant Asymmetry

Plane radiant temperature is defined as the uniform surface temperature of an enclosure that produces the same incident radiation on a small planar surface as in the actual environment. Radiant asymmetry is the difference between the plane radiant temperatures of small planes facing opposite directions. The radiant asymmetry probe consisted of two pairs of gold-plated and black-painted elements connected to thermopiles. Each side of the probe had a gold and a black element. The measurement is based on the fact that the gold element exchanges heat primarily by convection while the black element exchanges heat by both convection and radiation. Thus any voltage generated across the thermopiles results from heat transfer by radiation between the black element and the environment.

Illuminance and Chair Surface Temperature

Illuminance was considered an ancillary parameter that might be useful in later analysis. Cosine-corrected silicon photometers were used to measure illuminance in a horizontal plane. A spring-loaded platinum RTD was used to track the surface temperature of cart surfaces adjacent to the mid-height globe thermometer. The comfort standards do not require measurement of these variables.

Globe Temperature

This investigation of human thermal response required knowledge of the mean radiant temperature of the surrounding environment. Mean radiant temperature can be calculated as a function of air temperature, air velocity, and globe temperature. Globe temperature is measured as the internal temperature of a hollow sphere (typically painted black or gray) exposed to the environment. This internal temperature indicates the balance between heat lost and gained from radiation and convection. In principle, globe temperature is relatively easy to measure; however, the five-minute time limit at each workstation posed a challenging problem. We built and tested several alternative globes of various materials and sizes to develop a sensor with short response time and appropriate accuracy. Candidate globes included 5- and 6-in.-diameter spherical glass lightbulbs with the filament removed and smaller spherical Christmas tree ornaments. The sensor eventually adopted was constructed by inserting a type-T thermocouple into a table tennis ball coated with gray paint.

Humphreys (1977) proposed the 38-mm-diameter table tennis ball as useful for making indoor measurements because of its fast response and heat exchange properties similar to the human body at typical indoor air speeds. Tests were conducted to verify that 38-mm globes could, in fact, predict mean radiant temperature in 5 minutes as well as a standard 150 mm globe could after 15 minutes. A smaller globe was desirable for the mobile cart in any case, since the measurement standards required globes at three heights and three 150-mm globes within a 1.1 m by .5 m plane would pose obstructions for other sensors.

The candidate globes used small lengths of plastic pipe to position the thermocouples in the center of the globe. To test the accuracy and response times of the candidate globes, they were suspended on thin wire from a frame mounted on a mobile platform, which was rapidly moved from a cold hallway into a hot chamber equipped with radiant and convective heat sources plus a fan. This was done for a range of temperature differences, room air velocities, and radiant source intensities. The equation used for calculating mean radiant temperature from globe temperature was:

$$T_r = \left[\frac{6.32D^{-0.4}V^{0.5}}{\sigma\epsilon}(T_g - T_a) + T_g^4\right]^{0.25} \qquad (1)$$

where

D = diameter of the globe (m)
ϵ = emissivity of globe
σ = Stephan-Boltzmann constant (5.67×10^8 W/m^{2}K^4)
T_a = air temperature (K)
T_g = globe temperature (K)
T_r = mean radiant temperature (K)
V = air velocity (m/s)

and where the convective heat transfer coefficient ($h_c = 6.32\,D^{-0.4}V^{0.5}$) is taken from ASHRAE (1987).

As expected, the table tennis ball sensor had the most rapid response time. Although the time required to reach 90% of final value was 5.8 minutes, slightly longer than the workstation measurement period, this was considered acceptable because in practice the thermal differences between successive workstations were usually small. After correction for globe diameter, the differences in predicting mean radiant temperature using the 38-mm and larger globes were less than or equal to the accuracy of the thermocouples used. Side-by-side comparisons were made with a commercially available "ellipsoid-shaped" comfort sensor (see ASHRAE 1985) to obtain the operative temperature comparison shown in the globe temperature section of Table 1.

CALIBRATION

Although many of the transducers featured manufacturers' specifications that exceeded the comfort standards' requirements, a series of calibration measurements was performed on all sensors used in the study. Air temperature sensors were checked by placing them in a well-insulated lightweight box. The box's internal temperature was varied slowly through the range of values anticipated for interior office environments, while readings from the temperature sensors were compared to a laboratory-grade mercury thermometer. Results obtained for the shielded thermocouples produced an acceptable accuracy rating over the relatively narrow temperature range found in office buildings. The omnidirectional air velocity probes were new from the factory with calibrations within the requirements of ASHRAE (1981). Intercomparison of velocity readings in the flow of a portable desk fan confirmed the integrity of the factory calibration between sensors. The dew point sensor, also factory calibrated, was satisfactorily compared to a sling psychrometer and a thin-film, hygroscopic-salt relative humidity sensor; however, subsequent comparisons at the midpoint of the study suggest operational cautions concerning the dew point sensor (see the "Troubleshooting" section). The entire calibration exercise was conducted before and after the field measurements with intermediate calibration measurements on selected sensors. Calibration results are presented in Table 1.

DATA ACQUISITION TECHNIQUES

This section describes the two measurement units, one mobile and one stationary, developed to record physical and subjective data. The mobile system was used to visit individual workstations, where it recorded subjective occupant responses to a short

TABLE 1
Transducer Specifications

QUANTITY	SENSOR DESCRIPTION	SENSOR LOCATION*	MEASUREMENT ACCURACY				RESPONSE TIME
			ASHRAE 55-81	ISO-7726	MANUFACTURER	CALIBRATION	
Air Temperature	shielded platinum RTD	M: 0.6 m	±0.2°C	Required: ±0.5°C Desired: ±0.2°C	±0.2°C over range 5 to 40°C	±0.1°C over range 18.7 to 25.1°C	50 sec (90%) in still air
	shielded thermistor	S: 0.6, 1.1, 1.7 m	±0.2°C	Required: ±0.5°C Desired: ±0.2°C	±0.1°C over range 0 to 70°C	±0.2°C over range 20.7 to 28.5°C	5 sec (90%)
	shielded type T thermcouple	M: 0.1, 1.1 m	±0.2°C	Required: ±0.5°C Desired: ±0.2°C	±1.0°C over range 0 to 100°C	±0.1°C over range 18.7 to 25.1°C	<3 sec (90%)
Globe Temperature	type T thermocouple inside 38 mm diameter table tennis ball (painted grey)	M: 0.1, 0.6, 1.1m; S: 1.1 m	Desired: ±0.2°C (for MRT)	Required: ±2.0°C Desired: ±0.2°C (for MRT)	±1.0°C over range 0 to 100°C (for thermocouple)	±0.1°C over ranges 18.7 to 25.1°C (for thermocouple); ±1°C (for operative temp.)	2.5 min (63.2%); 5.8 min (90%)
Air Velocity	elliptical omnidirectional constant temperature anemometer	M: 0.6 m	±0.05 m/s over range 0.05 to 0.5 m/s	Required: ±5% ±0.05 m/s Desired: ±2% ±0.07 m/s over range 0.05 to 1.0 m/s	±5% ±0.05 m/s over range 0.05 to 1.0 m/s	factory calibration checked by intercomparison	0.2 sec (90%)
	spherical omnidirectional temp. compensated anemometer	M: 0.1, 1.1 m; S: 1.1 m	±0.05 m/s over range 0.05 to 0.5 m/s	Required: ±5% ±0.05 m/s Desired: ±2% ±0.07 m/s over range 0.05 to 1.0 m/s	±3% ±0.02 m/s for flow at 90° to probe; for other angles: <±10%	factory calibration checked by intercomparison	2 sec (67%); 4.1 sec (90%)
Humidity	chilled-mirror dew point sensor	M: 0.6 m	±0.6°C (for dew point temp.)	±0.15 kPa (for water vapor partial press)	±0.5°C (for dew point temp. over range: $T_{air}-T_{dp} < 10°C$)	factory calibration checked with sling psychrometer	2 minute measurement period
Plane Radiant Temperature Asymmetry	opposing plane radiant temperature sensors	M: 1.1 m	±1.0°C	Required: ±1.0°C Desired: ±0.5°C	±0.5°C for $\lvert T_{pr}-T_{air} \rvert \leqslant 15°C$	±0.4°C over range 18.7 to 25.1°C (for plane radiant temp.)	60 sec (90%)
Surface Temperature	spring loaded platinum RTD	M: 0.6 m	N/A	N/A	±0.5°C over range 5 to 40°C	±0.2°C over range 18.7 to 25.1°C	7 sec (90%)
Illuminance	silicon photovoltaic photometer	M: 1.1 m; S: 1.1 m	N/A	N/A	±5%	factory calibration checked by intercomparison	instantaneous

*M: mobile cart sensor; S: stationary sensor

questionnaire and detailed physical measurements to characterize the local environment. Each workstation was visited an average of five times during the week-long period of measurement in each building. The stationary system recorded overall physical trends through the week.

MOBILE SYSTEM

Figure 1 shows the cart that carried the mobile measuring system. A molded fiberglass seat was attached to the front of the cart to represent the shielding effect of the occupant's seat. The various sensors used for physical measurements were mounted above and below the chair at the 0.1 m, 0.6 m, and 1.1 m levels (representing ankles, mid-body, and head/neck of a seated subject). The sensors were protected (at the 0.1 m and 1.1 m heights) with a black metal tubing bumper to guard against encounters with office workers and furniture. The tubing and sensors were separated by sufficient space to minimize possible effects of the tubing on the readings. The shelves on the cart behind the chair contained the remainder of the system, including signal conditioners, data-recording devices, cables, and battery power.

As mentioned earlier, the measurement cart contained three separate data acquisition systems. The first, a portable laptop microcomputer, was used to administer the thermal assessment survey to each office worker participating in the study. The survey consisted of a series of questions and scales addressing the subject's response to his or her immediate thermal environment. At the time of each workstation visit, the computer was placed on the desk, and the subject was left alone to complete the survey by responding to a series of questions appearing on the computer screen (Figures 3a and 4b). Answers (typically yes/no, numerical, or positioning of the cursor along a scale) were typed on the keyboard, with results going directly into storage on diskette. To reduce the possibility of typing errors, an opaque plastic cover was built for the keyboard, exposing only the limited number of keys necessary for answering the questions.

The thermal assessment survey used the ASHRAE Thermal Sensation and McIntyre scales as the primary measures of thermal sensation and comfort. Data were also collected on a secondary series of office work area questions (general comfort, draftiness, and brightness using six-point scales) and the appropriateness of 26 affect ratings (adjectives). A clothing checklist screen (separate female and male versions were developed) presented an itemized list of clothing and asked for a rating on a four-point scale indicating the relative weight of each item. An activity checklist screen inquired about physical activity, eating, drinking (hot, cold, or caffeinated beverages), and smoking during the 15 minutes prior to taking the survey. A complete description of the subjective survey methods employed during the study, including a separate background information survey, is given by Schiller et al. (1988a).

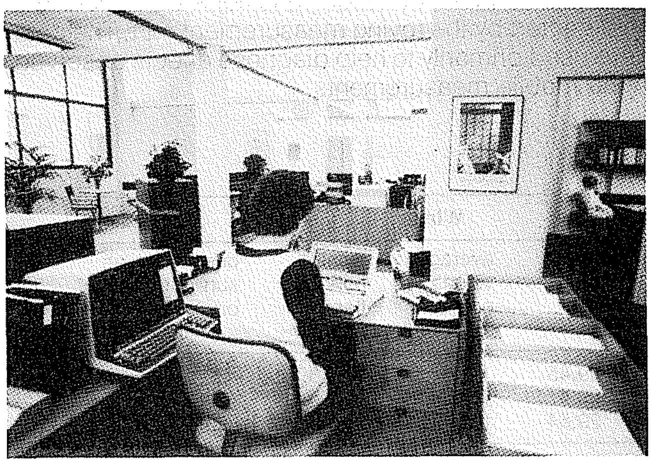


Figure 3a *Thermal assessment survey administered on laptop computer*

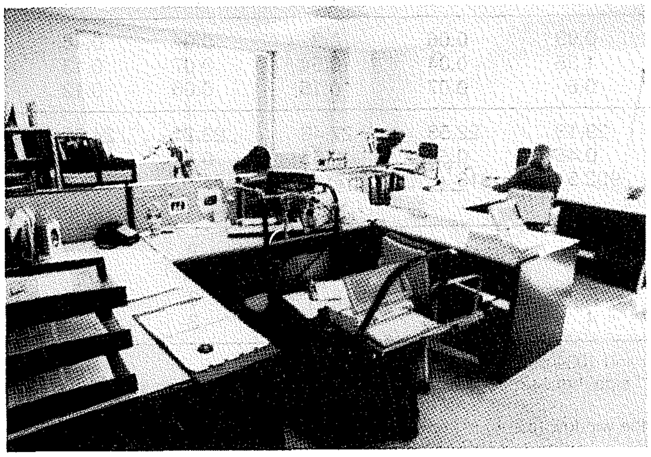


Figure 3b *Cart in position at workstation*

The second data acquisition system contained on the mobile cart was a packaged indoor environment measurement system, optimized to measure the four physical parameters necessary for the evaluation of thermal environments: air temperature, humidity, radiant temperature asymmetry, and air velocity. This specialized system had the additional advantage that the manufacturer's specifications complied with the required measurement accuracies of ASHRAE (1981) and ISO (1985). The sensors associated with this system were positioned to monitor the air temperature, humidity, and air velocity at the 0.6 m height, the maximum radiant temperature asymmetry in the horizontal direction above desk level, and the surface temperature of the chair shell (see Table 1 and Figure 1). A set of readings from these sensors was transmitted serially every 10 seconds to a second portable laptop computer, which employed custom software to record the data on diskette and display current values on its screen as a status check for the operator.

Project budget constraints would not allow the purchase of more than one of the packaged indoor environment measurement systems. Therefore, the additional physical measurement sensors were assembled and connected to a general-purpose, battery-operated microdatalogger, and together these formed the third data acquisition system on the mobile cart. These sensors included thermistors and thermocouples for air temperature and globe temperature measurements, spherical omnidirectional anemometers for air velocity measurements, and a silicon photometer for illumination measurements (see Table 1). The microdatalogger controlled the sensor scan rate (once per second), converted the incoming data to engineering units in real time, and transmitted the data to a cassette tape recorder for final storage.

The use of the multiple data acquisition systems required special procedures to ensure the proper time sequencing of each system over the measurement period. At the beginning of each day in the field, all system time clocks were synchronized. As all data were time stamped at collection during the course of the day, this allowed concurrent or sequential data from individual systems to be identified and assembled into complete data sets during the data analysis phase. In particular, the physical measurements at each workstation depended on the simultaneous operation of two data acquisition systems: the packaged indoor environment system and the microdatalogger-based system. This was accomplished by having the field researcher manually initiate the data collection process for both systems at the appropriate time. The measurement cart could then be left unattended (avoiding undesirable thermal effects of nearby research personnel) as the data collection process continued until it was terminated automatically.

The physical data at each workstation were collected for a total of five minutes. During this time, all sensors were scanned once per second with the exception of the chilled-mirror dew point sensor, which produced a new reading only every two minutes. The cart was positioned in the vicinity of the subject prior to the measurement period, allowing the transducers to equilibrate in the general area. Following the start of data collection, the first two minutes were used to allow all sensors to achieve final equilibrium with their surroundings. Ten-second average data were recorded for the entire five-minute period along with a single average value based on the final three-minute interval. The three-minute average data served as the primary values for data analysis and reporting, while the ten-second data were retained as a safety measure in the event of lost or inconsistent results. For both laptop computer-based systems, custom data management programs were developed to receive the data inputs, convert them into machine-readable format, and store them for subsequent data analysis.

Both average and sample data from the mobile cart are shown in Table 2. The cases presented in this table were selected to emphasize the utility of having a high level of detail in certain interior situations. The data clearly reveal local environmental asymmetries caused by solar gain, a personal fan, an open window, and a floor heater.

STATIONARY SYSTEM

Temporal variation in each building's interior thermal environment was monitored throughout the week-long measurement period. The stationary instrumentation was mounted on a large aluminum tripod and placed in a location representative of the areas being monitored (typically an unoccupied workstation). The environmental parameters monitored by the stationary system included air temperature at the 0.6 m, 1.1 m, and 1.7 m heights and globe temperature, air velocity, and illumination at the 1.1 m height (see Table 1). A general-purpose microdatalogger, identical to the one used on the mobile cart, controlled the data collection process. All sensors were scanned every 10 seconds, and 10-minute average values were calculated and recorded. The stationary data provided a continuous record of trends in interior conditions that could not be detected by the roving measurement cart. The data were used primarily to help diagnose effects observed in the mobile measurements.

TABLE 2
Sample Data

		Summer				**Winter**			
Physical Paramenter	**Units**	average values entire season[1]	small portable fan	operable window nearby	high internal gains	average values entire season[1]	small portable floor heater	direct sunlight on desk	high radiant asymmetery
Air Temperature 0.1 m	°C	23.16	26.89	22.47	29.45	22.5	32.8	22.1	23.9
Air Temperature 0.6 m	°C	23.16	27.58	22.16	29.4	22.64	31	23.2	24
Air Temperature 1.1 m	°C	23.58	28.34	22.27	29.64	23.14	25.5	23.19	25
Globe Temperature 0.1 m	°C	23.2	27.08	22.5	29.34	22.57	32.2	22.2	24.2
Globe Temperature 0.6 m	°C	23.42	27.71	22.56	29.49	22.9	29.5	23.5	25
Globe Temperature 1.1 m	°C	23.65	28.45	22.42	29.62	23.24	25	25	25
Radiant Asymmetry[2]	°C	0.22	0.32	0.28	−1.68	−0.08	−0.1	5.9	11.7
Dew Point Temperature	°C	15.12	12.2	13.9	14	7.3	6.84	4.39	7.59
Air Velocity 0.1 m	m/s	0.08	0.43	0.19	0.93	0.06	0.2	0.04	0.46
Air Velocity 0.6 m	m/s	0.11	0.28	0.22	1.35	0.04	0.54	0.07	0.13
Air Velocity 1.1 m	m/s	0.11	0.22	0.3	0.6	0.07	0.15	0.06	0.12
ET*	°C	23.53	27.36	22.66	29.13	22.53	27.43	23.21	24.67
Clo	clo	0.52	0.7	0.54	0.46	0.58	0.55	0.62	0.55
Illuminance (horiz. plane)	lux	776	1051	613.4	902.5	913	571.6	11434	3388
ASHRAE Vote[3]		0.28	3	0.5	2	0.18	1	2	1
McIntyre Vote[4]		0.24	1	0	1	0.1	0	1	1
General Comfort[5]		4.38	1	5	2	4.34	5	3	3
Ventilation Comfort[6]		3.55	5	5	4	3.5	3	3	3

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[1] These averages include data from 1308 workstation visits during the winter season and 1034 during the summer.

[2] The radiant asymmetry measurement is the difference between the "A" and the "B" side, hence a negative value indicates the "B" side was warmer than the "A" side.

Our convention was to orient the probe such that the "A" side was aimed toward the window (if any) in the workspace.

[3] ASHRAE scale: −3 (too cool) to +3 (too warm)

[4] McIntyre scale: −1 (I want to be warmer), 0 (I want no change), +1 (I want to be cooler)

[5] General Comfort scale: 1 (uncomfortable) to 6 (comfortable)

[6] Ventilation Comfort scale: 1 (stuffy) to 6 (drafty)

FIELD METHODS

Field researchers (typically one or two per day) spent a total of one week per season in each monitored building to set up equipment, collect data, and pack up. A shipping crate was constructed to protect the measurement cart and its instrumentation during transit by pickup truck from one building to the next. A large suitcase was modified with foam pads to accommodate the stationary measurement equipment during transport. These custom-built packages were extremely important to the smooth operation of the field study. They performed adequately for the duration of the study, as no catastrophic damage was experienced during the many months of work in the field.

Within each building, a secure "homebase" room was established in which the measurement cart could be parked and its batteries recharged overnight. The measurement cart with its fully charged data acquisition systems was then capable of collecting data throughout an 8- to 10-hour working day without further charging. A detailed set of instructions was available for the various field researchers (a total of eight individuals were used during the project) to follow during morning start-up, evening take-down, and troubleshooting procedures.

In order to study office workers in their normal work environment, the measurement procedure was designed to minimize disruptions to the subjects. The protocol for each workstation visit and approximate length of time for each task was as follows:

1. Researcher approaches subject and, if convenient to subject, presents the survey computer (1 min [Figure 4a]) while the cart is not visible to the subject;
2. Subject completes the thermal assessment survey (3 to 10 min [Figure 4b]);
3. Subject leaves desk, and field researcher positions measurement cart in place of the subject's chair (1 min);
4. Thermal measurements are recorded (5 min [Figure 4c]);
5. During survey and measurement periods, researcher records additional observations and sketches, takes photographs, and arranges for next workstation visit.

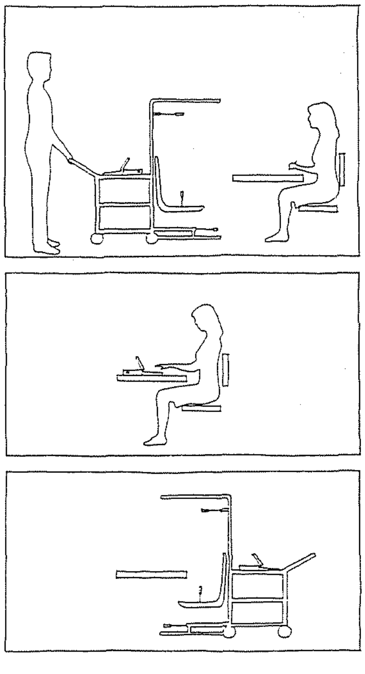
In this procedure, it was important for the researcher to leave the workstation area during the survey period to avoid disturbing the subject. The additional observations and recordings that the researcher collected in item 5 above proved to be quite valuable in interpreting unexpected or inconsistent data during the subsequent data analysis phase. The collected information included (1) sketches of the office layout and cart position (first visit only); (2) photographs of the work area using fisheye and wide-angle lenses (first visit only); (3) location, type, and status (on/off) of equipment affecting local thermal conditions (e.g., fans, electric heaters, HVAC diffusers, computer equipment, etc.); (4) openable window and movable shade positions; (5) unusual clothing on the subject; (6) unusual subject behavior patterns; and (7) observable thermal conditions (e.g., draft, incident beam sunlight, etc.).

DATA FLOW PATH

The daily yield of data from the operation of the systems was sizable. Data from the indoor environment measurement system, accumulated by its dedicated laptop microcomputer, were formatted into two separate ASCII microcomputer files. The first file contained average data from each transducer for 1-second periods, while the second provided summary data averaging the last 3 minutes of each workstation visit. The retrieval of these data, plus the diskette-based data from the thermal assessment survey laptop, required only the exchange of diskettes at day's end. The microdatalogger stored similar physical data from sensors at 0.1 m and 1.1 m heights on a proprietary cassette tape storage system. These data were transferred to microcomputer disk files through a special cassette tape interface at the end of each day. A similar cassette storage system was used for the stationary data acquisition system.

Data collected in machine-readable form were easy to review for errors on a daily basis. As the day's data scrolled by on the screen during transfer, the researcher scanned each channel to confirm that all sensors were operating properly.

The final step in the data flow path was the assembly of all three-minute average data from a building for a given week into a spreadsheet for final error checking and analysis. Using the spreadsheet, problems noted during data collection were resolved along with a careful rechecking of time synchronization between the data files. The summary data for each building were then transferred to mainframe computers for statistical analysis. The project's data spreadsheets are available from the authors.



Researcher approaches subject. Occasionally, arrangements for the timing of the next visit could be made at the conclusion of the previous visit. But usually, subjects were approached in a random order if the time of the last visit was not too recent depending on how busy they appeared.

After finding a willing subject, the researcher initialized the software in the laptop computer, identifying the subject by a number and then retreated to a respectable distance. While the subject took the survey, the researcher scouted possibilities for the next visit and took notes on anything unusual in the subject's clothing, attitude, and proximity and/or status of nearby fans, floor heaters and operable windows.

When the subject has finished with the survey the researcher returns and requested the subject to leave his or her desk for five minutes. The mobile cart is put into place and the measurement sequence initiated. All sensors are scanned at least every second for five minutes. The first two minutes were used to allow the sensors to equilibrate and a single average value is calculated based on the final three-minute interval

Figure 4 *Workstation measurement protocol*

TROUBLESHOOTING

Two instrumentation problems are worth noting: dirt on the dew point sensor mirror and the failure of both thermistors on the mobile cart. The dew point sensor design assumes that light scattered from its mirror surface is due to condensation. If soiling at the mirror surface scatters light instead, the result is an inaccurate reading. Measurements were found to be incorrect twice during the course of the project at roughly equal intervals, suggesting a more rigorous cleaning schedule for the mirror surface. The failure of the thermistors occurred when the battery charger on the cart caused a voltage spike, overloading their circuitry. This problem was addressed by retrofitting type-T thermocouples to these locations.

A final observation about cabling: data transfer cables on a mobile system of this type must be able to withstand frequent flexing and other stresses. A temporary failure of one DAS occurred when a cable developed an intermittent short at one of the plugs, presumably from recurring movement of the cable within the plug body.

CONCLUSIONS

In retrospect, a number of observations arise concerning the field performance of these data acquisition systems and the utility of the detailed data sets they collected. The instrumentation performed well in a challenging program and provided more than 2300 sets of detailed measurements at a performance reliability of approximately 98%. The battery-powered mobile cart could complete an entire day's measurements on an overnight recharging and proved ideal for roaming the corridors of an office (in one case covering several miles a day). The laptop microcomputer proved a convenient device for implementing the thermal assessment survey by providing both a novel, easy medium for the subjects and machine-readable data for the researchers. The daily collection and review of field data were remarkably manageable due to the direct storage of all monitored data in machine-readable form.

The field measurements included all variables specified in ASHRAE (1981) and ISO (1985) including repetition of measurements at 0.1 m, 0.6 m, and 1.1 m above the floor. For many workstation visits this repetition was excessive; average data for the 0.6 m height alone would have been sufficient to characterize the local environment. However, other workstations made it clear that data in this detail are necessary to fully understand the thermal character of workstations subject to nonuniformities in the surrounding environment. Indeed, many sources of discomfort (e.g., drafts, cold floors, asymmetric radiant exchanges) represent just this type of nonuniformity as do many of the workstation-based efforts at restoring comfort (e.g., fans and space heaters) and the effects of specific workstation geometries. The availability of microprocessor-based measurement equipment lessens the burden of making detailed measurements. The value of the entire ASHRAE (1981) measurement set seems well worth the modest incremental cost of additional transducers and the slight increase in data management overhead. It is clear from the study that the measurement specifications of ASHRAE (1981) can be implemented in the field.

The great majority of our analysis was based on average data for the last three minutes of each workstation visit. The more detailed data gathered by the mobile cart instrumentation (10-second average data) produced extensive data files that received relatively little analysis. However, these large data sets did prove to be very useful on several occasions, particularly when a portion of the summary data perished due to accidental erasure or an unusual transducer reading merited closer inspection.

Although it was scaled 1.4 m by 0.45 m in plan, the cart moved easily through the interior spaces of the study. Moving the cart between the test buildings was more difficult. The cart—with well-wrapped cable runs, securely mounted transducers, and a series of secured instrument boxes—was not easily disassembled. For transport between buildings, the entire cart was loaded into a custom-built packing crate. The crate's large dimensions, besides being clumsy, required the use of a light pickup truck or van for transport.

The coordination of time-stamped data from several data acquisition systems, although a manageable task, did require a weekly commitment of time for data formatting. A desire to simplify management of the field data sets, plus the appeal of a more transportable solution, has led to a new approach for the next version of the mobile cart. This version is based on a collapsible wheelchair chassis that carries a single data acquisition system for all physical measurements and features readily demountable components for easy transport.

In conclusion, experience with the field data systems of ASHRAE research project RP-462 was positive. We recommend these systems for further application as practical and useful tools in the study of thermal comfort.

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