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A Field Study of PEM (Personal Environmental Module) Performance in Bank of America's San Francisco Office Buildings

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CONTENTS

LIST OF TABLES AND FIGURES

TABLES

FIGURES

EXECUTIVE SUMMARY

This report describes the results of a field study performed by UC Berkeley in collaboration with Bank of America Corporate Real Estate and Johnson Controls World Services. The purpose of the study was to assess the impact of installing Personal Environmental Modules (PEMs) at 42 selected workstations within three Bank of America office buildings in San Francisco. The PEM is an example of a relatively new approach to space conditioning and control in which individuals are given the ability to control critical environmental conditions within their local work area (e.g., workstation). Each office worker can adjust air flow, temperature, lighting, and acoustic characteristics to maintain their own personal comfort levels. By improving employee satisfaction and well-being, it is anticipated that the installation of a PEM system could lead to increased worker productivity and effectiveness.

In this study, field measurements were performed both before and after the PEM installation to evaluate the impact of the PEM system on occupant satisfaction and thermal comfort, as well as the thermal environments within the office buildings. Within each building two distinct groups, each having approximately the same number of subjects, were selected to participate in the study: (1) PEM group, consisting of workers who occupied workstations in which PEM units were to be installed; and (2) control group, defined to be a group of workers in the same building having similar work conditions to the PEM group, but who would not be receiving PEMs in their workstations. By collecting and comparing measurement data from these two groups, it was anticipated that the impact of installing the PEMs could be most meaningfully evaluated.

The measurement methods used in this field study included (1) occupant surveys, (2) short-term physical measurements of environmental conditions at individual workstations, (3) long-term trend measurements of temperature, humidity, and air quality conditions, and (4) network-based monitoring of occupant use patterns of the PEM desktop controls. The first baseline field measurements were made in March 1996. The 42 PEM units were installed in the three buildings during the first two weeks of April. The follow-up field measurements were completed in July, three months after the PEM installation. During the follow-up field tests, measurements were repeated under three different room temperature setpoint conditions to investigate the occupants' ability to use the PEMs to control their local environment to satisfy their personal preferences above and below the typical ambient setpoint temperatures.

The major conclusions are as follows:

1. Installation of the PEM units increased overall occupant satisfaction in all six building assessment categories studied. The largest increases occurred for thermal quality, acoustical quality, and air quality. In terms of specific environmental factors, increased occupant satisfaction levels among the PEM group were strongly significant ($p\text{-value} < 0.05$) in comparison to changes within the control group for temperature and temperature control, and were somewhat significant ($0.05 \leq p\text{-value} < 0.10$) for air movement, lighting level, visual quality of computer screen,

background noise, freedom from distracting noises, and conversational privacy. Almost all of these factors are addressed by the personal control capabilities of the PEM.

2. The improvements in thermal quality and air quality produced by the installation of the PEMs is noteworthy because it runs contrary to the common trend among many recent field studies that have found thermal and air quality issues to usually be among the lowest rated categories for occupant satisfaction. In the post-installation survey, the PEM group gave these two categories their top two overall satisfaction ratings. In this same survey, the percent dissatisfied (defined as the percent of occupants indicating that they are either very or moderately dissatisfied) went to zero for all thermal quality factors, and was no higher than 6% for air quality factors. This result suggests that occupant complaints in these categories requiring response by building operators will be minimized.

3. Satisfaction ratings from both the March and July surveys were higher for all six assessment categories for the PEM group in comparison to the control group, indicating that the members of the PEM group were, in general, more satisfied with their work environment. Given this higher level of satisfaction in the PEM group, it is reasonable to assume that there would be less room for improvement after installation of the PEMs, making the findings of this study conservative. In comparison to an existing dataset based on surveys of 300 subjects in ten San Francisco Bay Area office buildings, both pre- and post-installation surveys from the PEM group had equal or higher satisfaction ratings for all environmental factors, except background sound level. Satisfaction ratings from the control group were more comparable to this existing dataset, with some higher and some lower scores.

4. Acoustical quality was the most poorly rated assessment category in these three Bank of America office buildings. Dissatisfaction with conversational privacy was the biggest contributing environmental factor to this result. In particular, 63-64% of the control group were either very or moderately dissatisfied with their conversational privacy in both surveys. The corresponding ratings by the PEM group were 61% dissatisfied in the March survey, decreasing to 37% dissatisfied in the July survey.

5. The job impact rating results displayed similar trends to those observed for the work area satisfaction results. For the PEM group, increases in job impact rating between the baseline and post-installation surveys were strongly significant for thermal quality, air quality, and acoustical quality. There were no significant changes for the control group, suggesting that the improvements in these three environmental factors produced by the PEMs had a positive impact on the occupants' ability to work effectively that would not have occurred if the PEMs were not installed.

6. Although the current study did not attempt to measure worker productivity, a rough estimate can be made of the impact on productivity of installing the PEMs in these three Bank of America buildings by comparison with the well-known West Bend Mutual Study [Kroner et al. 1992]. The West Bend Study investigated the impact on worker productivity of moving from an old headquarters building to a newly designed office building that included installation of PEM units in each occupant's workstation. If we make the assumption that overall occupant satisfaction and productivity are correlated in roughly a similar manner to that of the Kroner productivity study, the current data suggest that installation of the PEM units could produce improvements in productivity of a similar size (2.8%) to that found in the Kroner study.

7. When responses from the PEM workers in 560 Davis Street were split out from the other buildings, the performance of the PEM in comparison to conditions prior to installation was slightly less favorable than that reported in the other two buildings. This may be due in part to the fact that the PEM units in Davis Street were only recirculating room air to the occupants -- no cooler and fresh ventilation air is provided through the PEM nozzles on the desks. However, the small number of Davis occupants (6) made the analysis statistically inconclusive.

8. Within the PEM group, the mean acceptability rating at the time of measurement ("environmental conditions right now") increased substantially from the baseline to post-PEM surveys for three factors (temperature level, air movement, and ventilation quality), and increased moderately for three others (humidity, lighting level, and noise level). The percent unacceptable (defined as the percent of occupants indicating that they find the conditions to be either very or moderately unacceptable) decreased to zero for all environmental factors except noise level, representing a high level of overall acceptability for most occupants.

9. The increased satisfaction ratings for air movement were associated with the higher localized air movement provided by the PEM units. In general, the occupants chose to increase the local air movement. This was reflected in the average measured velocity, which increased from 0.08 to 0.11 m/s between surveys, as well as the increased perception of air movement shown in the survey results. The preference for higher air motion within the PEM group also decreased from 54% in the baseline survey to only 15% in the post-PEM survey, and 77% (up from 36%) indicated that no change was required. By comparison, almost 60% of the control group subjects indicated a preference for higher air movement in both surveys.

10. Survey results indicated that more than 80% of the PEM users adjusted the PEM controls less frequently than once each day. This suggests that it is more important for workers to have the ability to control their local environment than it is for them to actually make a large number of control adjustments. Monitored occupant use patterns found that about half of the PEM group adjusted the thermal controls in a way that was consistent with the change in temperature during the set-up and set-down

periods. Overall, 88% of the PEM group used the PEM thermal controls to some extent (although rather infrequently) over the July test period. Several examples from different individual PEM users demonstrated how occupants understood quite extensively how to use the PEM to control their local environment.

11. Some problems with the PEM system causing dissatisfaction among the occupants were observed, although in most cases adverse impacts could be avoided or minimized. (1) The installation into each workstation was quite intrusive, requiring at least two large holes to be drilled through the work surface. The occupants should be well-informed of the proposed design and placement of the supply outlets and controls, to avoid unnecessarily upsetting them during installation. (2) In one of the buildings, during the first few weeks after installation, the PEM units were consistently overpressurized by the air supply coming from the main HVAC system. This problem was eventually corrected, but it did lead to initial increased dissatisfaction among some of the PEM users because they had too much air supply, even when they turned down the fan control to its minimum setting. Clearly, it is important to achieve good control of the air being supplied to the PEM users, so that the PEM can be controlled in its intended manner. (3) In the above described overpressure problem, it was possible to reduce air flows by moving the air temperature control to its warmest setting, thereby closing down the damper on the overpressurized primary air supply, and opening the damper to allow more recirculated (warmer) room air to be supplied through the PEM nozzles. Although this was a solution that was available during that initial period when problems were occurring, all of the occupants were not made aware of how these controls could be used. As with any new technology, occupants should be properly trained to allow the operation and control of the PEM system to be optimized.

INTRODUCTION

In late 1995, Bank of America initiated a program to investigate alternative workplace strategies that reduce operating costs and improve the value of their facilities, while also increasing the productivity of their workers and effectiveness of their organization. Alternative officing (AO) has arisen as a solution to these corporate concerns by responding to the changing knowledge-based workplace. AO takes advantage of new and advanced technologies that support innovative approaches to knowledge-based work. These new building technologies allow flexible and responsive facilities to be produced in new construction or by upgrading existing building infrastructures. Advanced technologies that support AO include: extensive and expandable electrical and communication networks supporting information exchange, movable and adaptable office furniture systems, and task/ambient conditioning systems.

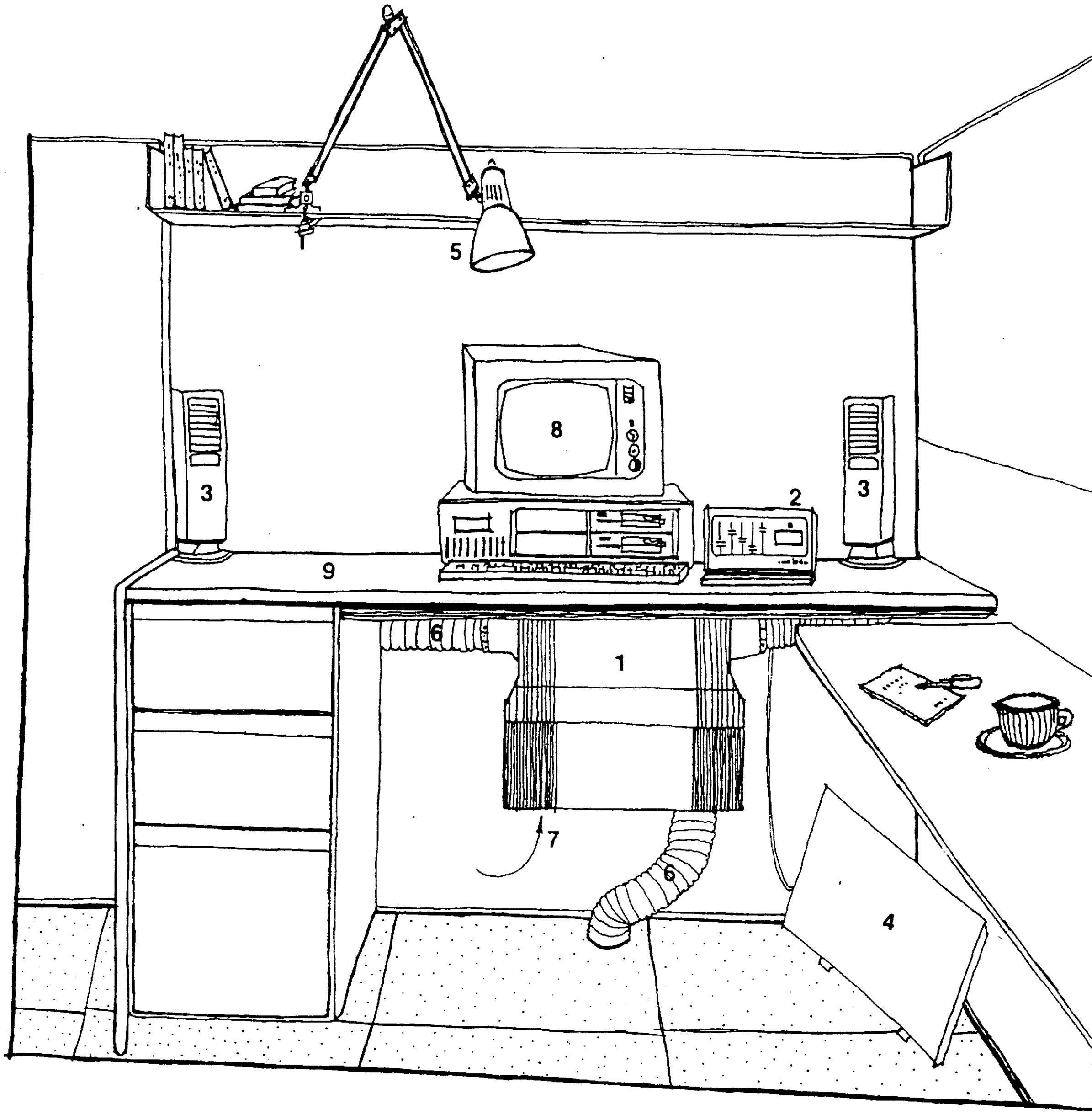
Bank of America was particularly attracted to one commercially available task/ambient conditioning system, the Personal Environmental Module (PEM), manufactured by Johnson Controls. The PEM is an example of a relatively new approach to space conditioning and control in which individuals are given the ability to control critical environmental conditions within their local work area (e.g., workstation). Each office worker can adjust air flow, temperature, lighting, and acoustic characteristics to maintain their own personal comfort levels. By improving employee satisfaction and well-being, it is anticipated that the installation of a PEM system can increase worker productivity. In addition, PEMs have the potential to improve indoor air quality and reduce energy use for space conditioning.

Bank of America decided to conduct a pilot study of PEM performance by installing PEM units at selected locations in three of their San Francisco office buildings. In collaboration with Johnson Controls, researchers at UC Berkeley were brought in to perform field measurements in these three buildings both before and after the PEM installation to evaluate the impact of the PEM system on occupant satisfaction and thermal comfort, as well as the thermal environments within the office buildings. The measurement methods used in this field study included (1) occupant surveys, (2) short-term physical measurements of environmental conditions at individual workstations, (3) long-term trend measurements of temperature, humidity, and air quality conditions, and (4) network-based monitoring of occupant use patterns of the PEM desktop controls. The first baseline field measurements were made in March 1996. The 42 PEM units were installed in the three buildings during the first two weeks of April. The follow-up field measurements were completed in July, three months after the PEM installation. During the follow-up field tests, measurements were repeated under three different room temperature setpoint conditions to investigate the occupants' ability to use the PEMs to control their local environment to satisfy their personal preferences even at higher and lower ambient temperatures.

This final report contains the following: (1) description of PEM and review of previous research; (2) description of PEM installation in three Bank of America office buildings; (3) description of experimental methodology, including survey and physical measurement instruments and procedures; (4) discussion and statistical analysis of survey results; (5) discussion of physical measurement results; (5) presentation of occupant comments; (6) plots of individual PEM user control patterns; and (7) summary and conclusions.

PERSONAL ENVIRONMENTAL MODULE (PEM) DESCRIPTION

The Personal Environmental Module (PEM) is manufactured by Johnson Controls, Milwaukee, Wisconsin. A sketch of a typical PEM installation in a workstation is shown in Figure 1. The PEM is a desk-mounted unit supplying conditioned or recirculated air at desktop level. It uses a self-powered mixing box that is hung in the back or corner of the knee space of the desk, and connected by flexible duct to two supply nozzles on the top of the desk. The supply vents may be rotated 360° in the horizontal plane and contain outlet vanes that are adjustable ±30° in the vertical plane. The mixing box uses a small variable-speed fan to pull conditioned air from either an underfloor air supply plenum (as indicated) or from vertical ducts down from the ceiling connected to an overhead air distribution system (this is the duct configuration used in two of the three



1 PEM supply module
2 PEM control panel
3 PEM supply nozzle
4 radiant heating panel
5 task light
6 flexible supply duct
7 recirculated room air
8 personal computer
9 desk

Figure 1. Personal Environmental Module (PEM)

B of A office buildings). Using damper control, the fan can also pull recirculated room air from the knee space through a mechanical prefilter. Both supply air and recirculated room air are drawn through an electrostatic air filter. The relative fractions of supply air and recirculated air are controlled by dampers on each of these two lines. For installations providing conditioned supply air to the PEMs, the main supply line damper is never allowed to close completely, thus ensuring the delivery of fresh ventilation air at all times.
An alternative PEM configuration provides no connection to the building's ventilation system, and therefore delivers only recirculated air through the desktop supply nozzles.

The key occupant-control component of the PEM is a desktop control panel containing adjustable sliders controlling the speed of the air emerging from the vents, its temperature (produced by adjusting the ratio of supply to recirculated air), the temperature of a 175 W radiant heating panel located in the knee space, the dimming of the occupant's task light, and a white noise generator in the unit that issues a rushing sound through the supply vents. The control panel also contains an infrared occupancy sensor that shuts the unit off when the workstation has been unoccupied for a few minutes. The control panel is connected to a microprocessor-based programmable controller contained inside the main PEM unit located under the desk. The controller utilizes an RS-485 communication link allowing multiple controllers to be networked together and to be connected to a central system controller. As described below, this communication capability was used to set up a PEM monitoring network in the three B of A office buildings.

Each PEM unit is capable of providing approximately 12-150 cfm (6-70 L/s) of supply air. For PEM units connected to the building's ventilation system, even when its internal fan is turned off, the PEM unit is designed to deliver 12 cfm (6 L/s) to satisfy minimum ventilation requirements. In operation, 55°F (13°C) is provided by a variable-air-volume ventilation system, with desk-level outlet temperatures in the range of 65°F (18°C).

UC Berkeley and Lawrence Berkeley Laboratory have conducted several experimental studies of the thermal and ventilation performance of PEMs in UCB's Controlled Environment Chamber. Results indicate that the PEMs are capable of controlling over a wide range of thermal conditions, allowing office workers the opportunity to fine-tune the local workstation environment to their individual comfort preferences [Arens et al. 1991, Bauman et al. 1993]. Under optimal operating conditions, the PEMs were able to provide true task ventilation (i.e., increased ventilation at the location of the occupant), with significantly lower ages of air at the breathing level in the workstation compared to that of the air leaving the room through the return grill [Faulkner et al. 1993].

The first large installation (370 units) of PEMs took place in a newly designed office building occupied by the West Bend Mutual (WBM) Insurance Company in West Bend, Wisconsin. The building was fully occupied in July 1991. Post (1993) describes the new WBM building and its intelligent building features that allowed it to lower operating costs, improve workplace productivity, and still cost less than conventional buildings. The WBM building provided a rare field research opportunity to study the impact of the PEM system on productivity. It was discovered that WBM had an established computer-based method for measuring the productivity of its employees. Researchers from Rensselaer's Center for Architectural Research, and Center for Services Research and Education, Troy, NY, carried out a study in which they used this existing WBM measure to track the productivity of over 100 employees for 27 weeks before, and for 24 weeks after they moved into the new building containing PEMs. The project investigators concluded that the PEMs increased worker productivity by 2.8%, although the validity of analysis methods used to extract productivity gains due to the PEM from gains resulting from the move to a new building and other factors is difficult to determine [Kroner et al. 1992].

Occupant comfort and energy use of PEMs was investigated as part of a field study of a small demonstration office containing four PEM units [Bauman and McClintock 1993]. Monitored occupancy patterns showed that the use of occupancy sensors is very effective at limiting excessive energy use associated with the PEM units and other workstation-based equipment that can be turned off when the workstation is unoccupied. In a second field study using the same demonstration office, a total of eight PEMs were installed and monitored, and the air distribution system was reconfigured to allow switching between the PEM system and a conventional ceiling-based air distribution system [Akimoto et al. 1996]. The study found that when the wall thermostat was maintained at a warm condition near the upper limit of the ASHRAE thermal comfort zone (26°C [79°F]), the PEM was able to maintain the average temperatures in the workstations to be 1-2°C (2-4°F) lower than the thermostat temperature, and at least 1°C (2°F) lower than that maintained by the overhead air distribution system under similar operating conditions.

In another study, annual building energy simulations using the DOE-2 computer program investigated the energy performance of a new prototypical office building in two California climates, Fresno and San Jose [Bauman et al. 1994]. The simulations compared three different task/ ambient conditioning system configurations (including the PEM system) versus a base case building consisting of a reasonably efficient standard overhead air distribution system with an air-side economizer. The simulation results showed that, in comparison to the base case, the PEM system in a San Jose office building could save annually as much as 18% of the cooling energy, 18% of the distribution (fans and pumps) energy, 10% of the total electricity, and 9% of the total electricity cost.

A recently published design guide [Bauman and Arens 1996] presents engineering and application guidelines for task/ambient conditioning (TAC) systems, including the PEM system. A well-designed TAC system should take maximum advantage of the potential improvements in thermal comfort, ventilation performance, indoor air quality, and occupant satisfaction and productivity while minimizing energy use and costs.

FIELD STUDY METHODOLOGY

Description of Test Sites and Subjects

Three Bank of America office buildings in San Francisco were designated as test sites for this field study. Within each building two distinct groups of subjects were selected to participate in the study: (1) PEM group, consisting of workers who originally occupied workstations in which PEM units were to be installed; and (2) control group, defined to be a group of workers in the same building having similar work conditions to the PEM group, but who would not be receiving PEMs in their workstations. By collecting and comparing measurement data from these two groups, it was anticipated that the impact of installing the PEMs could be most meaningfully evaluated.

A total of 42 PEMs were to be installed in the three buildings, so members of the three PEM groups included the 42 workers occupying these workstations at the time of our first baseline field measurements. Within each building we also attempted to select at least 10-12 workers for the control group. This enabled us to accumulate a control database that was based on a similar number of subjects as the PEM group. The three building test sites and the selected groups of participants are described briefly below.

1455 Market Street
Eighteen workers on the 22nd floor, including the Hardware Tech Support group, were selected to have PEM units installed in their workstations. Figure 2 shows the floor plan of the PEM group office space which borders along the northwest glazing of the 22nd floor. The space design was a typical open plan office with individual partitioned (65-inch high) workstations. Also shown in this figure, as well as in Figures 4-6, are the locations where portable dataloggers were used to record long-term trend measurements of temperature, relative humidity (RH), and CO_2 concentration. These dataloggers are discussed later in this report. Modifications were made to the existing overhead air distribution system to allow each PEM to be connected via a 6-inch acoustical flexible duct contained inside a vertical spiral duct as shown in Figure 3. The modifications included capping off and removing all perforated ceiling diffusers positioned over the PEM group office area. Perimeter slot diffusers were left in place to handle the more variable perimeter heating and cooling loads. Existing variable-air-volume (VAV) control boxes were adjusted or new VAV boxes were installed as needed to serve the air supply requirements of the 18 new PEM units. Air supply to the adjacent spaces on the 22nd floor continued to be provided by the existing overhead air distribution system.

Notes for Figure 2: 1455 Market Street, 22nd Floor

Sensor	Location
temperature/RH logger	top of cabinet, 5 ft height
temperature logger 1	shelf, 4.5 ft height
temperature logger 2	next to wall thermostat, 4.5 ft height
temperature logger 3	next to wall thermostat, 4.5 ft height
temperature logger 4	above return grill, ceiling level
temperature logger 5	shelf, 5 ft height
CO_2 logger	desk top, 2.7 ft height

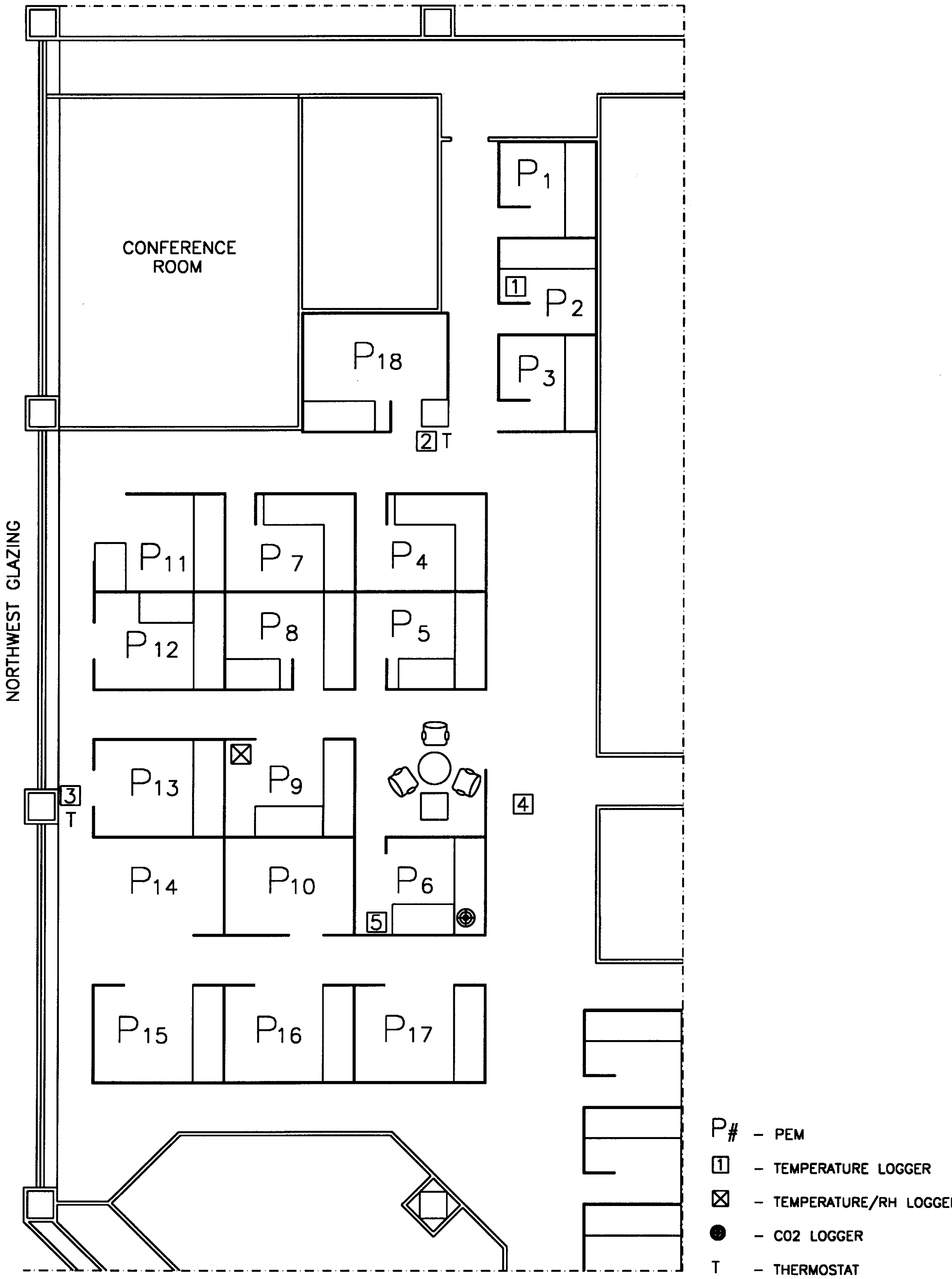


Figure 2. Floor Plan, PEM Group, 22nd Floor of 1455 Market St.

The control group in the 1455 Market building was selected from workers in Account Services located on the 17th floor. Figure 4 shows the floor plan for this office area, which also bordered along the northwest glazing of the building to match the solar exposure of the PEM group. The office had a typical design with some partitioned workstations and some open areas with free-standing desks. The office was conditioned by a conventional overhead air distribution system.

Notes for Figure 4: 1455 Market Street, 17th Floor

Sensor	Location
temperature/RH logger	top of cabinet, 5 ft height
temperature logger 1	next to wall thermostat, 5 ft height
temperature logger 2	above return grill, ceiling level
temperature logger 3	next to wall thermostat, 5 ft height
temperature logger 4	desk top, 2.7 ft height
temperature logger 5	top of cabinet, 4.5 ft height

One S. Van Ness Avenue

Fifteen workers in the Human Resources group on the 4th floor were selected to have PEM units installed in their partitioned (approximately 5 feet high) workstations. Figure 5 shows the floor plan of this larger open-plan office area, which also included members of the control group who were selected from the workstations outside of the two rows containing PEM units. This office area also bordered along the northwest side of the building. In a similar manner to that described above, the existing overhead air distribution system was modified to allow each PEM to be connected. In this case the connections were made via a vertical 6-inch by 6-inch supply air duct with 1/2-inch thick acoustical duct liner.

Notes for Figure 5: One S. Van Ness Avenue, 4th Floor

Sensor	Location
temperature/RH logger	top of fixed half-wall, 5 ft height
temperature logger 1	top of partition, 5 ft height
temperature logger 2	next to wall thermostat, 5 ft height
temperature logger 3	next to wall thermostat, 5 ft height
temperature logger 4	above return grill, ceiling level
temperature logger 5	shelf, 4 ft height
CO_2 logger	desk top, 2.7 ft height

560 Davis Street

Nine workers in the MIS department on the 2nd floor were selected to have PEM units installed in their workstations. The control group was selected from workers in an adjacent and similar office space. Figure 6 shows the floor plan of this office area, including both the PEM and control groups. The workstations in both office spaces

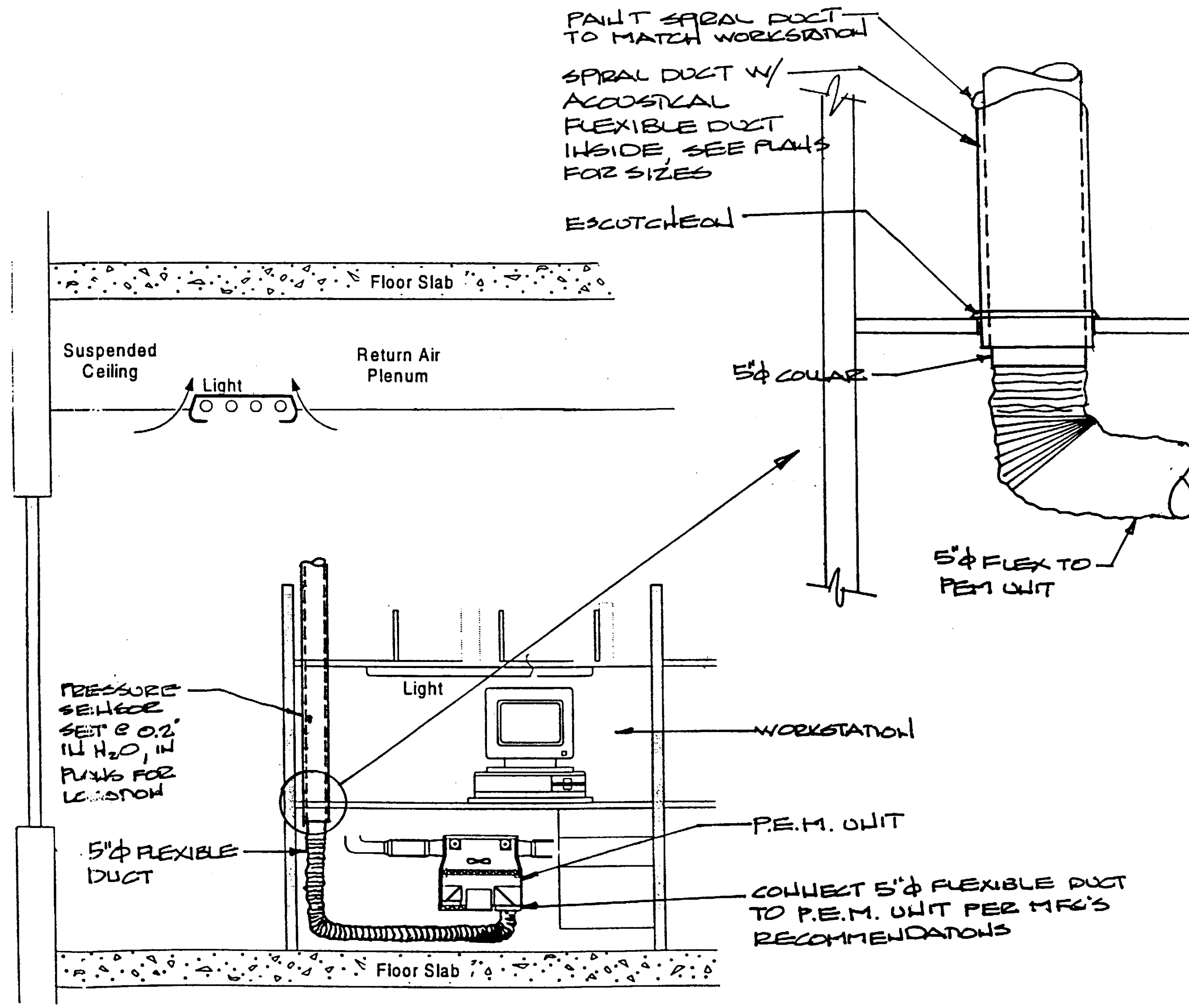


Figure 3. Typical PEM Installation in Workstation (courtesy of HOK)

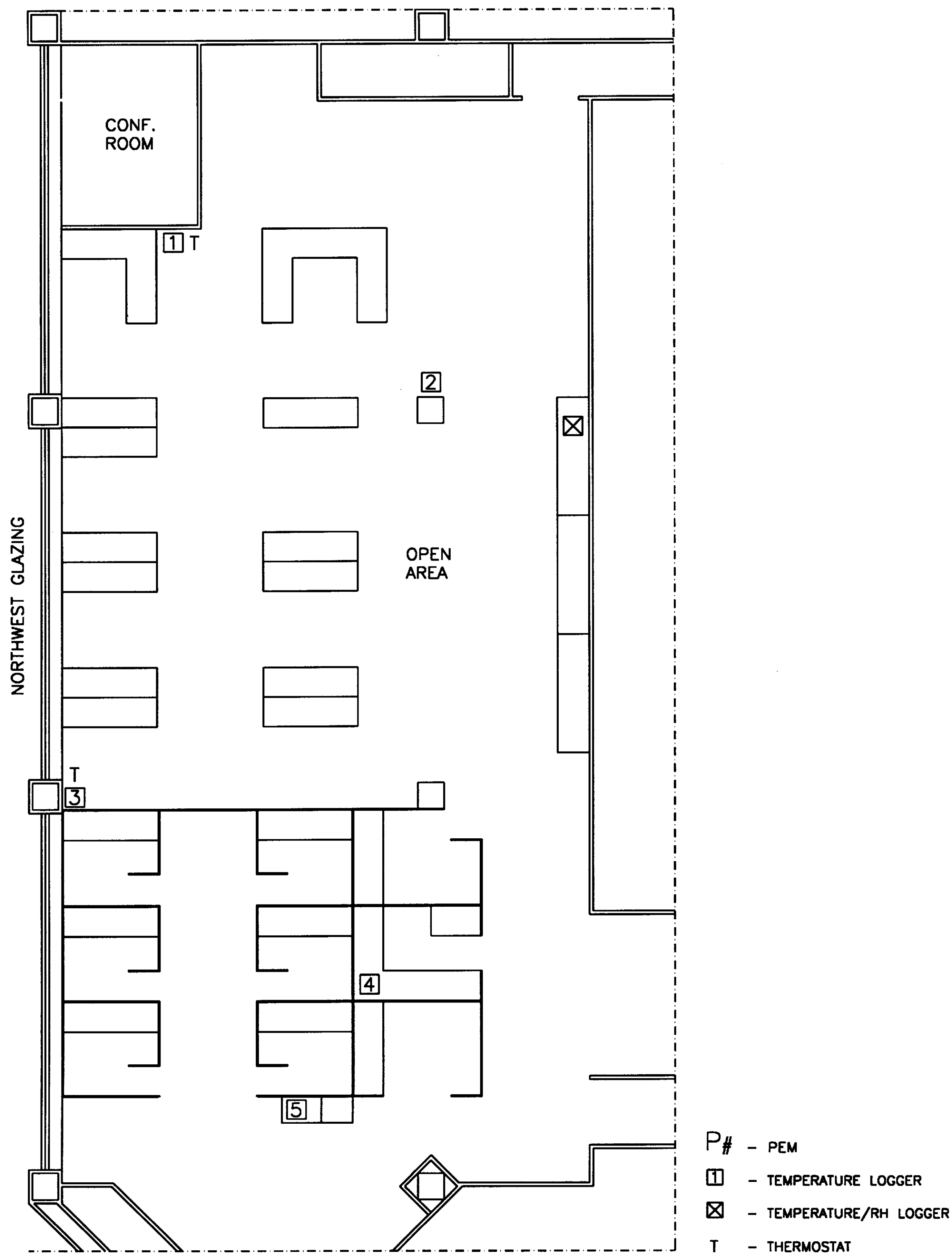


Figure 4. Floor Plan, Control Group, 17th Floor of 1455 Market St.

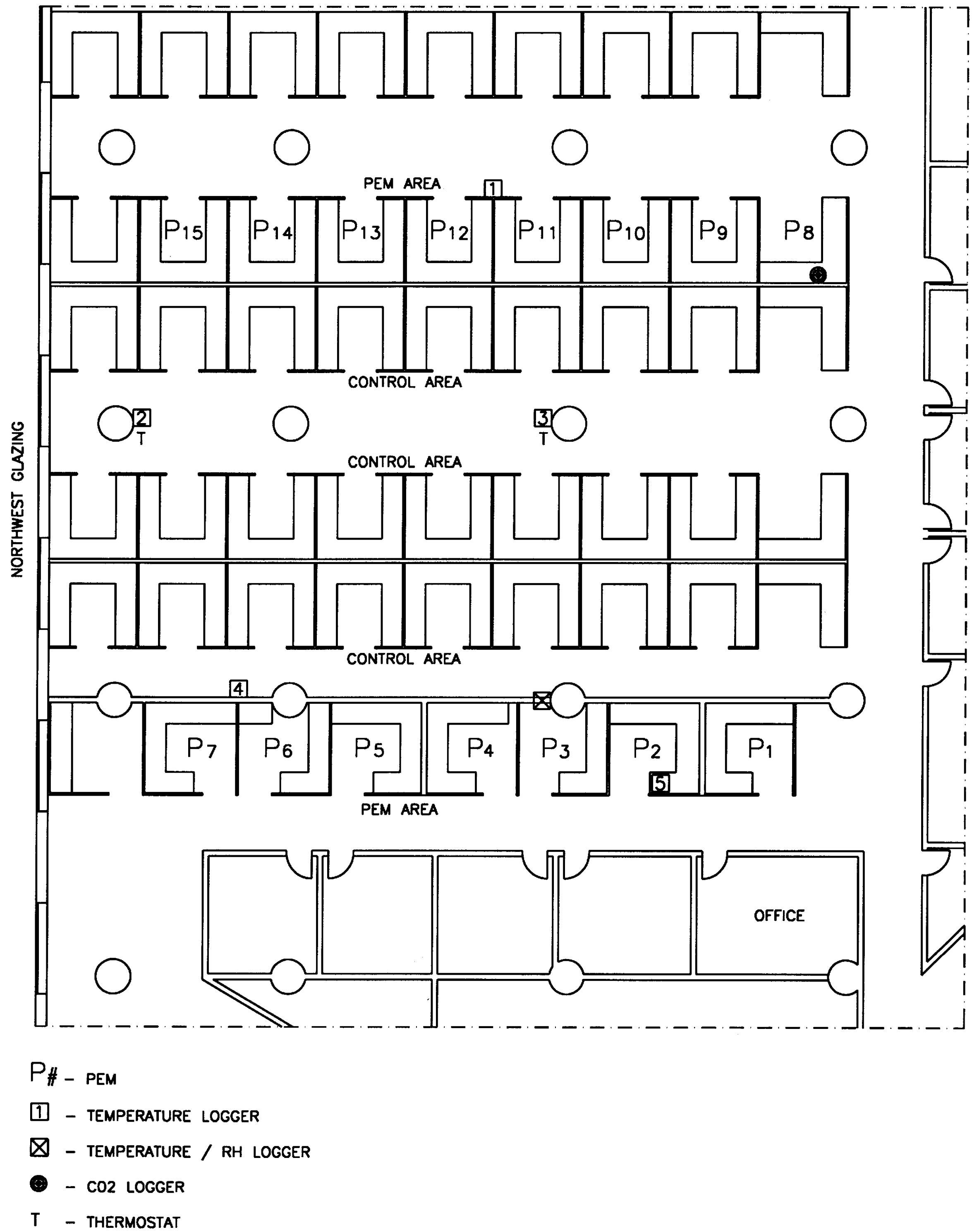


Figure 5. Floor Plan, PEM and Control Groups, 4th Floor of One S. Van Ness Ave.

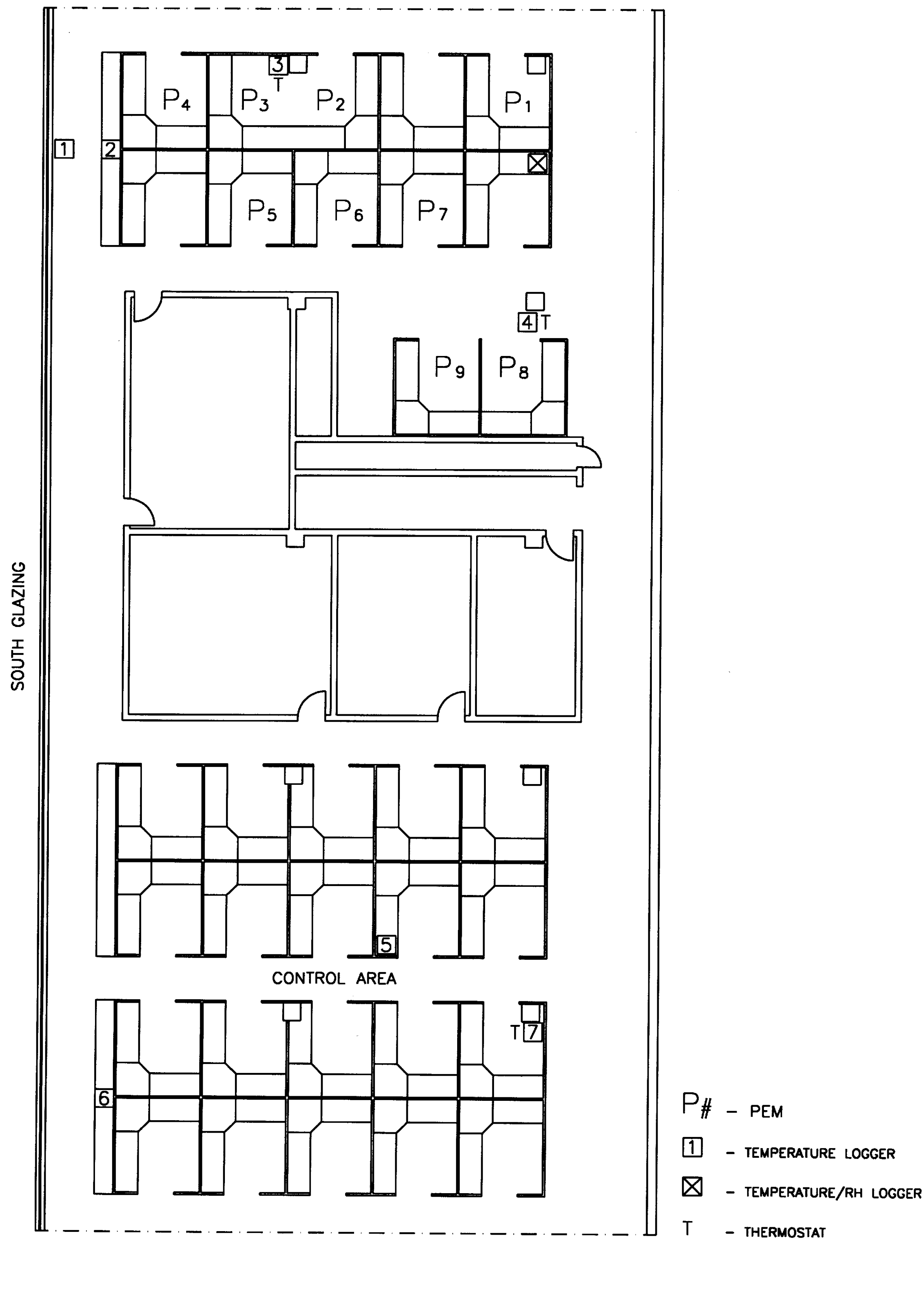


Figure 6. Floor Plan, PEM and Control Groups, 2nd Floor of 560 Davis St.

consisted of some taller (5-6 feet high) and some mid-height (3.5 feet high) partitions. The office
spaces both had the same southern exposure, although a large condominium building across the street provided shading during most of the day. For this installation, the PEMs were not connected to the building's overhead air distribution system. Each PEM unit therefore delivered only recirculated room air through its desktop supply nozzles.

Notes for Figure 6: 560 Davis Street, 2nd Floor

Sensor	Location
temperature/RH logger	shelf, 5.5 ft height
temperature logger 1	inlet to ceiling return plenum
temperature logger 2	top of partition, 4 ft height
temperature logger 3	next to wall thermostat, 5 ft height
temperature logger 4	next to wall thermostat, 5 ft height
temperature logger 5	desk top, 2.7 ft height
temperature logger 6	top of partition, 4 ft height
temperature logger 7	next to wall thermostat, 5 ft height

Occupant Survey

A survey was used to assess the response of the occupants to the quality of the physical environment at their work location, and in particular, their response to the installation of the PEM units. The survey was adapted from a previously developed questionnaire as part of an indoor environmental quality assessment system [Baughman et al. 1995]. The survey consisted of two types of questions: (1) background questions, which addressed some general information and the occupants' overall perception of their work environment over the past few months; and (2) questions on environmental conditions right now, which provided a snapshot of how the occupants perceived their work environment by asking how they felt at the time they were filling out the survey. Appendix A presents a complete listing of the occupant survey. Some questions were added or dropped, depending on when and to whom the survey was given. The survey is described in greater detail below.

Background Questions

The first page of the survey consists of a few background questions (e.g., How long have you worked in this building? How many hours per day do you sit at your work area?) that may be useful for diagnostic purposes. The next section beginning on page 2, entitled "Work Area Satisfaction," asks the occupants for their opinions of their work environment with regard to six major building assessment categories: spatial layout, office furnishings, thermal comfort, lighting quality, acoustical quality, and air quality. The standard metric used for most questions is the level of satisfaction, ranging from very satisfied (6) to very dissatisfied (1). Within each assessment category, three specific environmental factors are addressed. The average of the scores from these three factors makes up the overall occupant satisfaction rating for that category. The occupant is also asked to judge the level and frequency for those environmental parameters that vary over time. For example, the occupant is asked whether the temperature is “too cool,” “comfortable,” or “too warm” with frequency choices of “never,” “sometimes,” and “frequently” for each possible answer. These types of questions were asked explicitly because individual differences prevent the assumption that a certain satisfaction level corresponds to a certain environmental condition, or vice versa. Finally, for each major assessment category, the occupants were asked to rate the overall impact of each on their ability to perform their work effectively.

Because the background questions addressed overall impressions of the occupants' work environment, they were asked one time at the beginning of the study (March 1996) to establish baseline opinions and responses, and a second time near the end of the study (July 1996) to assess any changes in opinions three months after the PEM installation. During the follow-up field measurements, additional questions were added to the background section of all surveys as follows: (1) questions about the occurrence of various physiological symptoms, such as headache or sneezing (page 5 of survey); and (2) questions asking the occupant to rate the importance of the various environmental attributes to their work area satisfaction (page 8 of survey). To gather more specific information about the PEM performance, surveys administered to the PEM group during the follow-up field measurements also included the following: (1) questions comparing the comfort of their work environment with the PEM system to conditions prior to installation of the PEM units (page 6 of survey); (2) questions about the frequency of use of the various PEM controls (page 6 of survey); and (3) open-ended questions about the advantages, disadvantages, and which controls have the greatest impact on improving their comfort (page 7 of survey).

Questions on Environmental Conditions Right Now

Beginning on page 9 of the survey, the occupants are asked for their feelings and level of acceptability at the time they are filling out the survey regarding seven environmental conditions: brightness level, air movement, humidity, ventilation quality, odors, noise level, and thermal environment. On page 11, they are asked a short series of questions describing their recent activity and food and beverage consumption, which can affect their current thermal comfort response. The survey concludes on pages 11 and 12 with three open-ended questions asking the occupants for comments on: (1) seasonal differences in terms of comfort of their work area; (2) the most significant factor(s) of their work environment that contribute to their feeling of well-being; and (3) any other aspect of their work environment or the survey.

The subjective data from the “environment conditions right now” section of the survey can be directly related to the physical data collected immediately thereafter at the workstation by the portable measurement cart, as described below. This section of the survey was generally administered at the same time as the background section and at other selected times when we wanted to correlate the occupants' current subjective feelings with physical data we were collecting during the three testing periods (normal, set-up, and set-down) of the post-installation field test.

Physical Measurements

Short-Term Measurement of Workstation Environments

Physical measurements of the local workspace environment were made using our existing portable measurement system. These measurements were generally completed as part of visits to individual workstations during which the occupants also answered survey questions about their "environmental conditions right now," described above. The data are used to correlate the occupants' subjective responses with their actual physical environment and to record the individually controlled workstation environments produced by the local PEM units.

Figure 7 shows a sketch of the battery-powered portable measurement cart, which collects a complete set of detailed measurements characterizing the local environment using an automated approach. This system has been used in several previous field studies of office environments [Benton et al. 1990, Bauman and McClintock 1993, de Dear and Fountain 1994]. Data are collected for thermal (air temperature, globe temperature, air velocity/turbulence, humidity, and radiant temperature asymmetry) and other environmental parameters (illumination, CO_2 concentration, and sound level). The instrumentation contained on the cart is described in greater detail below.

The measurement cart's sensors are placed at heights above the floor and chosen to meet the response time and accuracy requirements specified in recognized indoor environmental standards [ASHRAE 1992, ISO 1985]. In general, the temperature sensors are accurate to within ±0.2°C and have a time-constant of several seconds. The sensors used are YSI Series 700 probes having a vinyl-coated tip on a flexible signal wire. Where globe temperature was measured, we mounted a table tennis ball on the cart with one of the YSI temperature sensors in the center of the "globe." The globe is painted gray for the proper emissivity and responds to the balance between radiation and convection in the physical environment. In an office environment where the differences between workstations are relatively small, the globe should reach equilibrium well within the 5-minute measurement period.

Air velocity is measured at three heights by Dantec 54R10 anemometers. The 54R10 is an omni-directional fully temperature-compensated sensor with a time constant of 0.1 second and an accuracy of ±0.01 m/s. A fast response time is essential for accurate measurement of turbulence in the airflow. Each sensor has two nickel-plated quartz spheres supplied with a small electrical current. The current heats the spheres which in turn are cooled by passing airflow. Velocity is measured by regulating the electrical current to maintain the spheres at a constant temperature.

Dewpoint temperature is measured by a General Eastern DEW-10 chilled mirror dewpoint transducer. In this transducer, a heated chimney draws a small sample of room air into a measuring chamber where a small mirror is continuously cooled. A nearby LED shines a beam of light at the mirror where it is reflected to a photosensor. When

- a transducers at 1.1 m (air temperature, globe temperature, air velocity)
- b transducers at 0.6 m (air temperature, globe temperature, air velocity)
- c transducers at 0.1 m (air temperature, globe temperature, air velocity)
- d radiant asymmetry transducer
- e illuminance sensor
- f inlet, dew point sensor
- g laptop computer
- h data acquisition and signal conditioning compartment
- i battery compartment
- j pseudo chair (storage compartment for subjective survey laptop computer)

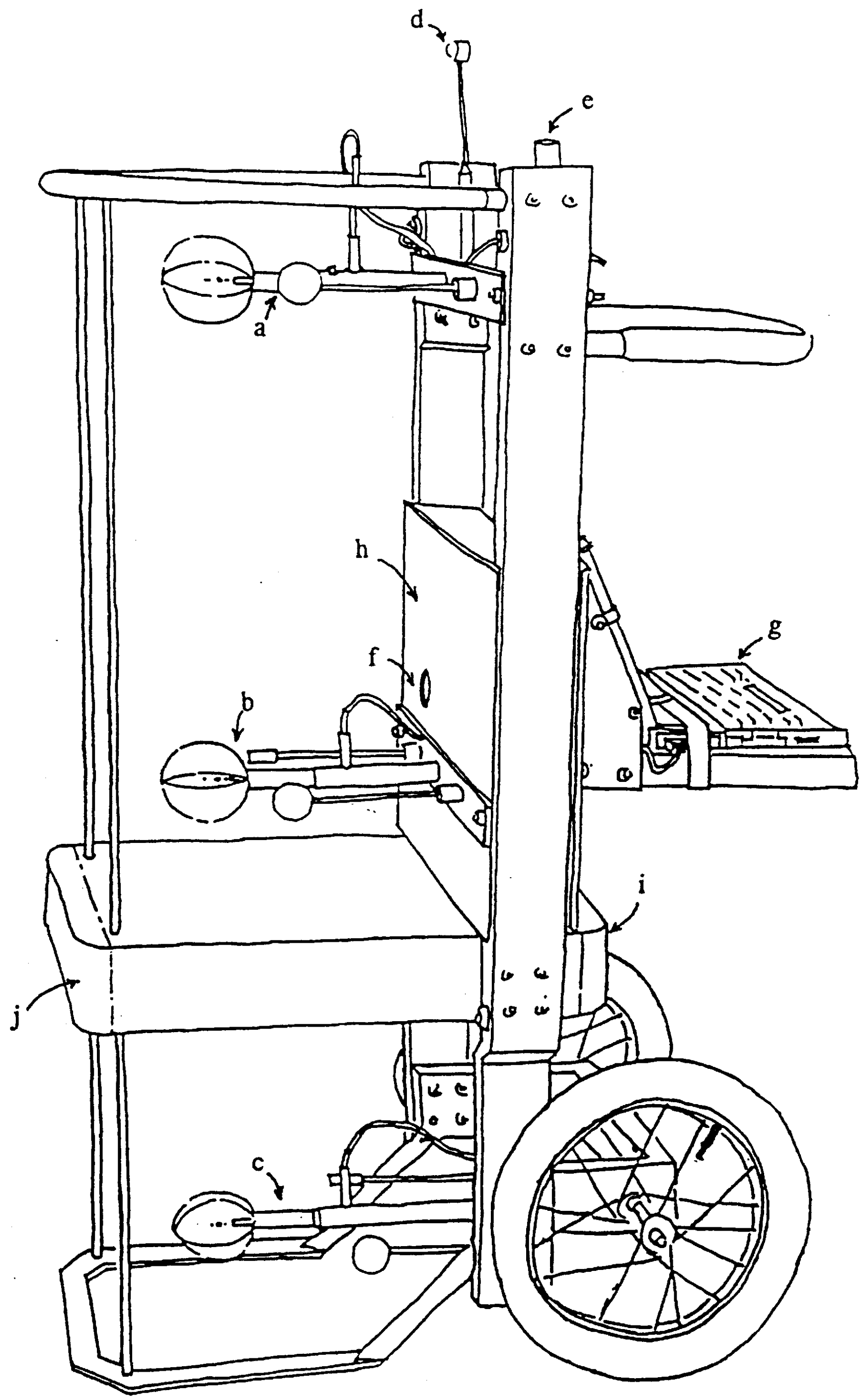


Figure 7. Portable Measurement Cart

the mirror reaches the dewpoint temperature of the air sample, water condenses on the mirror scattering the light beam so the signal to the photosensor is interrupted. Then the temperature of the mirror is measured (to ±0.5°C) and sent to the central datalogger.

Radiant asymmetry is measured by a Bruel and Kjaer Plane Radiant Asymmetry sensor. Plane radiant temperature is defined as the uniform surface temperature of a hemisphere that produces the same incident radiation on a black surface as the actual environment. Radiant asymmetry is the difference between the plane radiant temperatures of small planes facing opposite directions. Limits are specified in the environmental standards, but they are rarely approached in office environments (accuracy is ±0.5°C).

Illuminance in the horizontal plane is measured by a cosine-corrected silicon photometer manufactured by Li-Cor. The measurements, taken over the chair, give an indication of ambient light levels in the space (accuracy is ±5%).

CO_2 is measured by a Telaire Model 1050 Ventilation Efficiency Meter mounted on the cart (not shown in Figure 7). CO_2 is considered a good indicator of occupancy and the efficiency of ventilation within the space. The measured values can be compared to the limit specified in the ASHRAE ventilation standard [ASHRAE 1989], which states that indoor CO_2 levels should not exceed 1000 ppm. The accuracy of the Telaire meter is 5% of reading or 50 ppm, whichever is greater.

Sound pressure levels in dBA are measured using an ExTech Instruments Model 407735 Sound Level Meter mounted on the cart (not shown in Figure 7) during each workstation visit. However, such short-term measurements may not correlate well with the survey responses for acoustical comfort.

The cart's data acquisition system consists of several signal processors feeding a central datalogger programmed to poll the sensors and relay the data to a laptop computer for display and storage. The signals from all transducers and signal conditioning are sent continuously to the heart of the system, a Campbell Scientific 21X Micrologger. The datalogger measures the sensor signals and converts each to engineering units using polynomial curve fits or linear conversions as appropriate. The 21X is connected to a lightweight laptop computer that serves as data display, operator interface, and data storage device.

Long-Term Measurement with Distributed Sensors and Dataloggers

Temperature and humidity data were collected at regular intervals throughout the study period (March through July 1996) at various locations at each site. These measurements provide continuous trend data to complement the “snapshot in time” data provided by the portable measurement cart. The trend data were used to ensure that abnormal temperature or humidity conditions were not unexpected factors in influencing occupant satisfaction and comfort responses during the different test periods.

It was decided to use several miniature, battery-powered, portable dataloggers to collect data over the 5-month monitoring period. These small units with their connected sensors are very easy to install, as they are completely stand-alone. Because they are easily hidden from view, the installation is quite unobtrusive to the building occupants, an important consideration to the building owner. The portable dataloggers store data in non-volatile memory, and at the end of the monitoring period, the data are down-loaded via RS-232 interface to a laptop computer. Two types of sensors were installed to perform long-term measurements, as described below. Refer to the notes for Figures 2 and 4-6 for itemized lists of the installed sensor/loggers and details of their locations shown on the floor plans for each test site.

An internal thermistor and remote relative humidity probe (sulfonated polystyrene wafer) connected to an ACR SmartReader 2 Logger were used to monitor air temperature and relative humidity at one location within each office test site. The ACR loggers were programmed to store data at a 10-minute sampling interval and each logger can store up to 32,000 readings in memory. The accuracy specified by the manufacturer is ±0.2°C (±0.4°F) for temperature and ±4% for relative humidity.

A thermistor connected to Onset Computer's HOBO-TEMP-XT Logger was used for making air temperature measurements at selected locations throughout the office at each test site, including return air temperature at ceiling level. These small, self-contained dataloggers can store up to 1,800 total measurements in non-volatile memory, each reading representing a single scan of the connected thermistor. The HOBO loggers were programmed to record data at a 16-minute sampling interval, requiring their collected data to be downloaded every 20 days during the study period. The accuracy specified by the manufacturer is ±0.2°C (±0.4°F).

Longer term data on CO_2 levels in the space were collected by connecting a Telaire Model 1050 Ventilation Efficiency Meter to Onset Computer's HOBO-VOLT Logger, which monitors the 0-2 VDC output of the Telaire meter. We tried to install one CO_2 meter at two test sites (refer to Figures 2 and 5).

PEM Monitoring Network

Using a network communication capability provided by the PEMs, a monitoring network was set up at each test site to record data on individual PEM use patterns. The key hardware component of the monitoring network is the DR-9100 Digital Room Controller contained within each PEM unit, which can be networked together using an RS-485 communication link. This provided a convenient configuration at each test site to monitor PEM performance from a single host location, the Johnson Controls Companion. A modem connected to each Companion allowed remote access via phone lines to download data. Within each PEM unit, the DR-9100 allows the status of several PEM control parameters to be monitored: (1) discharge (mixed) air temperature (a built-in sensor measures the temperature of the air leaving the main under-desk PEM unit), (2) discharge air temperature setpoint, (3) radiant heater setpoint, (4) fan speed setpoint,

(5) task light setpoint, (6) white noise setpoint, and (7) occupancy sensor status. We would like to thank Johnson Controls for providing the hardware, software, and technical support to set up the PEM monitoring network. It was debugged and became operational at the beginning of July 1996.

Each site had a Johnson Controls Companion installed, allowing up to 16 PEMs to be networked together and monitored. Because the 1455 Market site had 18 PEMs, two could not be monitored remotely. Utility software provided by Johnson Controls was used to dial up the sites each night and download the data from the PEMs. The huge number of files were then manipulated with custom programs to produce a data file in spreadsheet form for each PEM for the period July 8 through August 4, 1996. These data are discussed in the section on *Occupant Use of PEM Units*.

Field Measurement Procedures

A one-page memo describing the nature of the "Building Quality Assessment Survey" (Figure 8) was distributed to the participants in all three test buildings prior to beginning the first field measurements. The procedures used to administer the occupant surveys and take physical measurements were similar to those used in our previous field work. Typically two or three researchers at a time were involved in conducting the field measurements in the test buildings. After first checking on availability, a researcher distributed the paper surveys to the participants. The occupants completed the surveys as they sat at their workstations, taking about 15 minutes to do so. Afterwards (within 15-20 minutes), the occupants were asked to leave the workstation for about 5 minutes while the portable measurement cart was positioned at the work location in front of the desk and recorded physical measurements of environmental conditions. On the first day at each test site the miniature dataloggers were also installed in the office space to collect long-term trend data on temperature, humidity, and CO_2 level.

The first baseline field measurements were made in March 1996. Occupants in the PEM group at 1455 Market Street were surveyed on March 5; the control group was surveyed on March 28. Occupants in both groups at One S. Van Ness Avenue were surveyed on March 7. Occupants in both groups at Davis Street were surveyed on March 12. The 42 PEM units were installed in the three buildings during the first two weeks of April.

The post-installation field measurements were completed in July, three months after the PEM installation. During these follow-up field tests, measurements were repeated under three different room temperature setpoint conditions to observe how occupants respond with their PEMs to different thermal environments.

BUILDING QUALITY ASSESSMENT SURVEY
March 1996

During the coming week, a group of building science researchers from UC Berkeley will be investigating the quality of work environments within your building. As part of this study, they will be collecting data on the physical environment along with the occupants' perception of environmental conditions via a paper survey. Specific issues to be examined include thermal comfort, acoustical quality, lighting quality, and air quality. The results of this study will provide quantitative information identifying environmental issues in your work area and will be presented to building managers and maintenance personnel.

As a participant, you will initially be asked to fill out the survey requiring approximately 10-15 minutes to complete. This survey addresses your overall impressions and satisfaction with a range of attributes of your working environment. It also includes a series of questions addressing your immediate comfort, clothing, and activity levels. After you have completed the survey you will be asked to step aside from your desk for five minutes while an instrumented cart is placed in your normal working position to gather measurements of your immediate surroundings. The objective is to be as unobtrusive as possible. If the researcher approaches you at an inconvenient time, please let him or her know when would be a more convenient time during that day.

The researchers are expected to be in your building on one day only during the week. It is very important that they have an opportunity to administer the survey and complete a measurement with the instrumented cart at your work location one time only during that day.

Please be assured that your identity will remain anonymous and your responses will be kept confidential. The success of the project hinges on the role of volunteers. We are sincerely grateful for your interest and cooperation.

Figure 8. Building Quality Assessment Survey Memo

July 10-11, 1996:	This period was “normal” in that the historical space temperature setpoints were used.
July 24-25, 1996:	This period was considered to be a “set-up” period where the space temperature setpoint was set up to try and achieve a higher (warmer) than normal space temperature.
July 31-Aug. 1, 1996:	This period was considered to be a “set-down” period where the space temperature setpoint was set down to try and achieve a lower (cooler) than normal space temperature.

To allow occupants to adapt to the different ambient conditions, the set-down and set-up periods began on Monday morning and continued through the site visits (Wednesday or Thursday). This gave occupants two days exposure to the different conditions prior to being surveyed. In all cases, temperatures though cooler or warmer were kept within limits that could conceivably be experienced by an office worker. Due to limitations in the mechanical systems, the “set-up” and “set-down” temperatures achieved were not as different from “normal” conditions as we had hoped. Table 1 summarizes the average space temperatures maintained during occupied hours (8:00 am - 5:00 pm on weekdays), as measured by the portable temperature loggers.

Table 1. Average Test Site Temperatures (Weekdays, 8:00 am-5:00 pm)

Test Site	Group	Baseline (March)	Post-PEM Normal (July 10-11)	Post-PEM Set-Up (July 24-25)	Post-PEM Set-Down (July 31-Aug. 1)
Van Ness	PEM	22.3°C	23.1°C	23.8°C	22.4°C
	Control	22.3°C	23.1°C	23.8°C	22.4°C
Market	PEM	22.8°C	22.3°C	21.9°C	21.0°C
	Control	22.9°C	22.7°C	N/A	N/A
Davis	PEM	23.2°C	21.9°C	24.9°C	21.7°C
	Control	22.8°C	22.3°C	N/A	N/A

From this table we see that not all set-ups and set-downs of ambient temperature were successful. In some cases, inherent limitations of the HVAC system and the mixing of air from adjacent zones in the building not included in the study prevented the desired conditions from being achieved. The set-up in 1455 Market turned out to be actually a small set-down; while the set-down turned out to be significant. The inability to raise the space temperature in 1455 Market was due to excessively cool supply air temperatures in the VAV system combined with relatively low loads (intermittent occupancy) in the test area. Even with the VAV boxes closed down to their minimum supply volumes, the space temperature still could not be increased. In One S. Van Ness a moderate set-up and set-down were achieved. In 560 Davis we were able to achieve a significant set-up, due to high internal heat loads from the large amount of new computer equipment that was being configured in the office during this week. The set-down achieved in Davis, however, was almost negligible.

RESULTS

Average Space Conditions -- Long Term Trend Data

Figure 9 presents the average space temperatures, as measured by the miniature portable dataloggers, for each of the four distinct test sites (4th floor, One S. Van Ness; 22nd floor, 1455 Market; 17th floor, 1455 Market; 2nd floor, 560 Davis). The measurement results are shown for the four week post-PEM test period beginning on Monday, July 8, 1996, and ending on July 31 or August 1, depending on when the loggers were removed. The typical diurnal temperature variations are seen for each site. Nighttime and weekend temperature variations are due in part to the buildings being operated in a set-back mode where space temperatures are allowed to drift away from occupied setpoints when the building is unoccupied. Also indicated in the figure are the normal, set-up, and set-down test periods. The shifts in temperature during both the set-up and set-down periods are apparent in comparison to the normal test period for One S. Van Ness though the warmer set-back temperatures at night make it difficult to visually separate the cooler occupied times during the day on this plot. As described above, the 22nd floor (PEM Group) at the 1455 Market site was noticeably cooler than the other sites. The set-down achieved in Market is somewhat apparent from the lower temperatures during the last few days (July 30 - August 1) shown on the right of the Market PEM Group plot. As would be expected, no observable shift in temperatures is seen between the three test periods for the control group on the 17th floor of 1455 Market. The significant temperature increase achieved during the set-up at 560 Davis is very noticeable. Although not shown in Figure 9, temperature trend data collected at all sites during the March baseline test period were very similar to that of the normal post-PEM test period (July 8-11), indicating that pre- and post-PEM occupant survey responses would not be influenced by a shift in average space temperature.

Average space relative humidity (RH) trend data by site are shown in Figure 10. For all sites the relative humidity varied by 6-8% RH through the 4 week period shown. Humidity is expected to change as air temperatures rise and fall. The variations shown in Figure 10 do not suggest that an external factor was biasing humidity so as to be a variable in our analysis of occupant response over the July test period. Measured relative humidities during the March baseline test period were also very similar to those measured in July.

Although not shown here, CO_2 levels recorded by the miniature portable dataloggers as well as those from the portable measurement cart suggest that CO_2 did not vary significantly between site visits; and therefore, CO_2 is not considered as a factor that would explain variations in occupant responses through the period of study. During the baseline survey in March, the maximum recorded CO_2 concentration was only 590 ppm in all three buildings. In the first post-installation survey during July, the maximum CO_2 concentration had risen to 694 ppm, but still well below the maximum allowable concentration of 1,000 ppm, as specified in ASHRAE Standard 62 [ASHRAE 1989].

Figure 9: Temperatures By Site Through Study Period

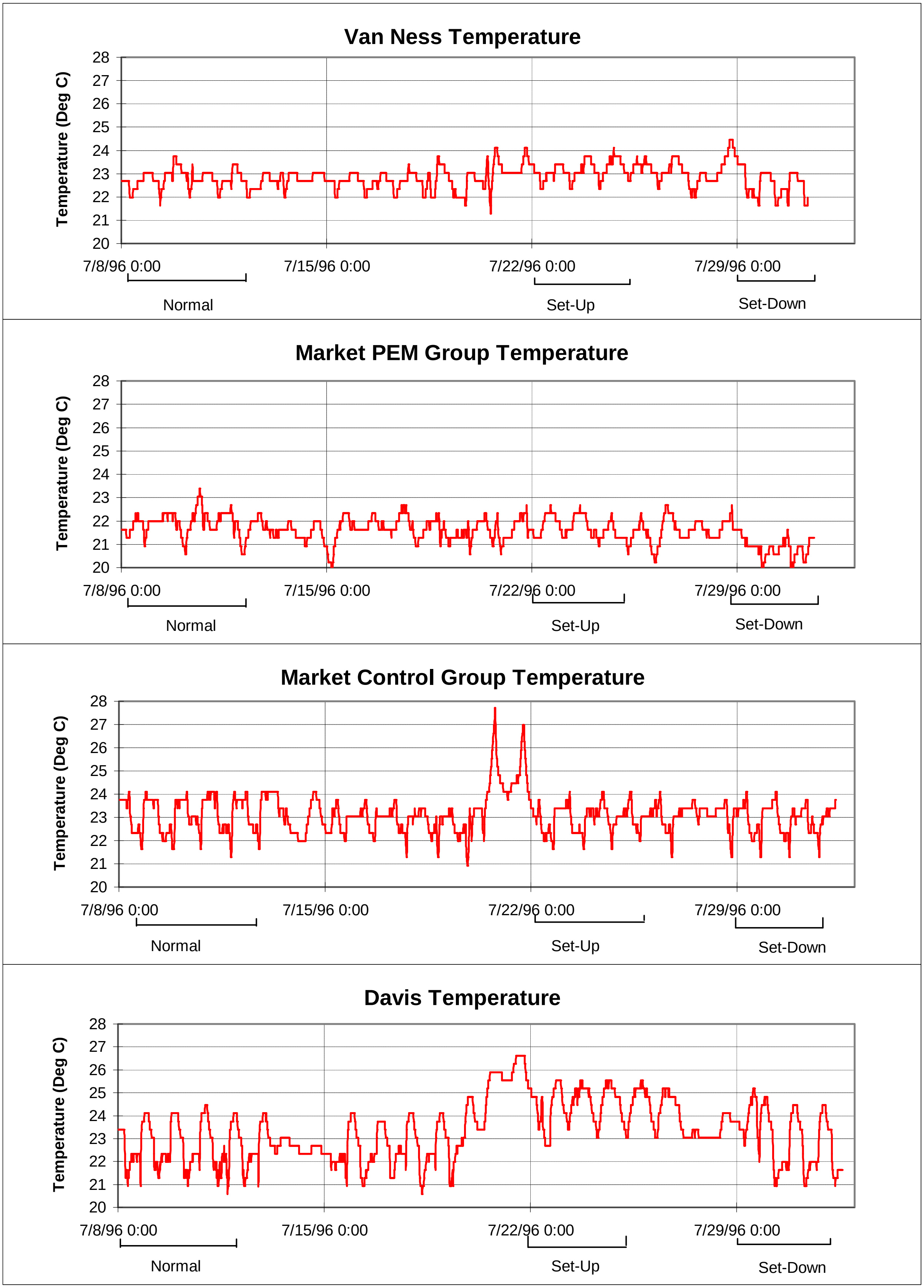
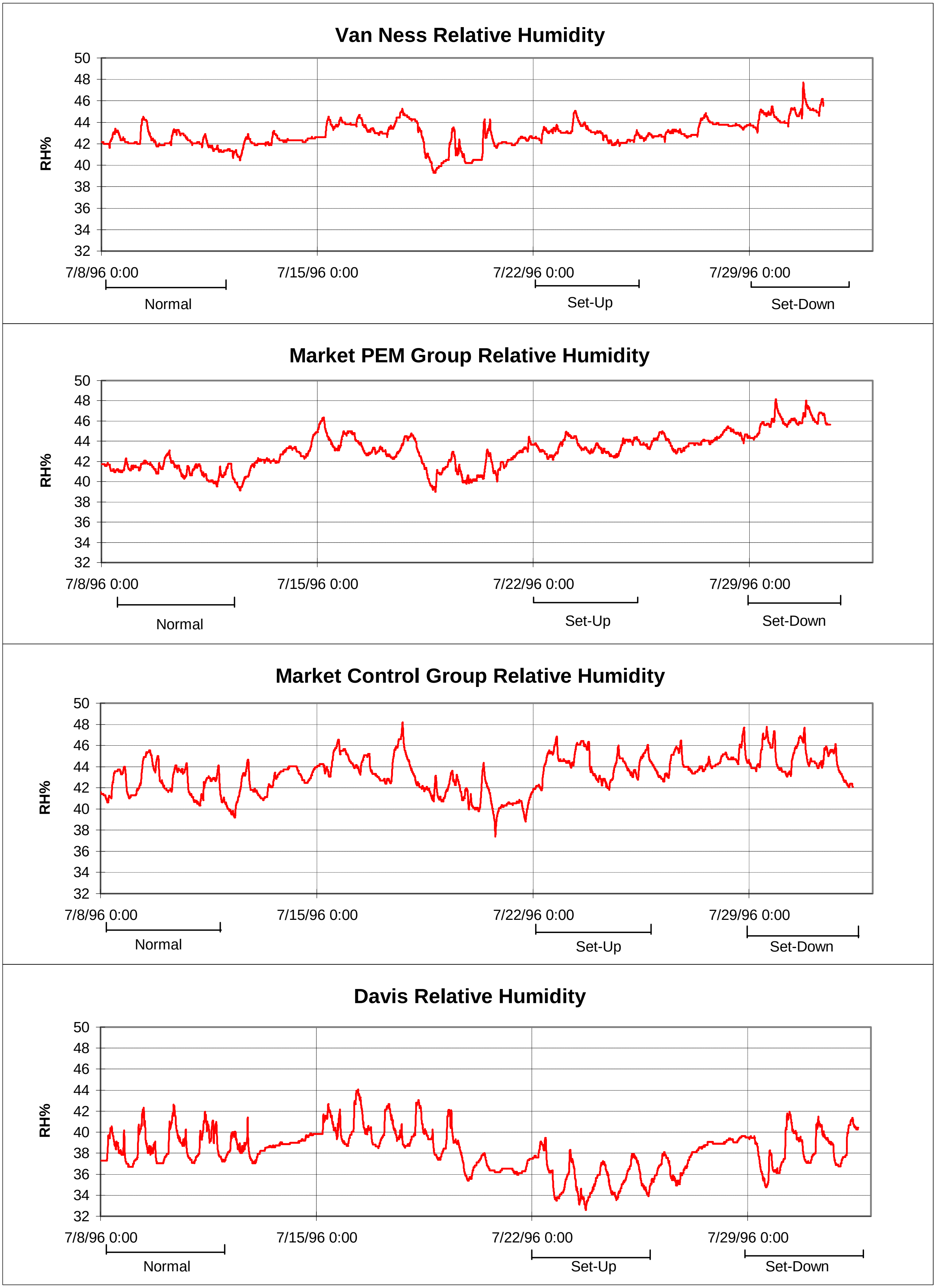


Figure 10: Relative Humidities By Site Through Study Period



Occupant Survey

Presented below is a summary of our key findings from the analysis of the collected survey data. To supplement these measured results, occupant comments and responses to all open-ended questions in the survey are listed in Appendix B.

Work Area Satisfaction

The results described below are based on responses to questions in the background section of the occupant survey addressing six building assessment categories: spatial layout, office furnishings, thermal quality, air quality, lighting quality, and acoustical quality. In this portion of the survey the occupants were asked to respond based on their perception of the environment over the previous two-month period. The statistical analysis is primarily based on a comparison of the pre-installation (baseline) survey (March 1996) and the post-installation survey (July 1996) for each group (PEM and control). By comparing responses from the same individuals before and after the PEM installation, individual differences could be factored out. Inclusion of the control group in the database accounts for any response changes due to environmental factors not directly caused by the installation of the PEMs. For example, seasonal differences may allow changes in the use of an outside air economizer (affecting the ventilation rate), changes in humidity levels, or changes in lighting levels due to natural light.

The background section of the survey was administered once in March and once again during the first test period of July when room setpoint temperatures were maintained at their normal levels (no set-up or set-down). During the baseline field test, we initially surveyed 42 occupants in the PEM group and 40 occupants in the control group between all three buildings. Primarily due to personnel changes, occupant unavailability, and relocations, we were only able to obtain surveys during the post-installation field test from 28 members of the original PEM group and 25 members of the original control group. Unless otherwise noted, the results presented below are based on this set of 53 occupants for which both baseline and post-installation surveys were obtained. To maintain the largest possible database for statistical significance, we have analyzed all three building test sites together.

Figure 11 summarizes and compares the overall occupant satisfaction ratings from the baseline (March) and post-installation (July) surveys for both the PEM and control groups and for each of the six building assessment categories. Occupant satisfaction was measured on a scale from very satisfied (6) to very dissatisfied (1). Detailed occupant satisfaction results for the six assessment categories are presented in Figures 12-17 for the PEM group and Figures 18-23 for the control group. Refer to the occupant survey in Appendix A for the exact wording of the questions asked.

In Figures 12-23, the data are presented in a consistent format. Side-by-side histograms are used, allowing easy comparison of the baseline (March) and post-installation (July) survey results. The results for the first four assessment categories (thermal, air, lighting, and acoustical quality) consist of two sets of figures: (a) satisfaction/dissatisfaction responses on the left side of the page, and (b) answers to related descriptive

Figure 11

Building Assessment Report

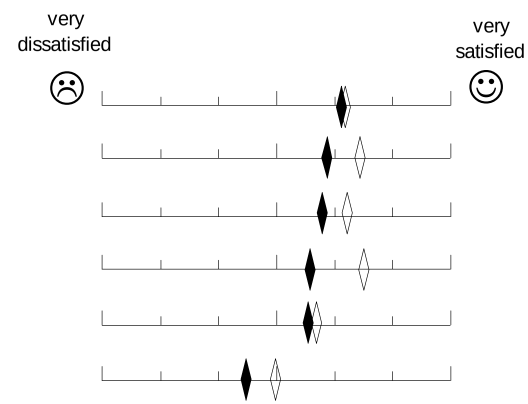
BANK OF AMERICA

Survey results - all buildings combined

Overall Occupant Satisfaction Ratings

PEM Group

	March pre-PEM installation	July post-PEM installation
Lighting Quality	**4.56**	**4.63**
Air Quality	**4.42**	**4.88**
Furnishings	**4.29**	**4.62**
Thermal Quality	**4.12**	**4.96**
Spatial Layout	**4.00**	**4.20**
Acoustics	**2.90**	**3.48**
legend	♦ (filled)	◊ (open)



Control Group

	March pre-PEM installation	July post-PEM installation
Lighting Quality	**4.16**	**3.97**
Air Quality	**3.66**	**4.01**
Furnishings	**3.92**	**4.03**
Thermal Quality	**3.45**	**3.61**
Spatial Layout	**3.45**	**3.43**
Acoustics	**2.41**	**2.59**
legend	♦ (filled)	◊ (open)

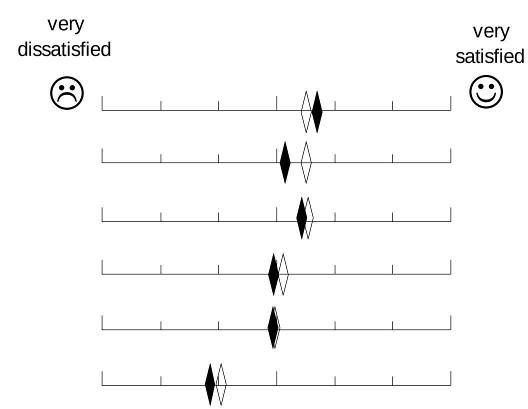


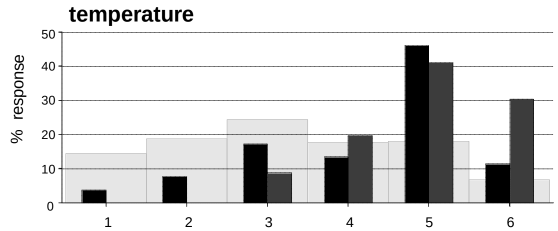
Figure 12

PEM Group (sample size = 28)

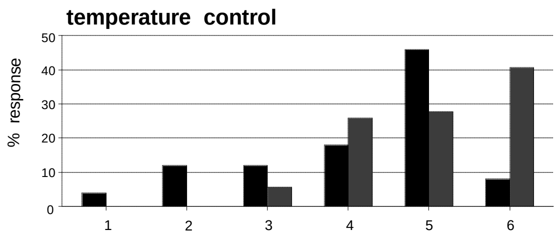
Occupant Satisfaction
THERMAL QUALITY

overall rating

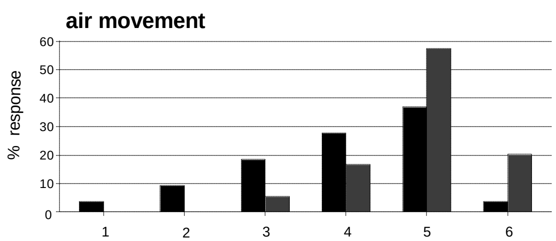
March '96	July '96
4.12	4.96



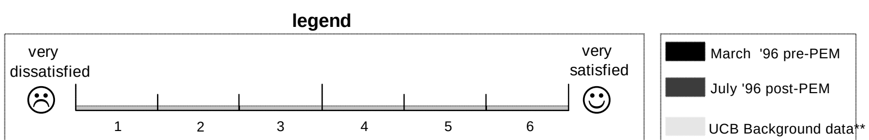
	mean rating	% dissatisfied *
March 1996	4.2	11%
July 1996	4.9	0%
background data set **	3.3	33%



	mean rating	% dissatisfied
March 1996	4.1	16%
July 1996	5.0	0%



	mean rating	% dissatisfied
March 1996	4.0	13%
July 1996	4.9	0%

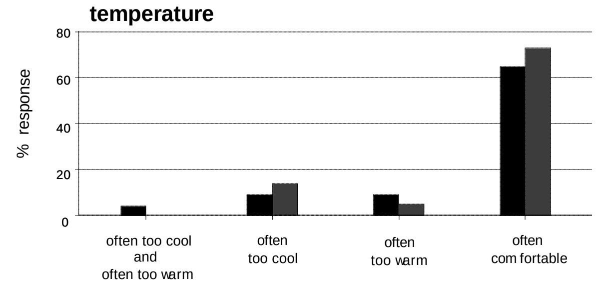


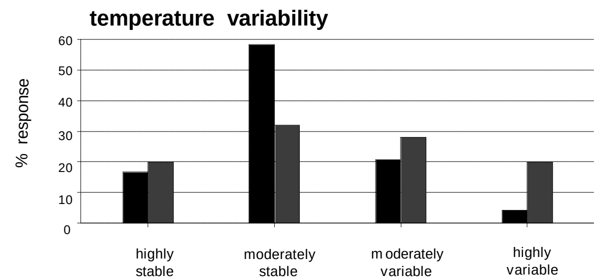
* The % dissatisfied are those respondents who indicated that they were moderately or highly dissatisfied (range of 1-2 on scale).

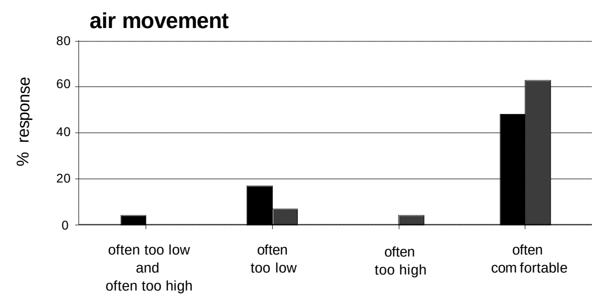
** The background data set consists of 300 subjects from 10 office buildings within the San Francisco Bay Area.

PEM Group (sample size = 28)

Occupant Satisfaction
THERMAL QUALITY







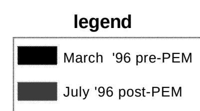
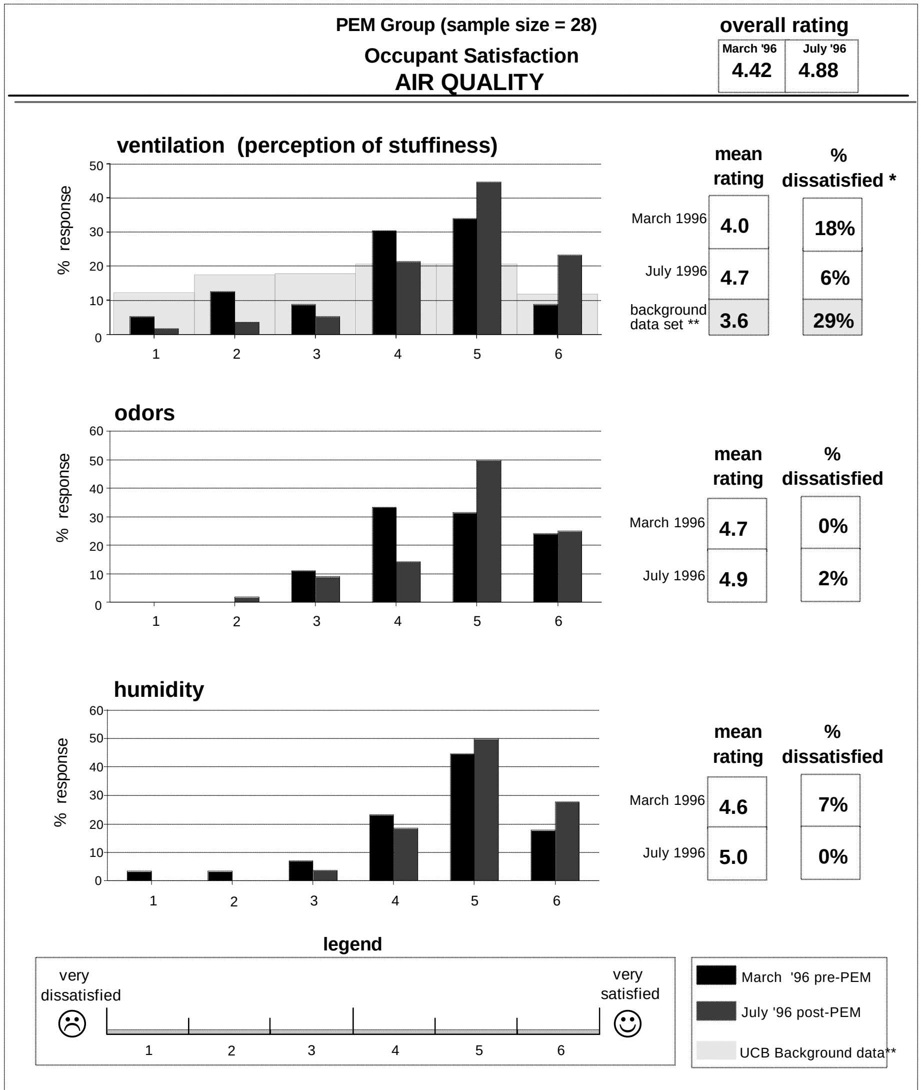


Figure 13



* The % dissatisfied are those respondents who indicated that they were moderately or highly dissatisfied (range of 1-2 on scale).

** The background data set consists of 300 subjects from 10 office buildings within the San Francisco Bay Area.

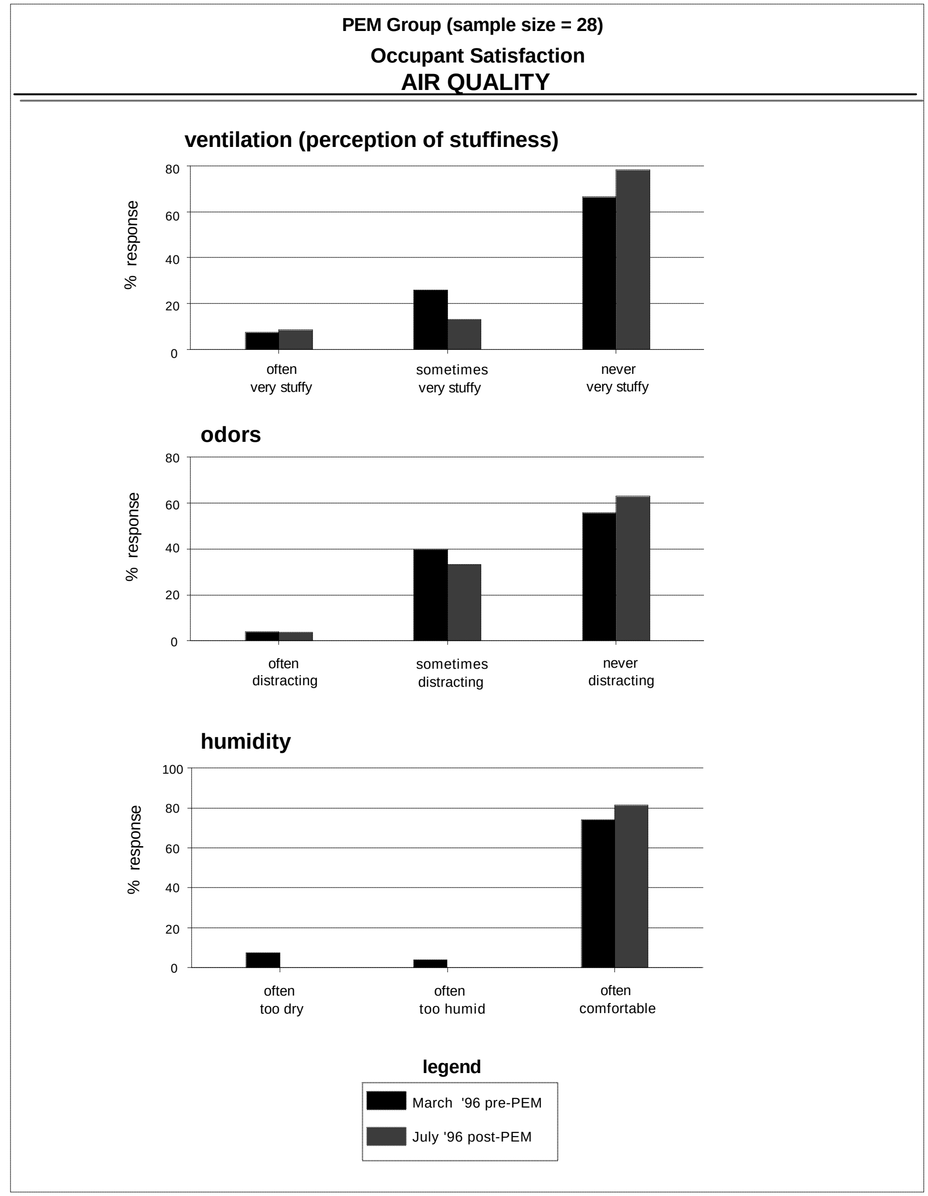


Figure 14

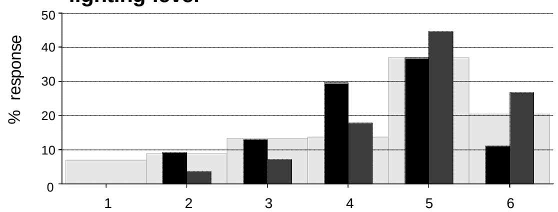
PEM Group (sample size = 28)

Occupant Satisfaction
LIGHTING QUALITY

overall rating

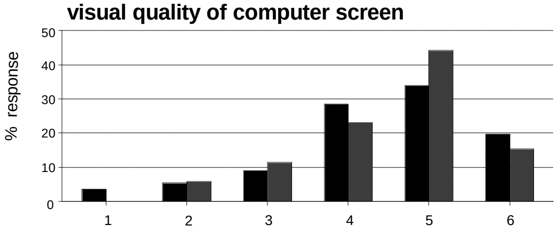
March '96	July '96
4.56	4.63

lighting level



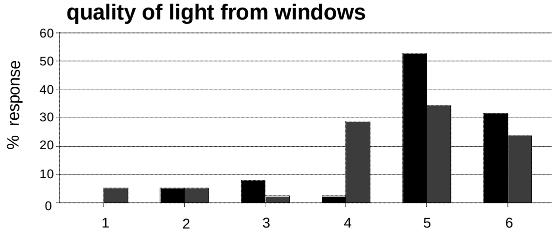
	mean rating	% dissatisfied *
March 1996	4.3	9%
July 1996	4.8	4%
background data set **	4.3	16%

visual quality of computer screen



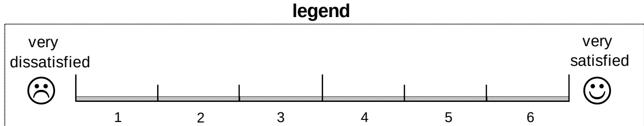
	mean rating	% dissatisfied
March 1996	4.4	9%
July 1996	4.5	6%

quality of light from windows



	mean rating	% dissatisfied
March 1996	5.0	5%
July 1996	4.5	11%

legend



- March '96 pre-PEM
- July '96 post-PEM
- UCB Background data**

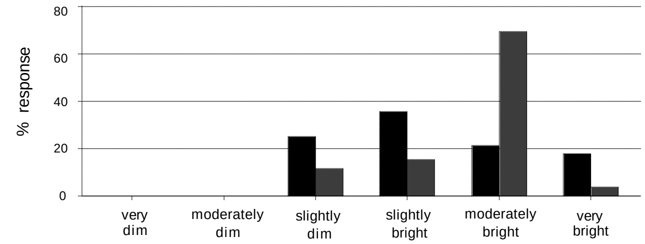
* The % dissatisfied are those respondents who indicated that they were moderately or highly dissatisfied (range of 1-2 on scale).

** The background data set consists of 300 subjects from 10 office buildings within the San Francisco Bay Area.

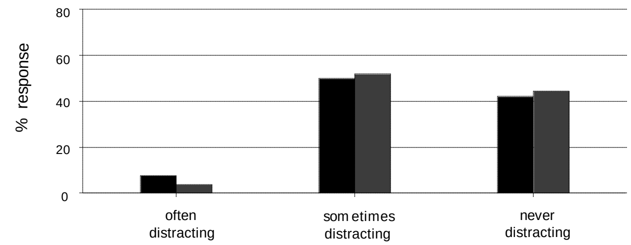
PEM Group (sample size = 28)

Occupant Satisfaction
LIGHTING QUALITY

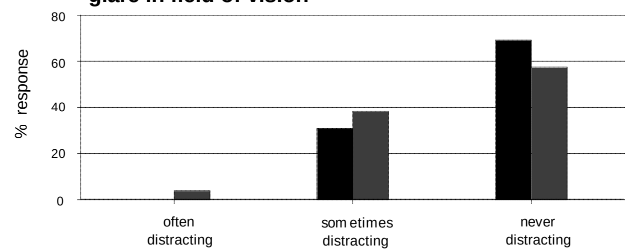
lighting level



glare on computer screen



glare in field of vision



legend

- March '96 pre-PEM
- July '96 post-PEM

Figure 15

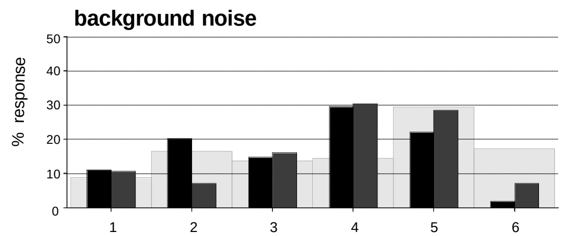
PEM Group (sample size = 28)

Occupant Satisfaction

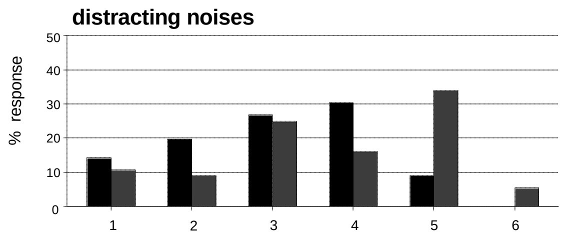
ACOUSTICAL QUALITY

overall rating

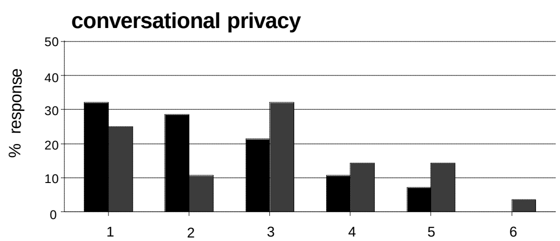
March '96	July '96
2.90	3.48



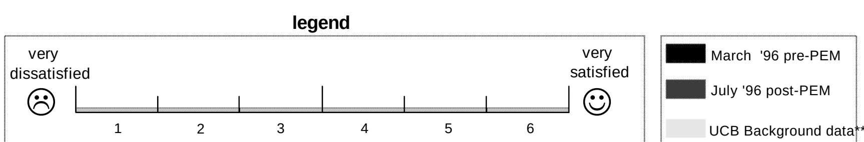
	mean rating	% dissatisfied *
March 1996	3.4	31%
July 1996	3.8	18%
background data set **	3.9	25%



	mean rating	% dissatisfied
March 1996	3.0	34%
July 1996	3.7	20%



	mean rating	% dissatisfied
March 1996	2.3	61%
July 1996	2.9	37%



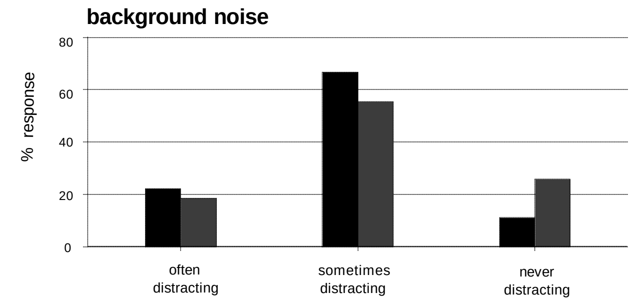
* The % dissatisfied are those respondents who indicated that they were moderately or highly dissatisfied (range of 1-2 on scale).

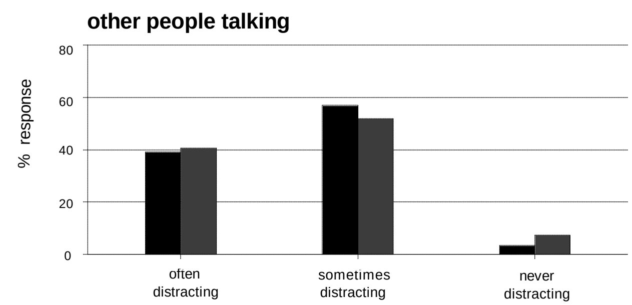
** The background data set consists of 300 subjects from 10 office buildings within the San Francisco Bay Area.

PEM Group (sample size = 28)

Occupant Satisfaction

ACOUSTICAL QUALITY





legend

- March '96 pre-PEM
- July '96 post-PEM

Figure 16

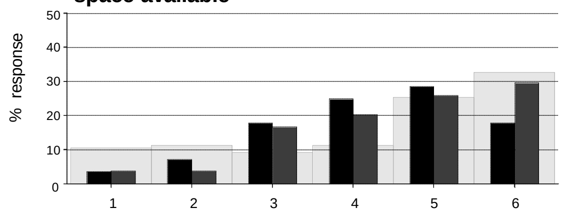
PEM Group (sample size = 28)

Occupant Satisfaction

SPATIAL LAYOUT

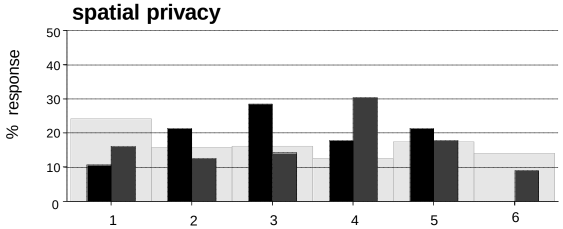
overall rating	
March '96	July '96
4.00	4.20

space available



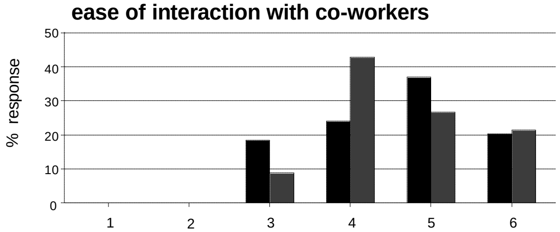
	mean rating	% dissatisfied *
March 1996	4.2	11%
July 1996	4.5	7%
background data set **	4.3	22%

spatial privacy



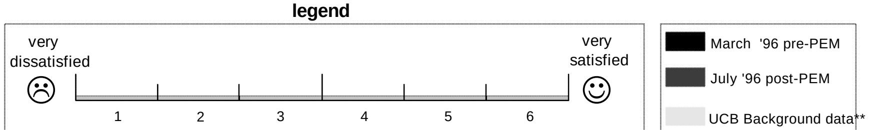
	mean rating	% dissatisfied
March 1996	3.2	32%
July 1996	3.5	29%
background data set **	3.3	40%

ease of interaction with co-workers



	mean rating	% dissatisfied
March 1996	4.6	0%
July 1996	4.6	0%

legend



* The % dissatisfied are those respondents who indicated that they were moderately or highly dissatisfied (range of 1-2 on scale).

** The background data set consists of 300 subjects from 10 office buildings within the San Francisco Bay Area.

Figure 17

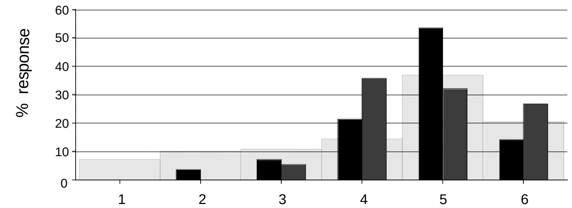
PEM Group (sample size = 28)

Occupant Satisfaction

OFFICE FURNISHINGS

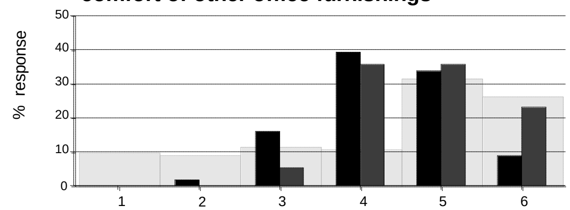
overall rating	
March '96	July '96
4.29	4.62

comfort of chair



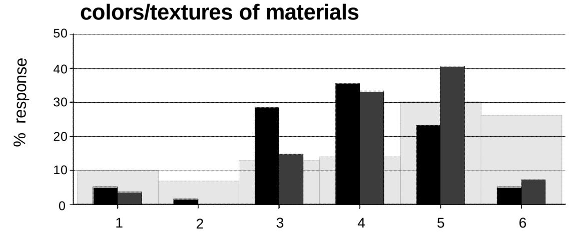
	mean rating	% dissatisfied *
March 1996	4.7	4%
July 1996	4.8	0%
background data set **	4.3	17%

comfort of other office furnishings



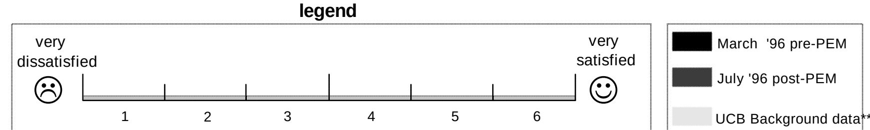
	mean rating	% dissatisfied
March 1996	4.3	2%
July 1996	4.8	0%
background data set **	4.2	19%

colors/textures of materials



	mean rating	% dissatisfied
March 1996	3.9	7%
July 1996	4.3	4%
background data set **	4.3	17%

legend



* The % dissatisfied are those respondents who indicated that they were moderately or highly dissatisfied (range of 1-2 on scale).

** The background data set consists of 300 subjects from 10 office buildings within the San Francisco Bay Area.

Figure 18

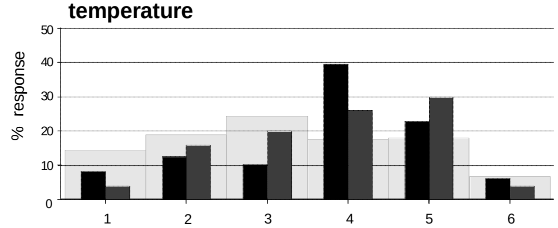
Control Group (sample size = 25)

Occupant Satisfaction
THERMAL QUALITY

overall rating

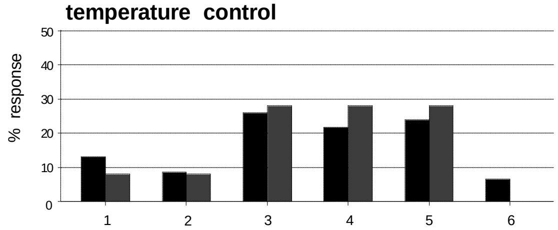
March '96	July '96
3.45	3.61

temperature



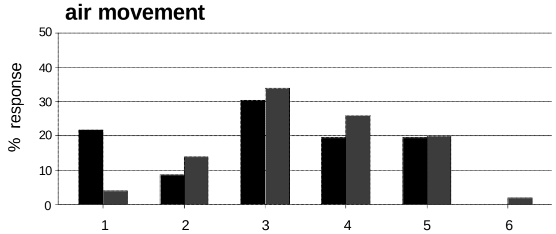
	mean rating	% dissatisfied *
March 1996	3.8	21%
July 1996	3.7	20%
background data set **	3.3	33%

temperature control



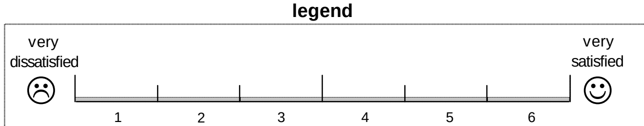
	mean rating	% dissatisfied
March 1996	3.5	22%
July 1996	3.6	16%

air movement



	mean rating	% dissatisfied
March 1996	3.1	30%
July 1996	3.5	18%

legend



- March '96 pre-PEM
- July '96 post-PEM
- UCB Background data**

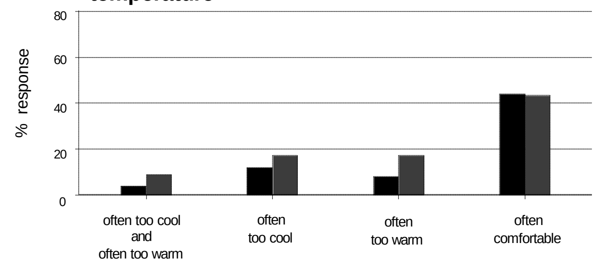
* The % dissatisfied are those respondents who indicated that they were moderately or highly dissatisfied (range of 1-2 on scale).

** The background data set consists of 300 subjects from 10 office buildings within the San Francisco Bay Area.

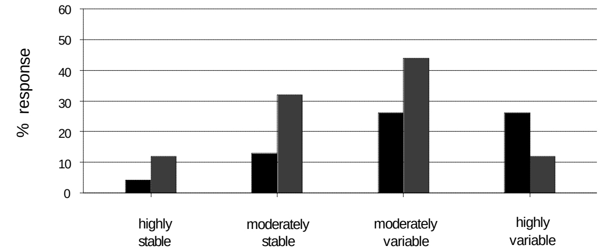
Control Group (sample size = 25)

Occupant Satisfaction
THERMAL QUALITY

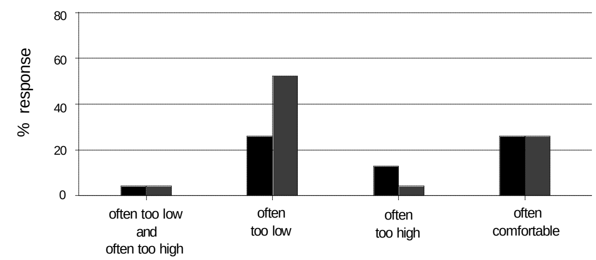
temperature



temperature variability



air movement



legend

- March '96 pre-PEM
- July '96 post-PEM

Figure 19

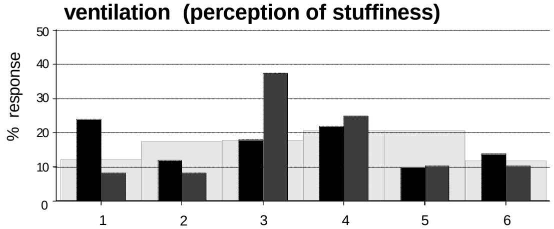
Control Group (sample size = 25)

Occupant Satisfaction
AIR QUALITY

overall rating

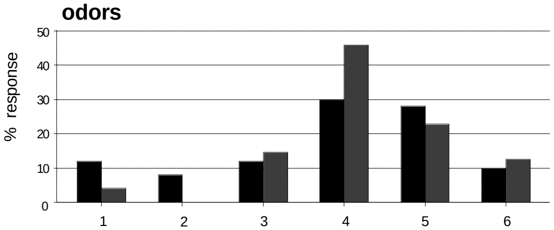
March '96	July '96
3.66	4.01

ventilation (perception of stuffiness)



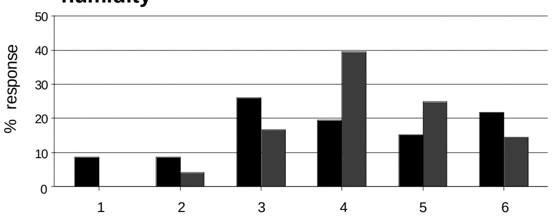
	mean rating	% dissatisfied *
March 1996	3.2	36%
July 1996	3.5	17%
background data set **	3.6	29%

odors



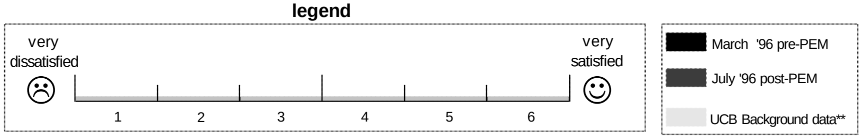
	mean rating	% dissatisfied
March 1996	3.8	20%
July 1996	4.2	4%

humidity



	mean rating	% dissatisfied
March 1996	3.9	17%
July 1996	4.3	4%

legend



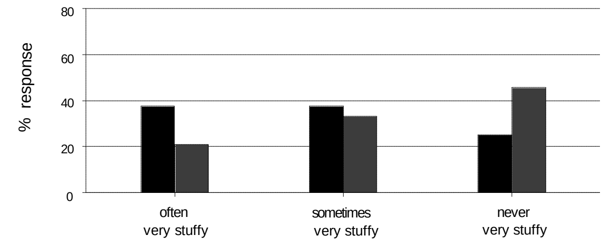
* The % dissatisfied are those respondents who indicated that they were moderately or highly dissatisfied (range of 1-2 on scale).

** The background data set consists of 300 subjects from 10 office buildings within the San Francisco Bay Area.

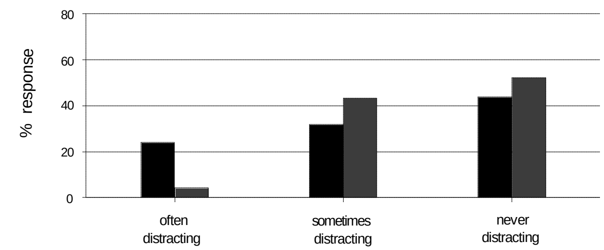
Control Group (sample size = 25)

Occupant Satisfaction
AIR QUALITY

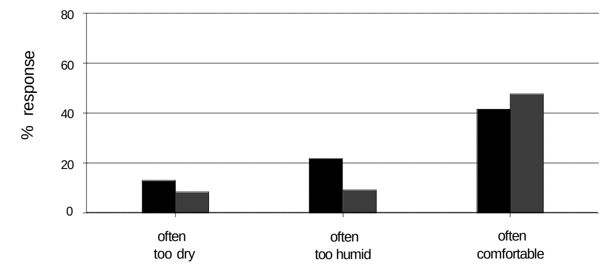
ventilation (perception of stuffiness)



odors



humidity



legend

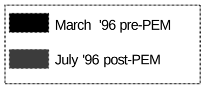


Figure 20

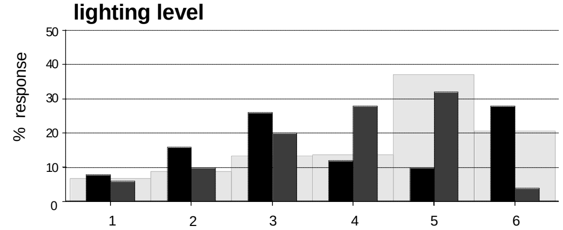
Control Group (sample size = 25)

Occupant Satisfaction
LIGHTING QUALITY

overall rating

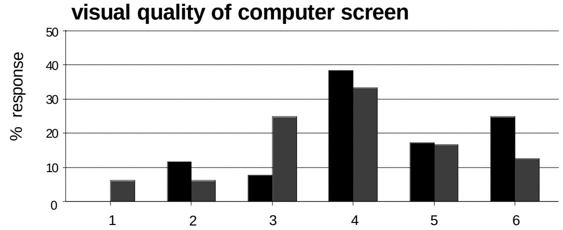
March '96	July '96
4.16	3.97

lighting level



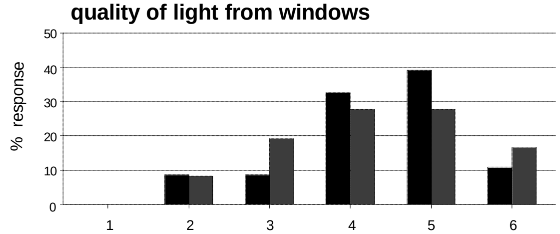
	mean rating	% dissatisfied *
March 1996	3.8	24%
July 1996	3.8	16%
background data set **	4.3	16%

visual quality of computer screen



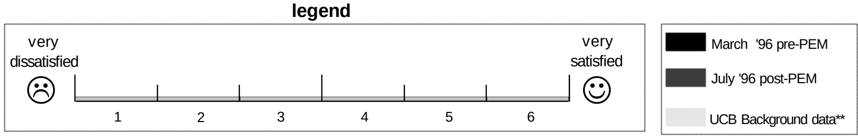
	mean rating	% dissatisfied
March 1996	4.3	12%
July 1996	3.9	13%

quality of light from windows



	mean rating	% dissatisfied
March 1996	4.4	9%
July 1996	4.3	8%

legend



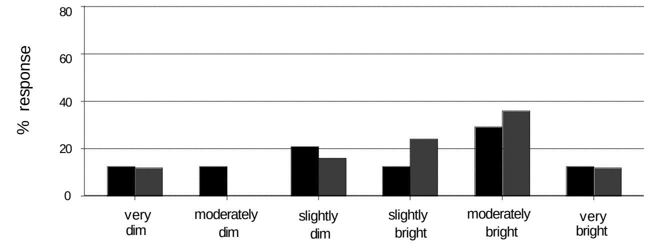
* The % dissatisfied are those respondents who indicated that they were moderately or highly dissatisfied (range of 1-2 on scale).

** The background data set consists of 300 subjects from 10 office buildings within the San Francisco Bay Area.

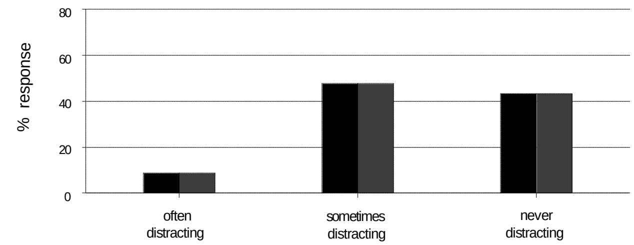
Control Group (sample size = 25)

Occupant Satisfaction
LIGHTING QUALITY

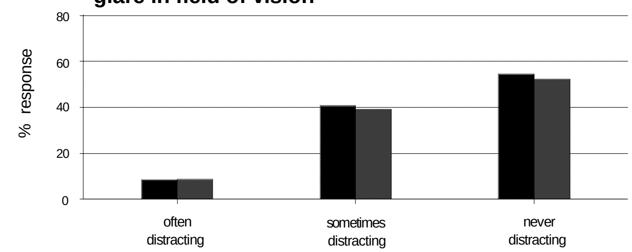
lighting level



glare on computer screen



glare in field of vision



legend

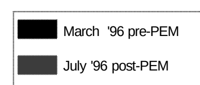


Figure 21

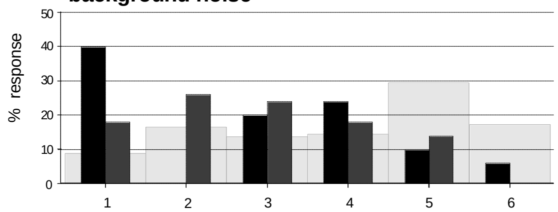
Control Group (sample size = 25)

Occupant Satisfaction
ACOUSTICAL QUALITY

overall rating

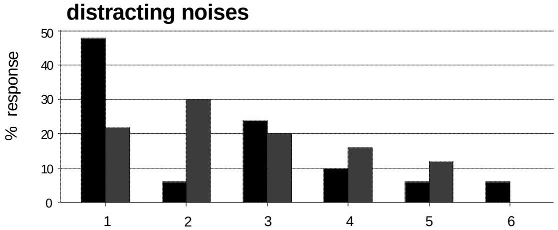
March '96	July '96
2.41	2.59

background noise



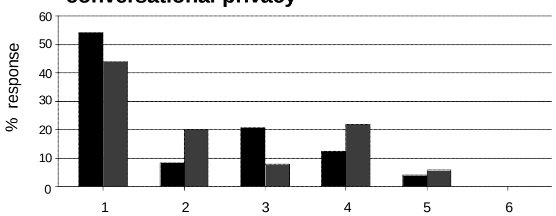
	mean rating	% dissatisfied *
March 1996	2.8	40%
July 1996	2.8	44%
background data set **	3.9	25%

distracting noises



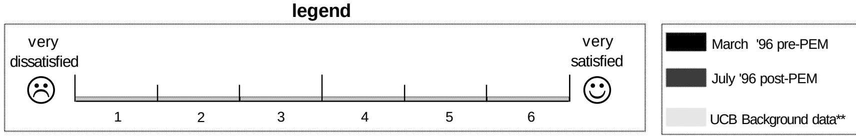
	mean rating	% dissatisfied
March 1996	2.4	54%
July 1996	2.7	52%

conversational privacy



	mean rating	% dissatisfied
March 1996	2.0	63%
July 1996	2.3	64%

legend



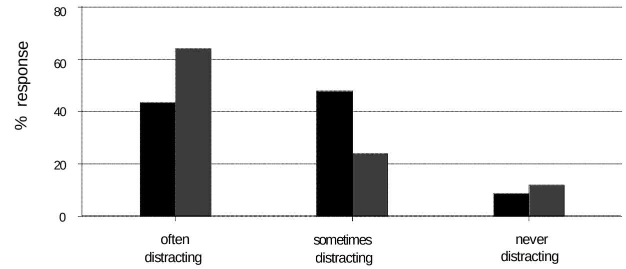
* The % dissatisfied are those respondents who indicated that they were moderately or highly dissatisfied (range of 1-2 on scale).

** The background data set consists of 300 subjects from 10 office buildings within the San Francisco Bay Area.

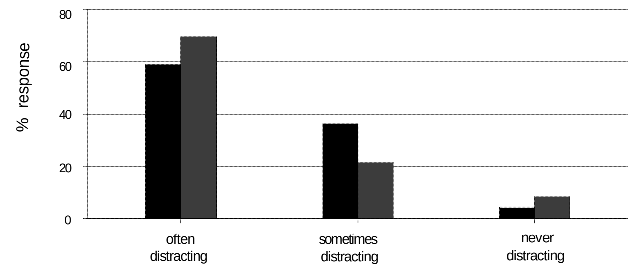
Control Group (sample size = 25)

Occupant Satisfaction
ACOUSTICAL QUALITY

background noise



other people talking



legend

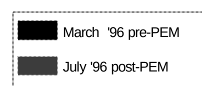


Figure 22

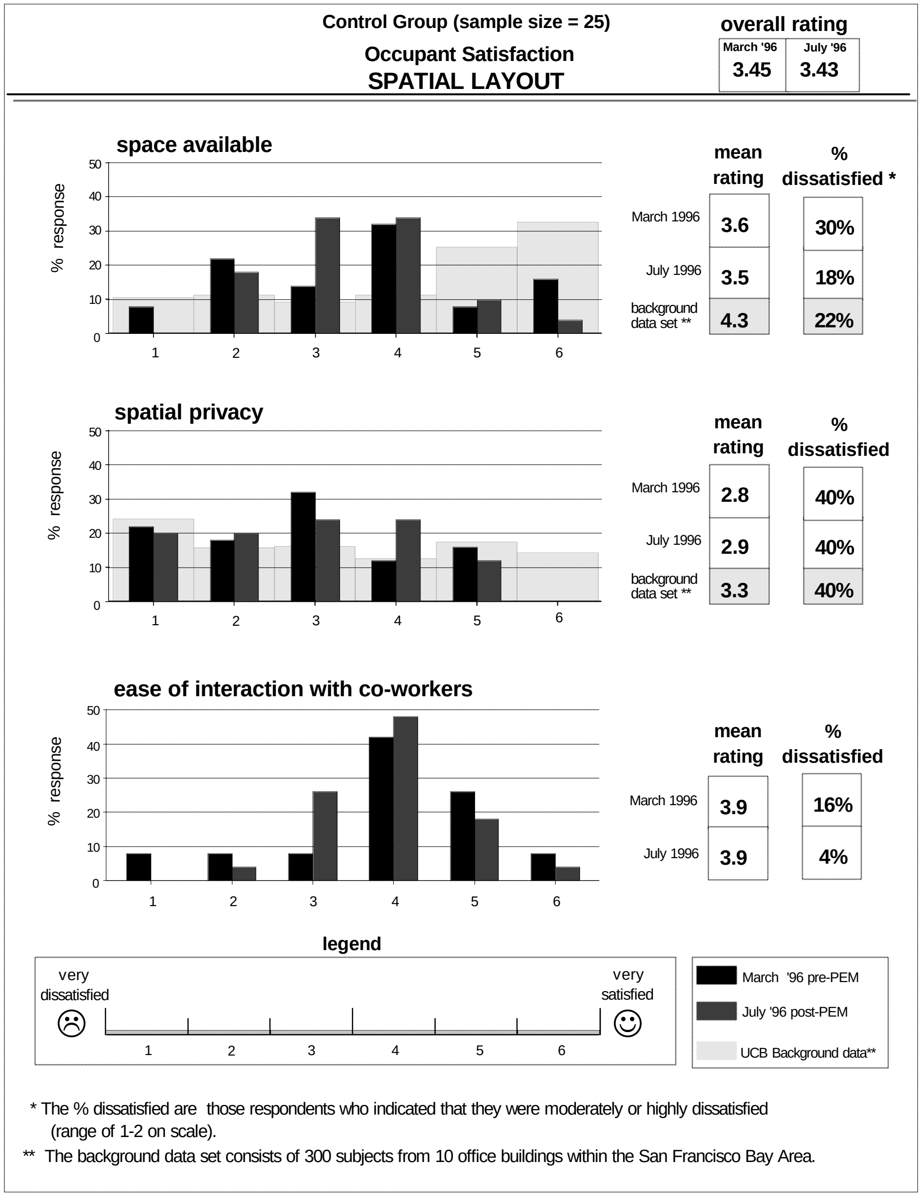
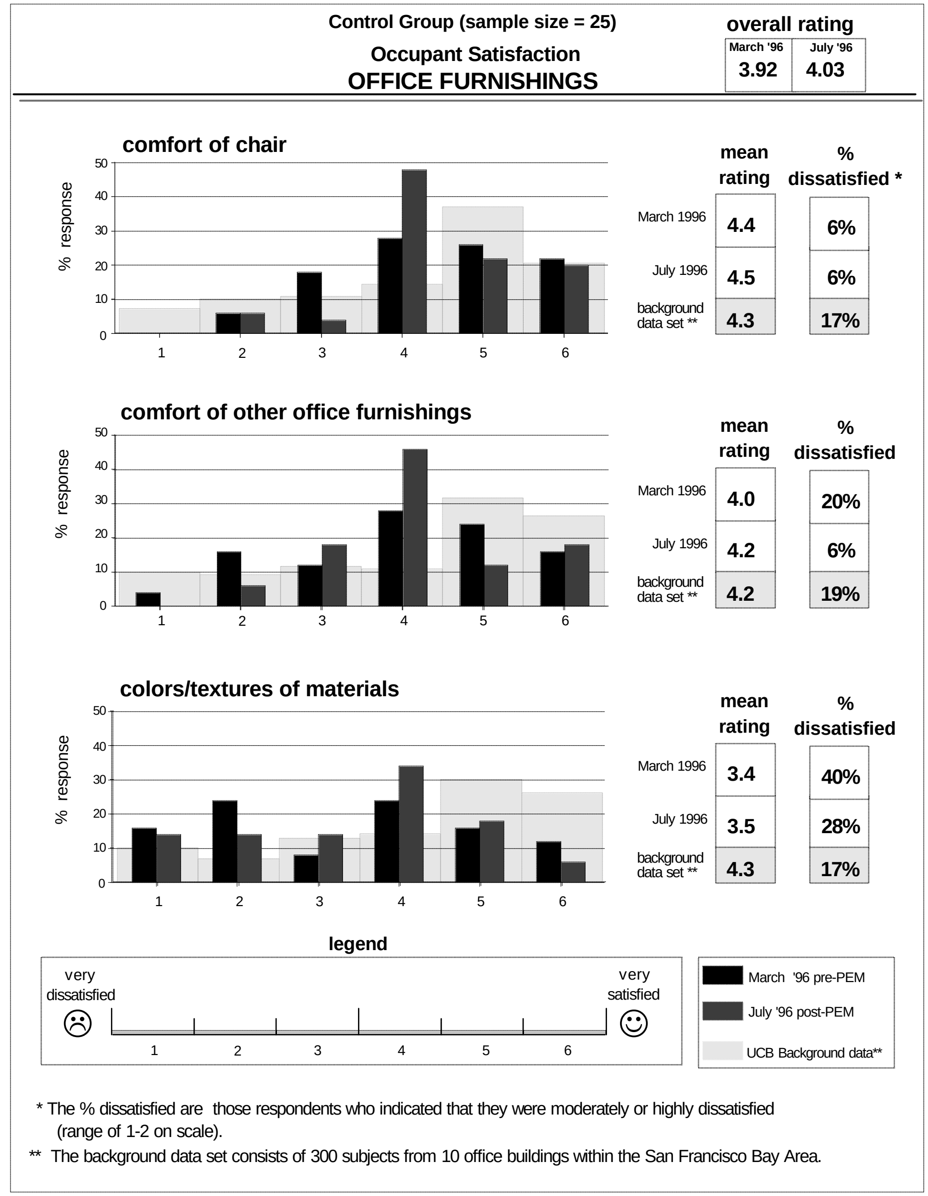


Figure 23



frequency questions on the right side of the page. The last two assessment categories (spatial layout and office furnishings) contain only the satisfaction/dissatisfaction responses since these attributes do not change over time. The histograms presenting the satisfaction results show the percent occupant response binned according to the six-point satisfaction scale. Some of the specific questions were included in a previous field study that included 300 subjects from ten office buildings in the San Francisco Bay area [Schiller et al. 1988]. This large background database is also shown on the histograms when available to allow a benchmark comparison with these Bank of America office buildings. To the right of each satisfaction histogram appear the mean ratings for each survey and the percent dissatisfied (defined to be those respondents who indicated that they were either moderately or highly dissatisfied [range of 1-2 on scale]). The overall category ratings are shown at the top of each figure; these are the results that are summarized in Figure 11. The descriptive frequency questions varied for each topic and are self-explanatory.

As seen in Figure 11, the assessment categories that showed the largest increases in occupant satisfaction after installation of the PEMs were thermal quality (+0.84), acoustical quality (+0.58), and air quality (+0.46). The magnitudes of these increases are all larger than the corresponding differences observed for the control group. It is not surprising that these three categories also all represent environmental factors addressed by the control capabilities of the PEM unit. It is also noteworthy that the satisfaction ratings from both the March and July surveys are higher for all six categories for the PEM group in comparison to the control group, indicating that the members of the PEM group are, in general, more satisfied with their work environment both before and after installation of the PEMs. It is reasonable to hypothesize that given this higher level of satisfaction, there would be less room for improvement after installation of the PEMs, making these findings conservative.

The statistical significance of the change in occupant satisfaction from baseline to post-installation conditions has been characterized by using t-test analysis. The results of these t-tests are presented in Tables 2-4. Table 2 summarizes the results in which for each environmental factor, the average change (increase or decrease) in occupant satisfaction from baseline to post-installation conditions for the PEM group is compared with that for the control group. Table 3 presents results comparing baseline and post-installation satisfaction levels for the PEM group only. Table 4 presents the same comparison as Table 3 for the control group only. In this analysis, a p-value of less than 0.05 is defined as having a strong level of significance (i.e., less than a 5% probability that the difference occurred by chance). A p-value between 0.05 and 0.10 is defined as having some level of significance (5-10% probability that the difference occurred by chance). The tables also show whether a one- or two-tailed t-test was used for the values presented. One-tailed tests have been used for environmental factors that are expected to demonstrate increased levels of occupant satisfaction after the PEMs have been installed. These are factors in the thermal, air, lighting, and acoustical quality categories for the PEM group, all of which are influenced by the environmental control capabilities of the PEM.

Table 2. Statistical Comparison of Change in Occupant Satisfaction Between Baseline and Post-Installation Surveys for PEM and Control Groups

Assessment Category	Environmental Factor	PEM Ave. Δ	Control Ave. Δ	P-Value	1- or 2-Tailed	Level of Significance
Thermal Quality	temperature	0.71	-0.06	0.046	1	strong
	temperature control	0.94	-0.02	0.020	1	strong
	air movement	1.06	0.52	0.087	1	some
Air Quality	ventilation	0.71	0.40	0.203	1	–
	odors	0.28	0.38	0.737	2	–
	humidity	0.52	0.41	0.792	2	–
Lighting Quality	lighting level	0.52	-0.02	0.075	1	some
	computer screen	0.17	-0.42	0.094	2	some
	light from window	0.09	-0.32	0.367	2	–
Acoustical Quality	background noise	0.50	0.02	0.099	1	some
	distracting noises	0.70	0.28	0.085	1	some
	conversational privacy	0.61	0.27	0.091	1	some
Spatial Layout	space available	0.35	-0.10	0.130	2	–
	spatial privacy	0.30	0.06	0.516	2	–
	ease of interaction	0.00	-0.02	0.957	2	–
Office Furnishings	comfort of chair	0.13	0.06	0.839	2	–
	comfort of other furn.	0.45	0.18	0.421	2	–
	colors/textures	0.44	0.10	0.267	2	–

Table 3. Statistical Comparison of Change in Occupant Satisfaction Between Baseline and Post-Installation PEM Group

Assessment Category	Environmental Factor	P-Value	1- or 2-tailed	Significance
Thermal Quality	temperature	0.017	1	strong
	temperature control	0.004	1	strong
	air movement	0.001	1	strong
Air Quality	ventilation	0.017	1	strong
	odors	0.460	2	–
	humidity	0.090	2	some
Lighting Quality	lighting level	0.029	1	strong
	computer screen	0.776	2	–
	light from window	0.266	2	–
Acoustical Quality	background noise	0.127	1	–
	distracting noises	0.027	1	strong
	conversational privacy	0.051	1	some
Spatial Layout	space available	0.435	2	–
	spatial privacy	0.429	2	–
	ease of interaction	0.956	2	–
Office Furnishings	comfort of chair	0.608	2	–
	comfort of other furn.	0.065	2	some
	colors/textures	0.140	2	–

Table 4. Statistical Comparison of Change in Occupant Satisfaction Between Baseline and Post-Installation Control Group

Assessment Category	Environmental Factor	P-Value	1- or 2-tailed	Significance
Thermal Quality	temperature	0.979	2	–
	temperature control	0.885	2	–
	air movement	0.251	2	–
Air Quality	ventilation	0.528	2	–
	odors	0.328	2	–
	humidity	0.315	2	–
Lighting Quality	lighting level	0.963	2	–
	computer screen	0.232	2	–
	light from window	0.790	2	–
Acoustical Quality	background noise	0.963	2	–
	distracting noises	0.503	2	–
	conversational privacy	0.573	2	–
Spatial Layout	space available	0.789	2	–
	spatial privacy	0.875	2	–
	ease of interaction	0.950	2	–
Office Furnishings	comfort of chair	0.851	2	–
	comfort of other furn.	0.623	2	–
	colors/textures	0.823	2	–

Thermal Quality. The overall rating for thermal quality is based on the satisfaction ratings for the three environmental factors: temperature, temperature control, and air movement. Thermal quality received the highest net increase and the highest overall satisfaction rating of 4.96 after the installation of the PEMs. The histograms in Figure 12 show how there is a large increase in mean ratings for all three of these factors within the PEM group (+0.7 for temperature, +0.9 for temperature control, and +0.9 for air movement). The t-test statistics show that these increased occupant satisfaction levels are strongly significant for temperature and temperature control, and somewhat significant for air movement, in comparison to the control group (Table 2). Figure 18 shows that the overall rating for thermal quality in the control group changes by only 0.16 between the March and July surveys (3.45 vs. 3.61). Differences between satisfaction ratings in the control group for each of the three environmental factors are also relatively small (-0.1 for temperature, -0.1 for temperature control, and +0.4 for air movement).

Within the PEM group alone, the increased satisfaction levels are strongly significant for all three factors compared to baseline conditions (Table 3). As shown in Figure 12, in all three cases, this increase is characterized by a noticeable increase in the number of occupants indicating that they are very satisfied (bin 6 on scale) and a complete elimination of occupants indicating that they are either moderately or very dissatisfied (bins 1 and 2 on scale). The “0% dissatisfied” result for all three thermal factors suggests that practically all complaints related to thermal issues will be avoided for these occupants with the PEM system in place. In comparison to the background data set shown on the temperature histogram, the Bank of America office buildings receive a much higher occupant satisfaction rating within the PEM group for both baseline and post-installation surveys. As would be expected, the t-test statistics indicate no significant differences between baseline and post-installation satisfaction levels within the control group (Table 4). Despite the overall lower rating for the control group, the buildings still achieved a higher score than the background data set in the temperature category.

The descriptive frequency results on the right side of Figure 12 show that within the PEM group, over 60% in the baseline survey and over 70% in the post-installation survey said the space was often comfortable. In comparison, only a little over 40% of the control group felt the same way about their space (Figure 18). Temperature variability increased noticeably within the PEM group between surveys. Given the large increase in satisfaction with temperature control, this suggests that people prefer some amount of temperature variability (under their control). During the July survey, the air movement was perceived to be "often comfortable" by over 60% of the PEM group vs. less than 25% of the control group. In the control group, it is noteworthy that over 50% of the respondents in the July survey stated that air movement was often too low, a response reported by less than 10% of the PEM group during this same survey period.

Acoustical Quality. The overall rating for acoustical quality is based on satisfaction ratings for the three environmental factors: background noise, distracting noises, and conversational privacy. After thermal quality, the next highest change in overall rating within the PEM group occurred for acoustical quality, which increased by 0.58 from 2.90 to 3.48 (Figure 15). This is a larger change than the control group, which only increased by 0.18 from 2.41 to 2.59 (Figure 21). The t-test statistics show that these increased occupant satisfaction levels are somewhat significant for all three environmental factors in comparison to the control group (Table 2). Within the PEM group alone, the increased satisfaction levels are strongly significant for distracting noises and somewhat significant for conversational privacy compared to baseline conditions (Table 3). The white noise control of the PEM is probably responsible for this improvement, however, some people indicated that they did not find it to be effective (see comments in Appendix B). Some people also indicated that they found the fan noise to be more soothing than the white noise generator.

Acoustical quality is the most poorly rated assessment category in these three Bank of America office buildings. Dissatisfaction with conversational privacy (defined as the ability to overhear your neighbors' conversations, and vice versa) is the biggest contributing environmental factor to this result. In particular, 63-64% of the control group were either very or moderately dissatisfied (bins 1 and 2 on scale) with their conversational privacy in both surveys. The corresponding ratings by the PEM group were 61% dissatisfied in the March survey, and 37% dissatisfied in the July survey.

Air Quality. The overall rating for air quality is based on satisfaction ratings for the three environmental factors: ventilation (perception of stuffiness), odors, and humidity.

The category of air quality received the third highest change in overall rating within the PEM group, as it increased by 0.46 from 4.42 to 4.88 (Figure 13). In the July post-installation survey, air quality along with thermal quality were rated as the top two categories by the PEM group. This is an important result as it runs contrary to the common trend among many recent field studies that have found thermal and air quality issues to usually be among the lowest rated categories for occupant satisfaction (e.g., see Schiller et al. 1988, Baughman et al. 1995). Among the three environmental factors within the air quality category, ventilation received the highest increase of +0.7 in comparison to the change of +0.3 for the same factor for the control group (Figure 19). The t-test statistics show that none of the environmental factors in the air quality category have changes in occupant satisfaction levels that are significantly higher in comparison to the corresponding changes within the control group (Table 2). In the case of ventilation, which is expected to be improved with localized ventilation from the PEM units, the rather large increase in satisfaction for the control group accounts for this result.

Within the PEM group, the increased satisfaction levels are strongly significant for ventilation and somewhat significant for humidity compared to baseline conditions (Table 3). PEM group satisfaction with odors did not demonstrate a significant improvement compared to the control group, probably because there were few distracting odors during the baseline survey in March (mean rating of 4.7 and 0% dissatisfied), and therefore little room for improvement. It is often difficult for people to detect subtle changes in humidity level. Physical monitoring of space conditions indicated that there was little change in humidity between the two survey periods, suggesting that the noted increase in humidity satisfaction rating (+0.5) was related to the occupants' improved overall satisfaction with the quality of the environment. The percent dissatisfied (bins 1 and 2 on scale) for all three air quality factors in the PEM group were reduced to a maximum of only 6% for ventilation, again suggesting that air quality complaints could be practically eliminated with the PEM units in place. Mean satisfaction ratings for ventilation were higher than the background data set in both PEM group surveys and slightly lower in both control group surveys.

Lighting Quality. The overall rating for lighting quality is based on satisfaction ratings for the three environmental factors: lighting level, visual quality of computer screen, and quality of light from windows. Lighting quality received the highest overall satisfaction rating among the six building assessment categories during the baseline field test (March) for both the PEM group (Figure 14) and control group (Figure 20). However, the change in overall rating between the baseline and post-installation surveys was not much larger for the PEM group compared to the control group. This is not surprising because two of the three lighting quality factors (computer screen and light from windows) are not directly controlled by the PEM unit. Any changes between the two surveys observed for these two factors may, in fact, be due more to seasonal variations with respect to the angle of the incoming solar radiation. Lighting level would be expected to benefit from the dimming control of the task light by the PEM. Figure 14 shows that this is indeed the case for the PEM group, as the mean satisfaction rating increases by 0.5 from 4.3 to 4.8. This is a noticeable change in comparison to the results for lighting level satisfaction for the control group shown in Figure 20, for which the average ratings from the two surveys are identical (3.8). The t-test statistics show that the observed increased occupant satisfaction levels are somewhat significant for lighting level and for visual quality of the computer screen in comparison to the control group (Table 2). Within the PEM group alone, the increased satisfaction levels are strongly significant for lighting level compared to baseline conditions (Table 3). Compared to the background dataset, the PEM group lighting level satisfaction rating is equal or higher, while the control group rating is lower.

The descriptive frequency results on the right side of Figure 14 suggest that members of the PEM group prefer moderately bright lighting conditions. Nearly 70% of the respondents in the July survey compared with only 20% in the March survey said they had moderately bright lighting conditions at their work area. Presumably this was due to the improved task lighting that was installed in connection with the PEMs. Very little change is observed in the descriptive frequency results for "glare on computer screen" and "glare in field of vision," two factors that would not be expected to be strongly influenced by the PEM lighting control.

Spatial Layout and Office Furnishings. The overall rating for spatial layout is based on satisfaction ratings for the three environmental factors: space available, spatial privacy, and ease of interaction with co-workers. The overall rating for office furnishings is based on satisfaction ratings for the three environmental factors: comfort of chair, comfort of other office furnishings, and colors/textures of materials. All six of the environmental factors within these two categories are not expected to be significantly influenced by the installation of the PEM units. The results support this conclusion as the observed changes for the PEM group (Figures 16 and 17) are not much larger than those for the control group (Figures 22 and 23) for spatial layout satisfaction rating (+0.20 vs. +0.02) and office furnishings satisfaction rating (+0.33 vs. +0.11). In comparison to the background data set, the PEM group has higher satisfaction ratings for comfort of chair and comfort of other office furnishings, and about equal ratings for space available, spatial privacy, and colors/textures of materials. The same comparison to the background data set shows that the control group has slightly higher satisfaction ratings for comfort of chair, about equal ratings for comfort of office furnishings, and lower ratings for space available, spatial privacy, and colors/textures of materials.

Job Impact Rating

In the background section of the survey, occupants were asked to rate the overall impact that each of the six building assessment categories had on their ability to work effectively. The job impact rating was measured on a six-point scale from very positive impact (6) to very negative impact (1). The detailed results for the six categories are presented in Figures 24a and 24b for the PEM group and in Figures 25a and 25b for the control group. Using the same format as in previous figures, the side-by-side histograms compare the distribution of occupant responses binned among the six-point scale for the baseline survey (March 1996) and post-installation survey (July 1996). Mean overall ratings are shown to the right of each histogram. The p-value statistics are summarized in Table 5 for the job impact ratings. The table compares the

Figure 24a

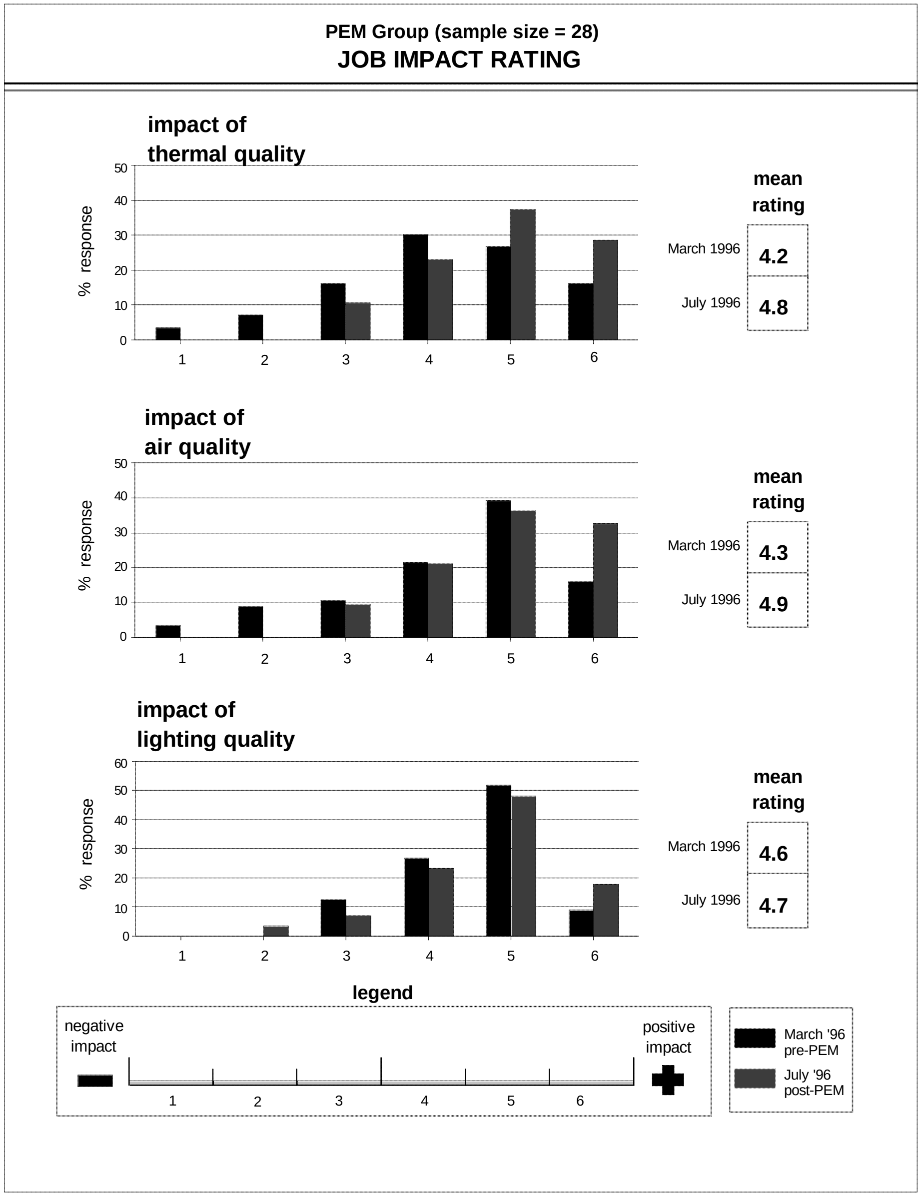


Figure 24b

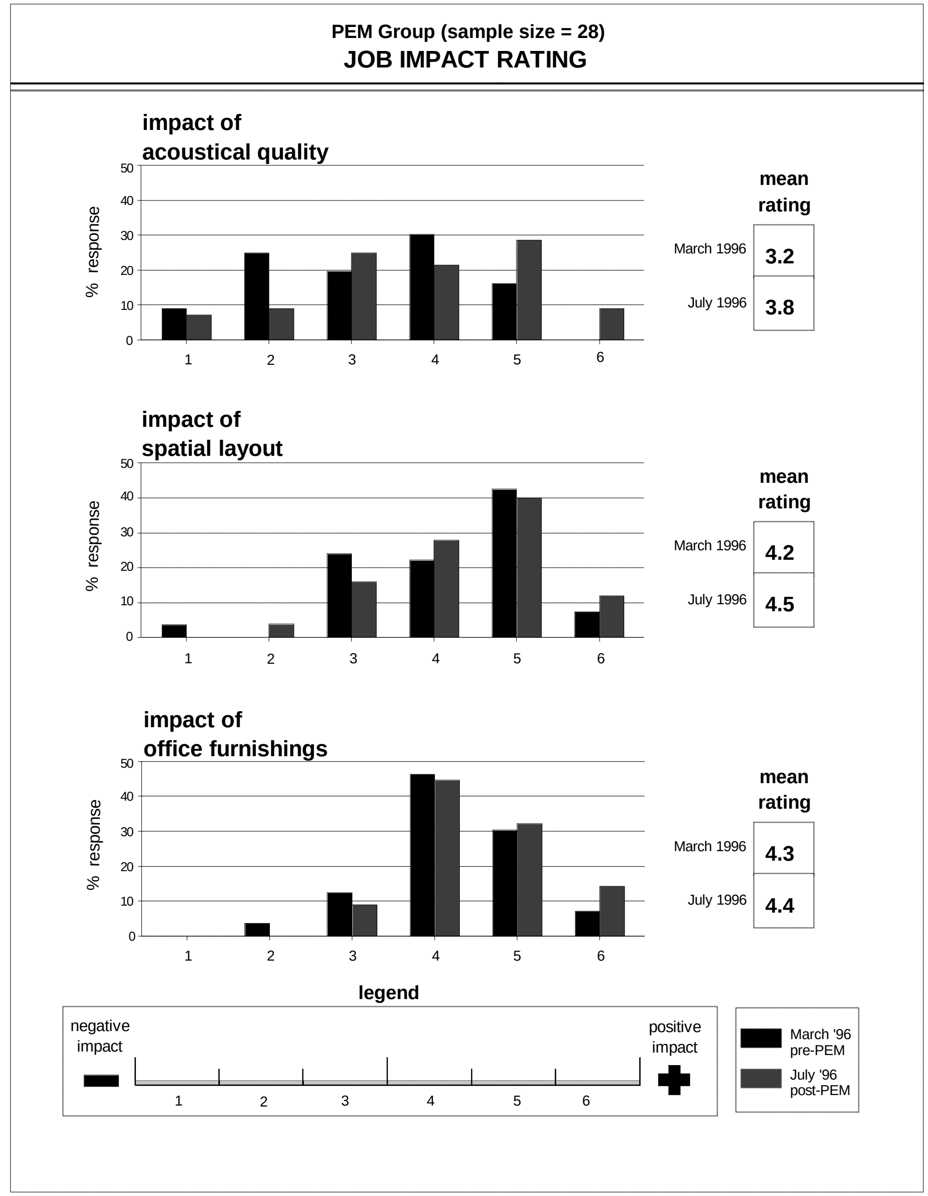


Figure 25a

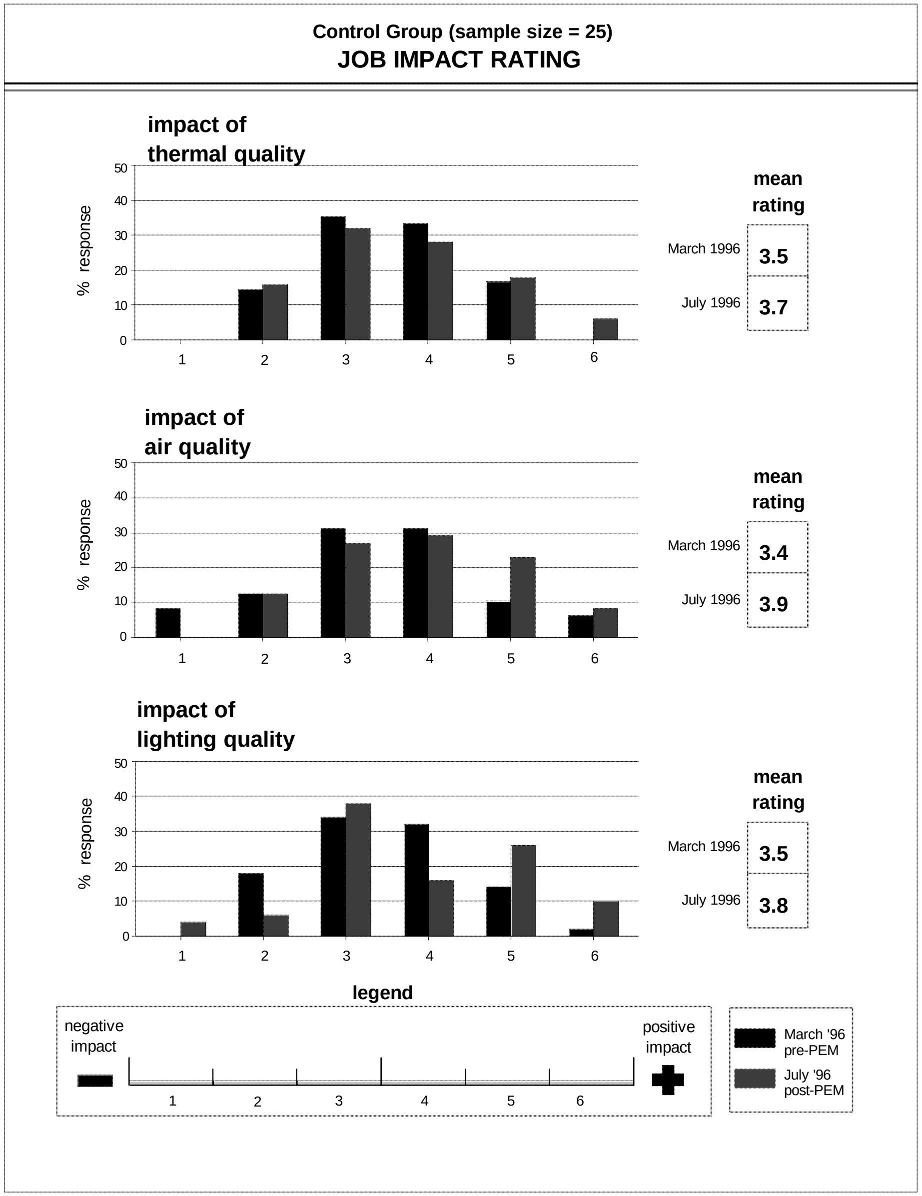
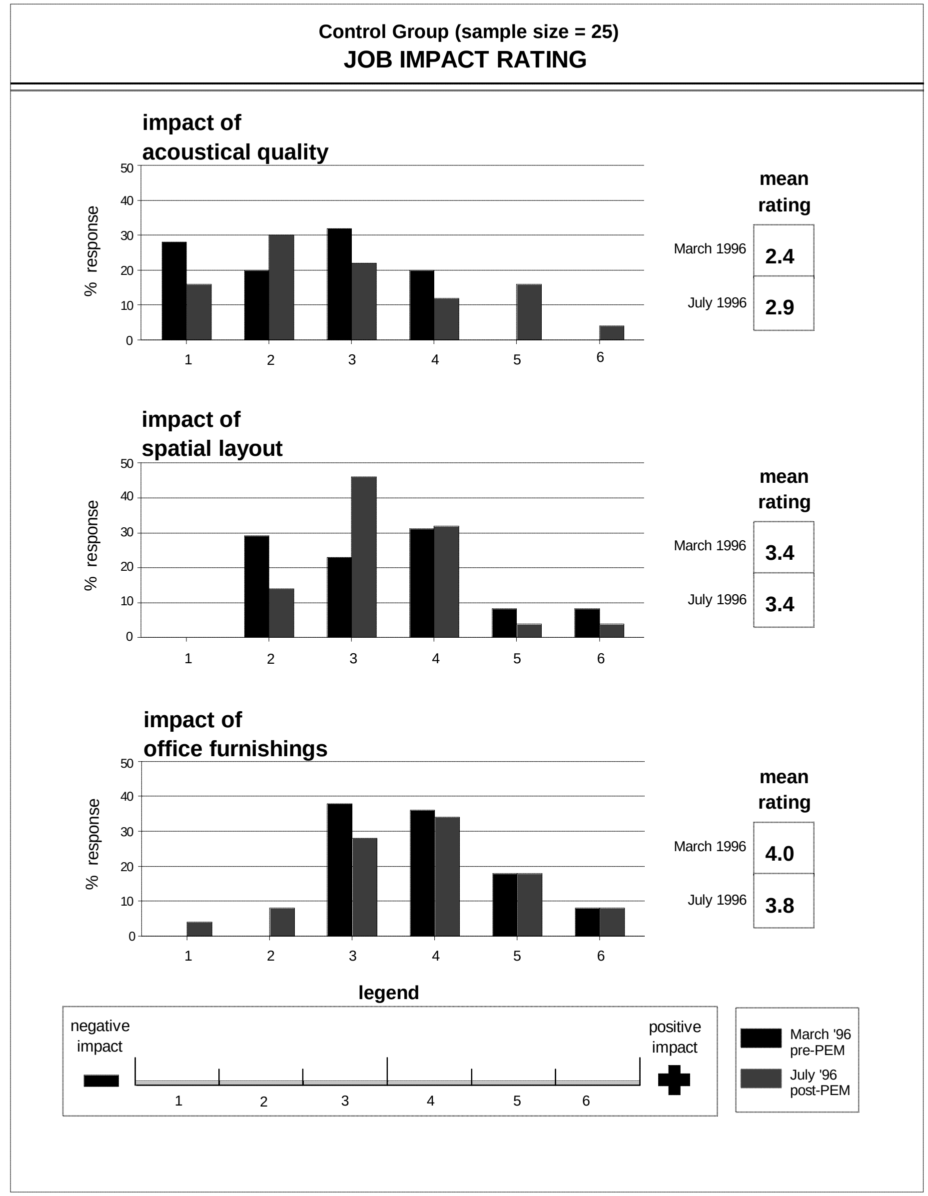


Figure 25b



statistical significance of changes in job impact rating between the baseline and post-installation surveys for the PEM group with that for the control group.

The job impact rating results display similar trends to those observed for the work area satisfaction results discussed above. For the PEM group, the largest differences in job impact rating between the baseline and post-installation surveys occur for thermal quality (+0.6), air quality (+0.6), and acoustical quality (+0.6). As shown in Table 5, these differences are all strongly significant for the PEM group. In comparison, the differences for the control group are not significant. These results indicate that the improvements in thermal quality, air quality, and acoustical quality produced by the PEMs have a positive impact on the occupants' ability to work effectively that would not have occurred if the PEMs were not installed. Differences between survey results for the other three categories (lighting quality, spatial layout, and office furnishings) are of similar small magnitude for both the PEM and control groups, and the p-values indicate no significant change in job impact rating for any of these categories.

Table 5. Statistical Comparison of Change in Job Impact Rating Within PEM Group to Change in Job Impact Rating Within Control Group

Assessment Category	Group	P-Value	1- or 2-tailed	Significance
Thermal Quality	PEM	0.016	1	strong
	Control	0.541	2	–
Air Quality	PEM	0.029	1	strong
	Control	0.196	2	–
Lighting Quality	PEM	0.598	2	–
	Control	0.271	2	–
Acoustical Quality	PEM	0.039	1	strong
	Control	0.179	2	–
Spatial Layout	PEM	0.549	2	–
	Control	0.854	2	–
Office Furnishings	PEM	0.246	2	–
	Control	0.553	2	–

Physiological Symptoms

During the July survey only, occupants were asked to report the frequency with which they experienced various physiological symptoms while working in the building. Figures 26 and 27 present the results for each symptom in terms of a stacked-bar chart showing the percent response for each of the four frequency categories (ranging from "every or almost every day" to "not in the last four weeks"). Figure 26 shows that for the PEM group, only two symptoms ("unusual tiredness, fatigue, or drowsiness" and "dry or itchy skin") were experienced as frequently as 1-3 days per week by more than 10% of the respondents. The symptom that was reported during the previous four weeks by the largest number of respondents (60%) was "tired or strained eyes." In comparison, Figure 27 shows a higher reported frequency for all symptoms within the

Figure26

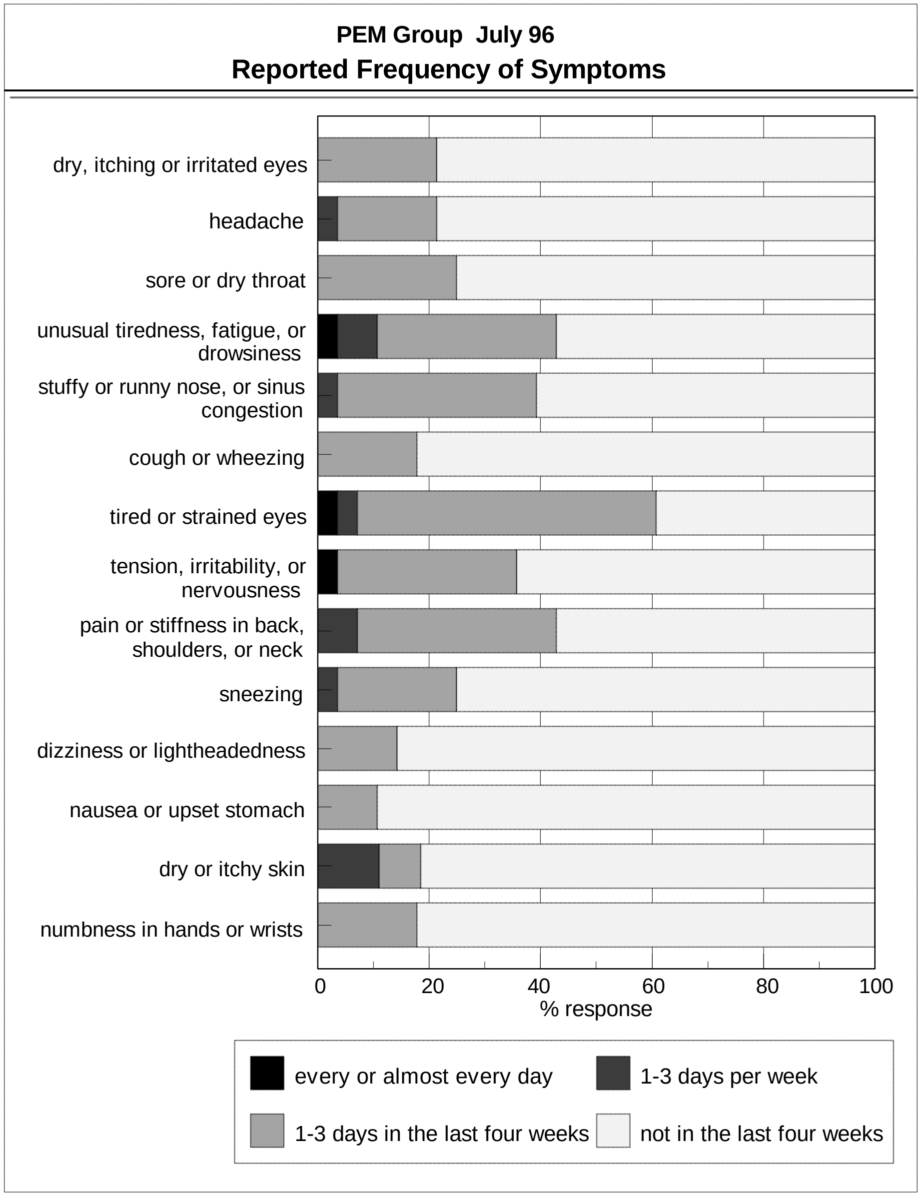
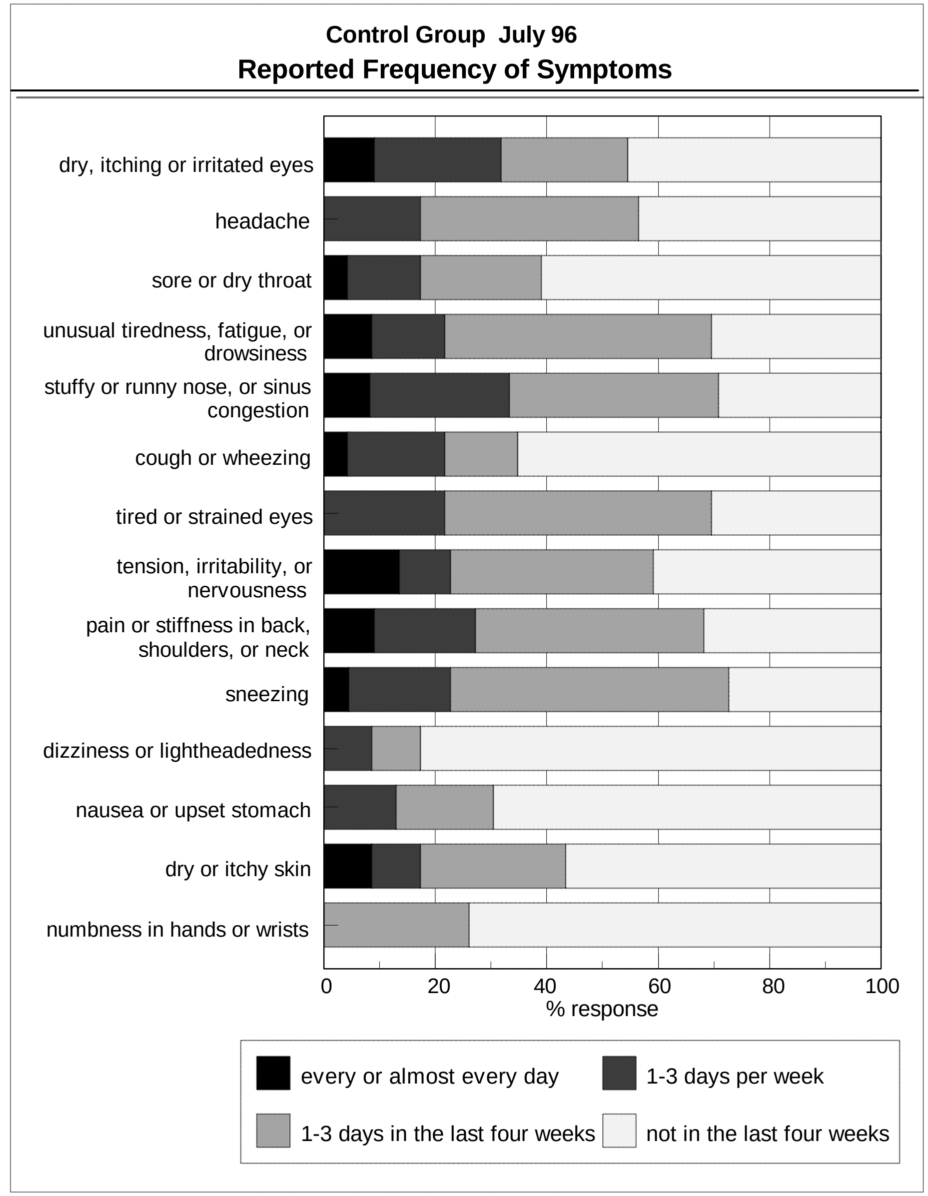


Figure27



control group. This observed difference cannot be attributed to the existence of the PEM (although it seems likely to at least be partially correlated) because no baseline data were collected for these questions. For the control group, most symptoms are experienced as fre
quently as 1-3 days per week by about 20% or more of the respondents. There were five symptoms that were reported at all by 68-72% of the respondents. These were “unusual tiredness, fatigue, or drowsiness,” “stuffy or runny nose, or sinus congestion,” “tired or strained eyes,” “pain or stiffness in back, shoulders, or neck,” and “sneezing.”

Comparative Performance
Members of the PEM group were asked during the July post-installation survey to compare the comfort of their work environment provided by the PEM system to conditions that existed prior to installation of the PEMs. The results are shown in Figures 28(a, b, c) and 29(a, b, c), and are based on responses received from 34 occupants. Figure 28 shows that for almost all environmental factors, the PEM system is highly preferred over the previous system. In particular, less than 10% of the respondents said the PEM system was any worse at all compared to the previous system (bins 1-3) for three factors: temperature, avoiding overheating problems, and air movement and circulation. Figure 29 presents the same results as Figure 28, but splits out the six respondents for 560 Davis to allow comparison with the 28 respondents from the other two buildings. The comparative performance of the PEMs in 560 Davis is somewhat worse than that of the PEMs in the other two buildings for all environmental factors. In terms of factors involving air movement and temperature control, this may be due in part to the fact that the PEM units in Davis Street are only recirculating room air to the occupants -- no fresh ventilation air is provided through the PEM nozzles on the desks. However, the small number of Davis occupants (6) make the analysis statistically inconclusive.

Environmental Adjustments
During the July survey, members of the PEM group were asked how often they adjusted the various controls on their PEM unit. For each of the six different PEM control functions, Figure 30 shows the percent response for the various frequency of adjustment categories (ranging from “never” to “several times each day”). The results show that except for the radiant panel (12%), less than 10% of the respondents adjusted any of their controls several times a day. In fact, according to these survey findings, more than about 80% of the PEM users adjusted any of the controls less frequently than once each day. This suggests that it is more important for workers to have the ability to control their local environment than it is for them to actually make a large number of control adjustments. Of course, if the ambient conditions are well controlled, the occupants would have less reason to adjust the PEM controls. The frequency of use of the PEM controls is discussed further below in *Occupant Use of PEM Units*.

Environmental Conditions Right Now
Figures 31-36 present a comparison of the occupant perception of the environment at the time of sampling for the baseline (March) survey and the “normal” post-PEM survey (first July survey). Figures 31-33 show results for the PEM group and Figures 34-36

Figure 28a

PEM Group (sample size = 34) July 96 only

Comparative Performance

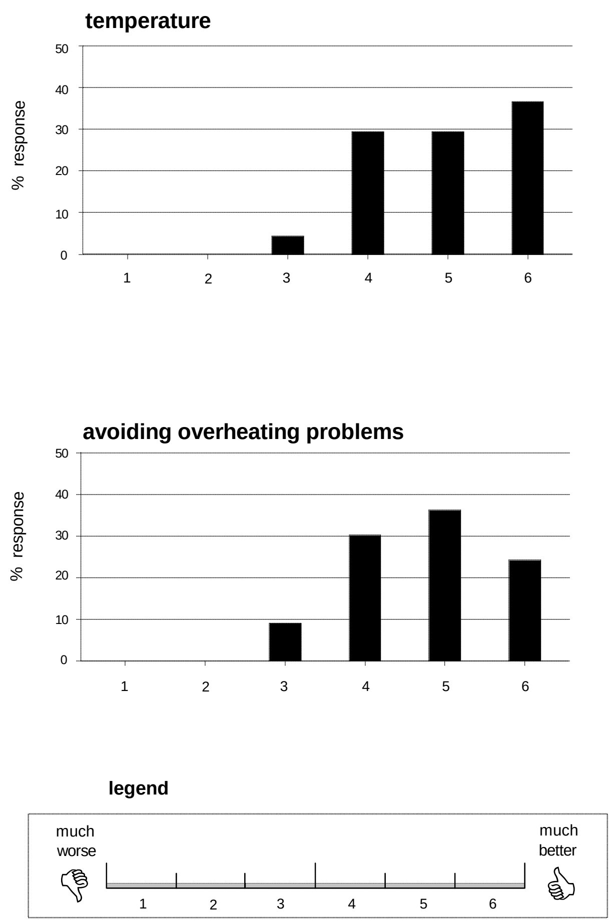


Figure 28b

PEM Group (sample size = 34) July 96 only

Comparative Performance

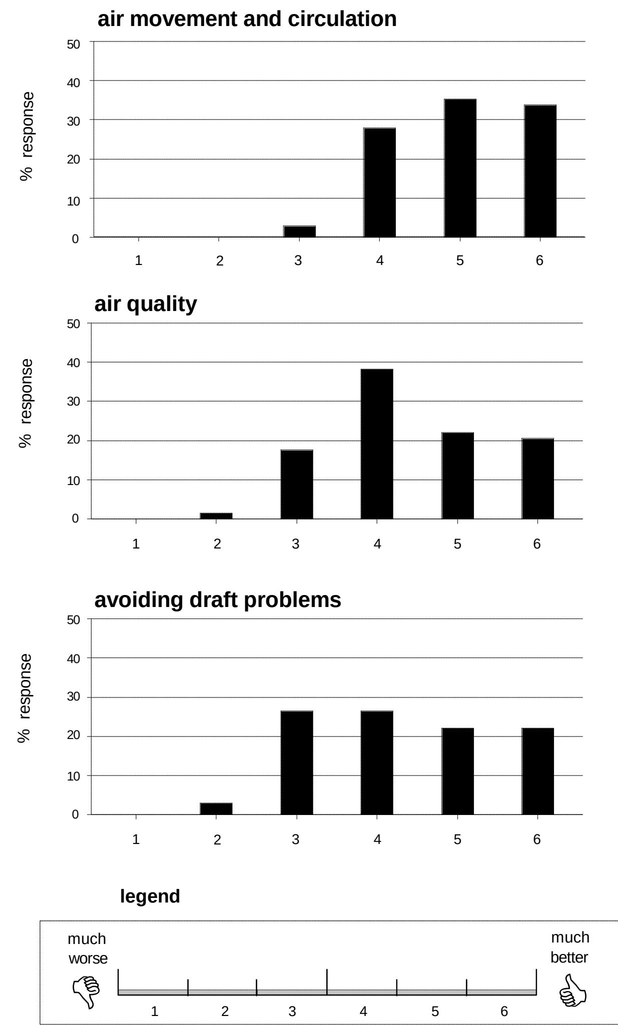
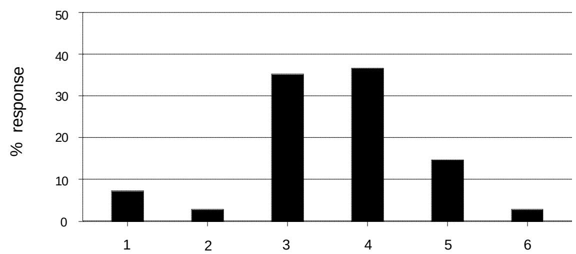


Figure 28c

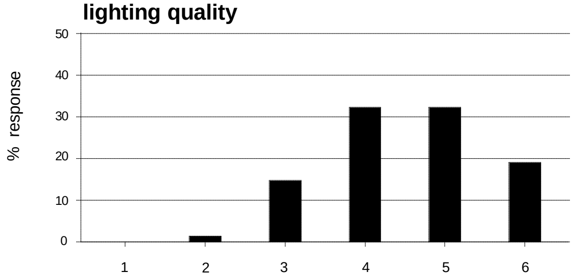
PEM Group (sample size = 34) July 96 only

Comparative Performance

freedom from distracting noises



lighting quality



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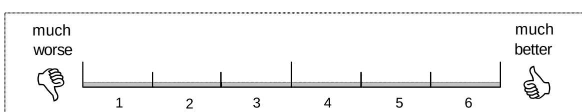
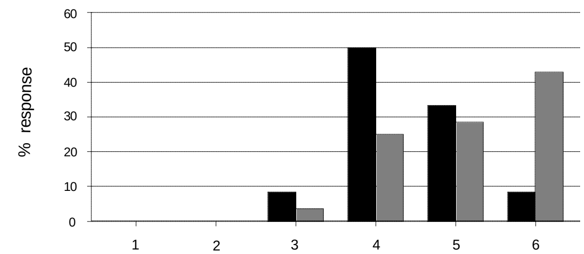


Figure 29a

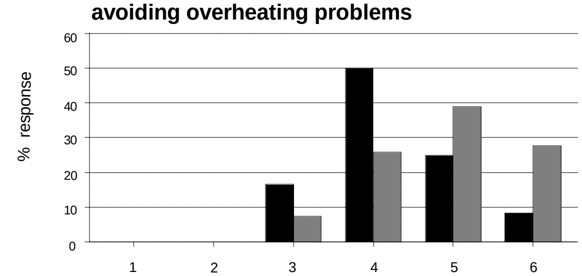
PEM Group July 96 only

Comparative Performance

temperature



avoiding overheating problems



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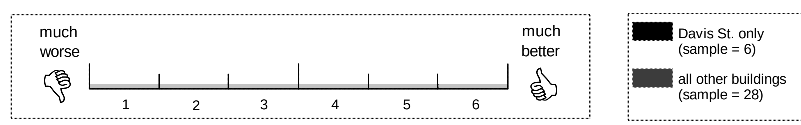


Figure 29b

PEM Group (sample size = 34) July 96 only

Comparative Performance

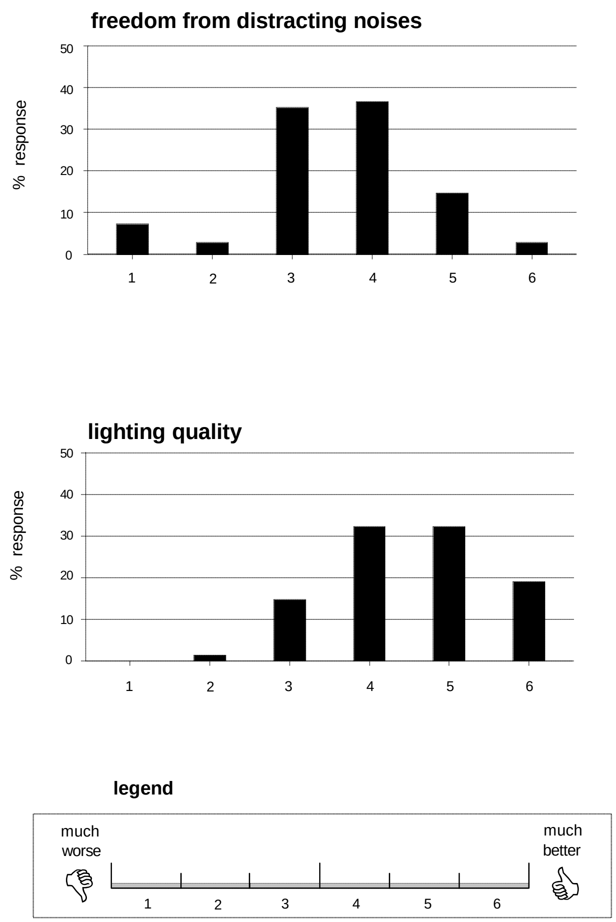


Figure 29c

PEM Group July 96 only

Comparative Performance

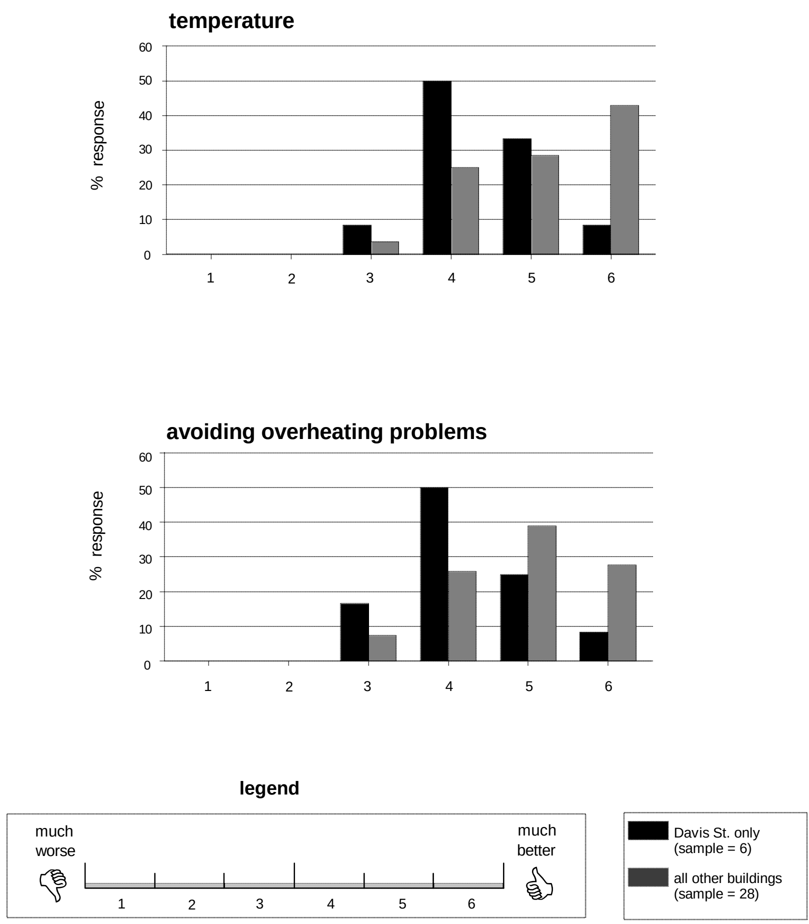
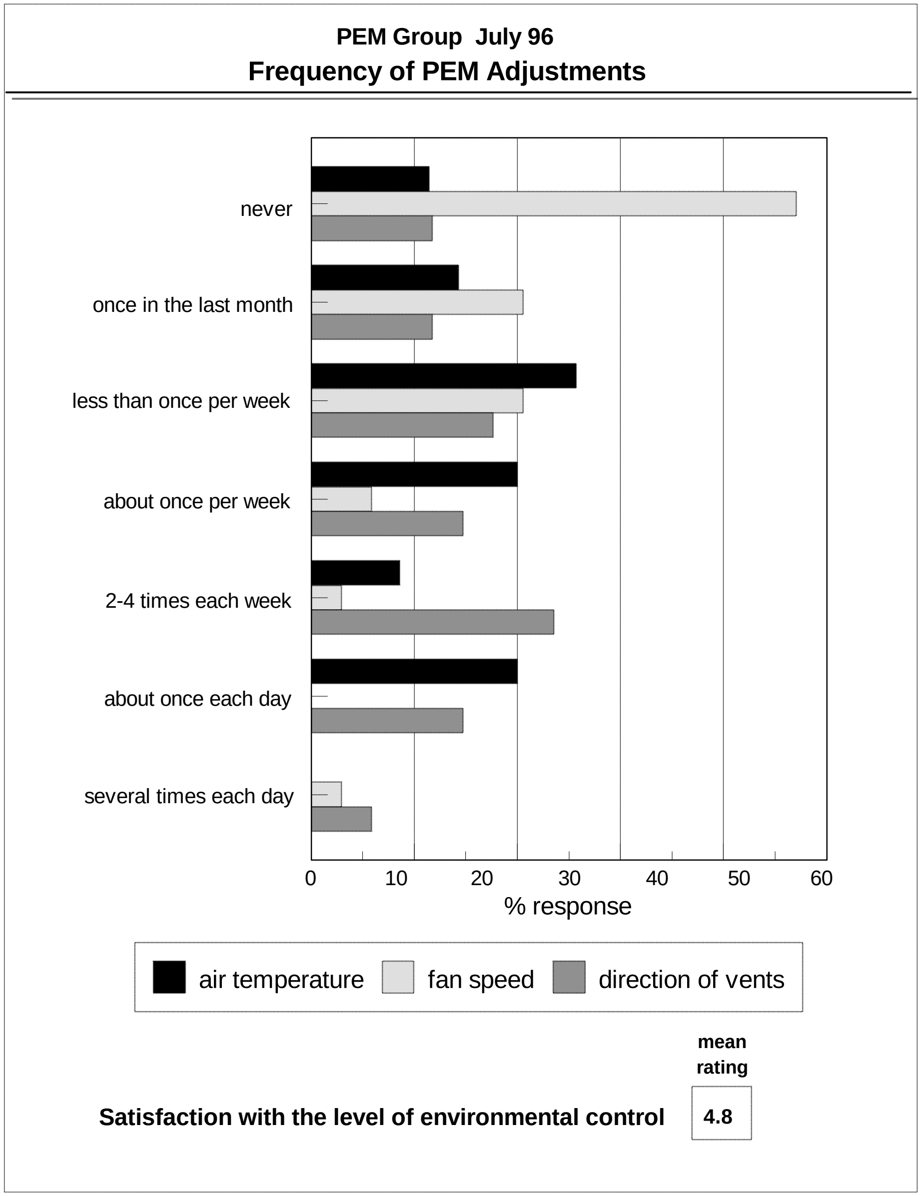
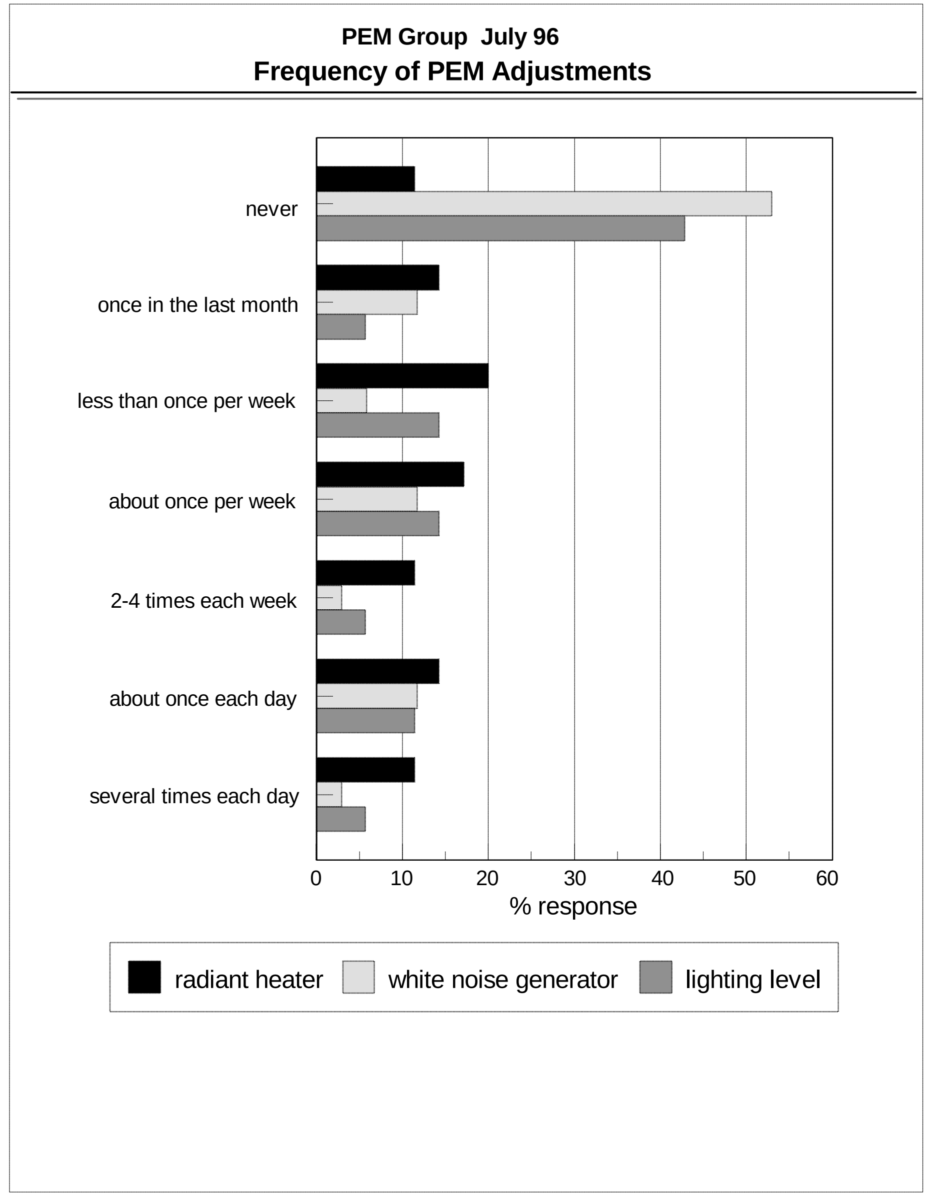


Figure 30



PEM Group July 96
Frequency of PEM Adjustments
never
once in the last month
less than once per week
about once per week
2-4 times each week
about once each day
several times each day
0
10
20
30
40
50
60
% response
air temperature
fan speed
direction of vents
mean rating
Satisfaction with the level of environmental control
4.8



PEM Group July 96
Frequency of PEM Adjustments
never
once in the last month
less than once per week
about once per week
2-4 times each week
about once each day
several times each day
0
10
20
30
40
50
60
% response
radiant heater
white noise generator
lighting level

Figure 31a

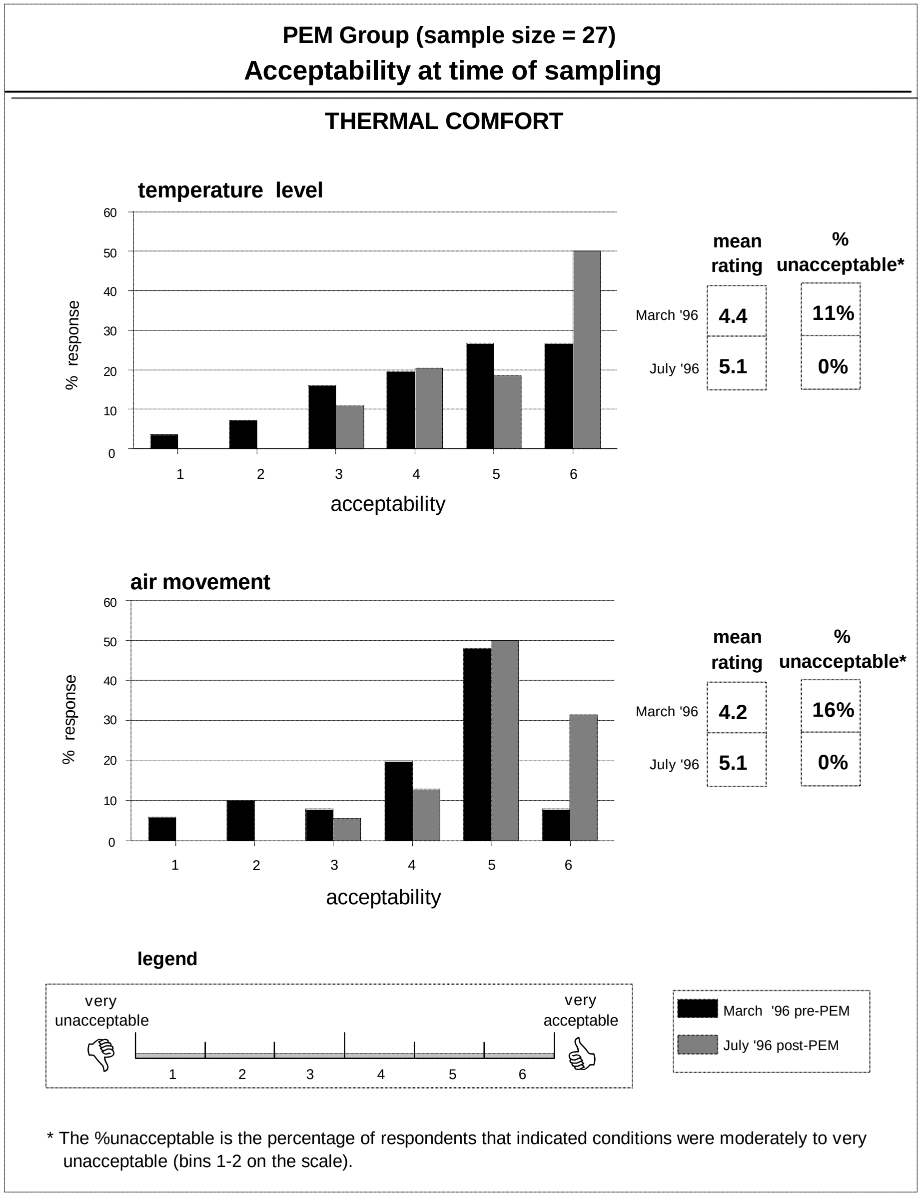


Figure31b

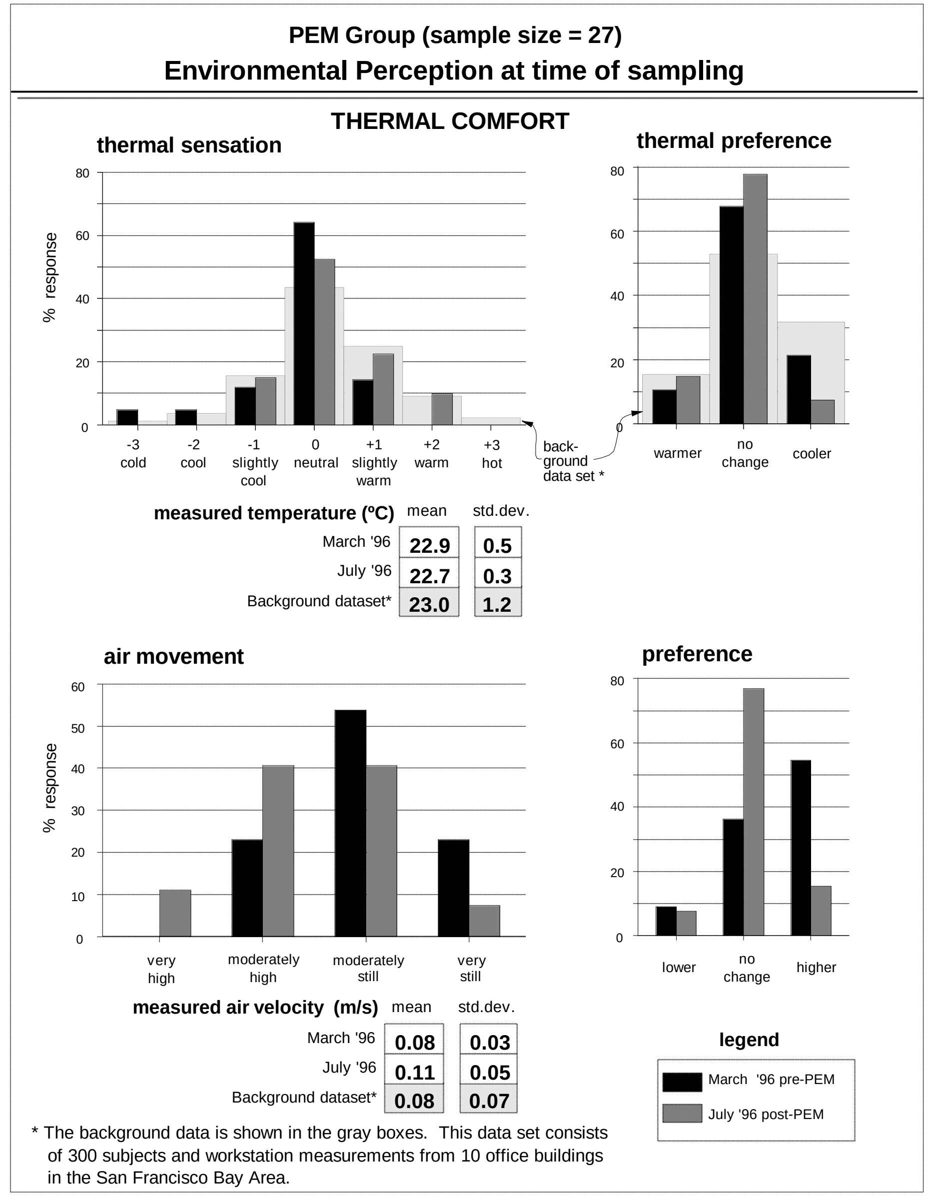
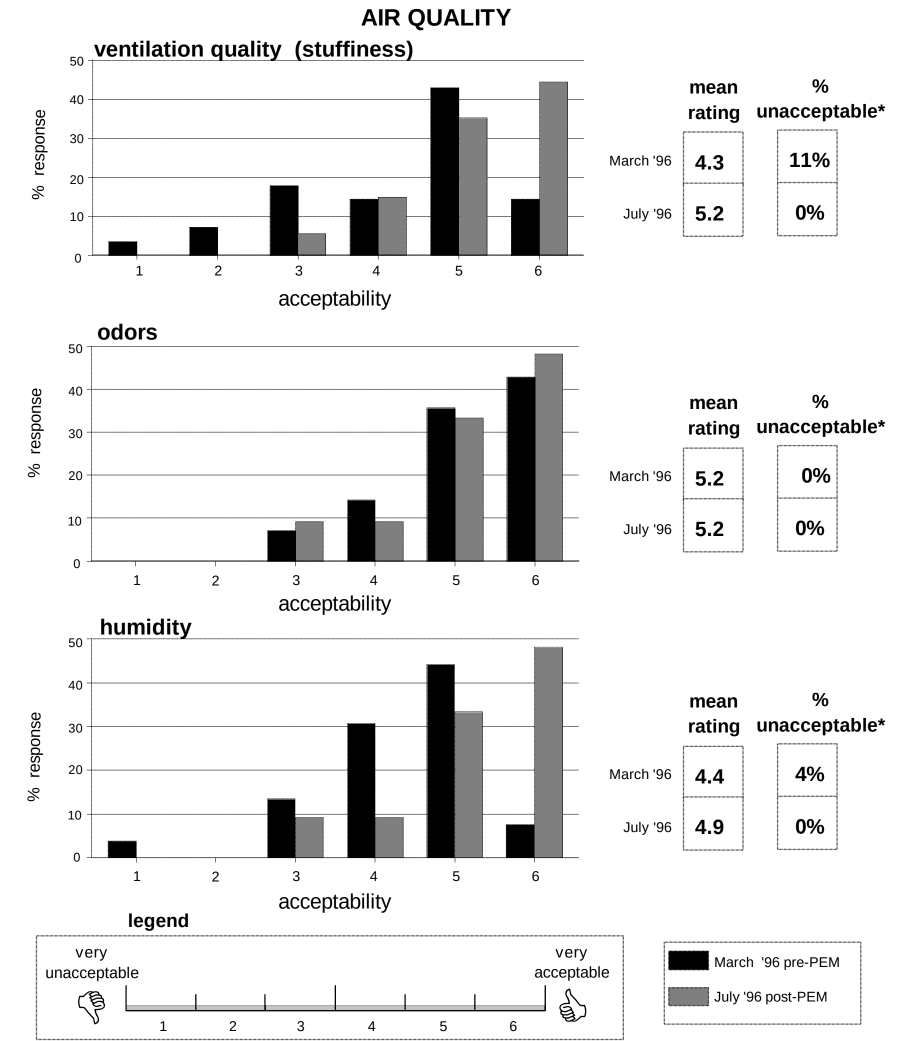


Figure 32a

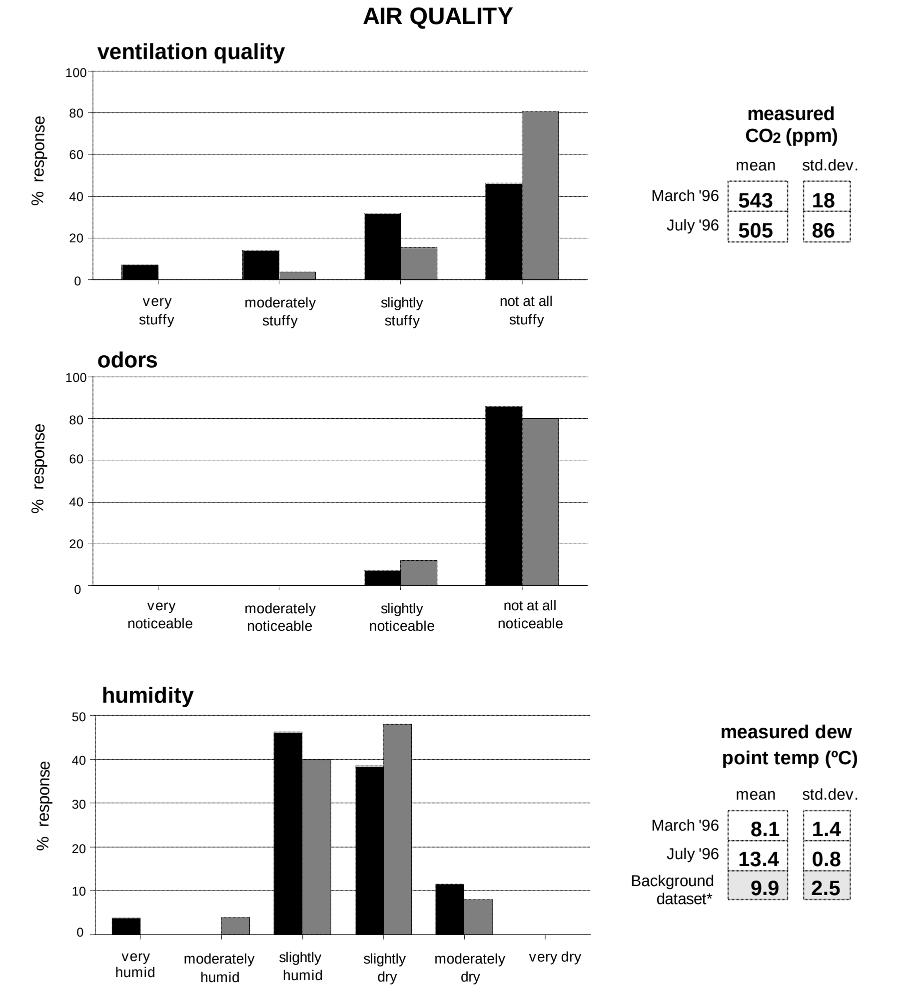
PEM Group (sample size = 27)
Acceptability at time of sampling



* The %unacceptable is the percentage of respondents that indicated conditions were moderately to very unacceptable (bins 1-2 on the scale).

Figure32b

PEM Group (sample size = 27)
Environmental Perception at time of sampling



* The background data is shown in the gray boxes. This data set consists of 300 subjects and workstation measurements from 10 office buildings in the San Francisco Bay Area.

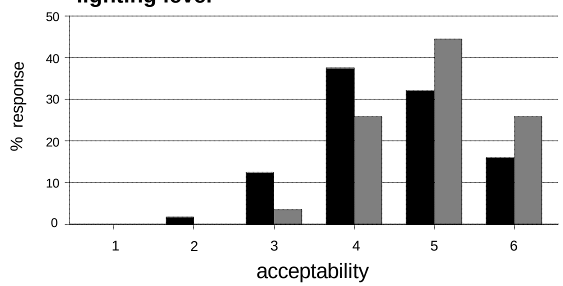
Figure 33a

PEM Group (sample size = 27)

Acceptability at time of sampling

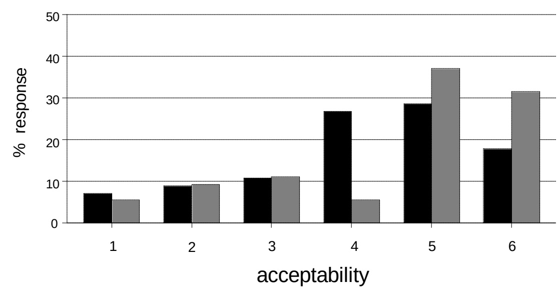
LIGHTING AND ACOUSTICAL COMFORT

lighting level



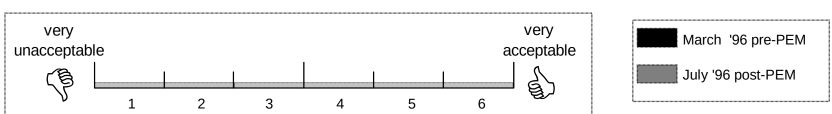
	mean rating	% unacceptable*
March '96	4.5	2%
July '96	4.9	0%

noise level



	mean rating	% unacceptable*
March '96	4.1	16%
July '96	4.5	15%

legend



* The %unacceptable is the percentage of respondents that indicated conditions were moderately to very unacceptable (bins 1-2 on the scale).

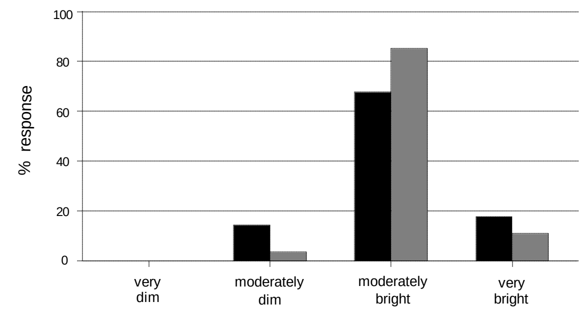
Figure33b

PEM Group (sample size = 27)

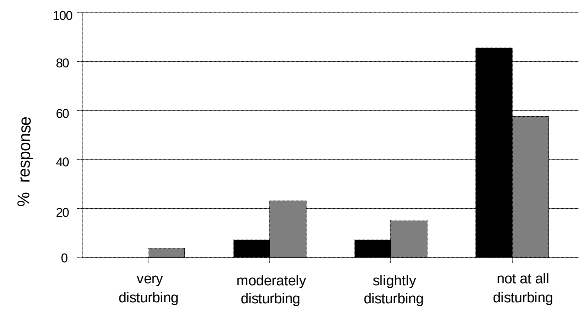
Environmental Perception at time of sampling

LIGHTING AND ACOUSTICAL COMFORT

lighting level



noise level



measured background sound level (dBA)

	mean	std.dev.
March '96	46	3
July '96	47	3

legend

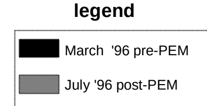


Figure 34a

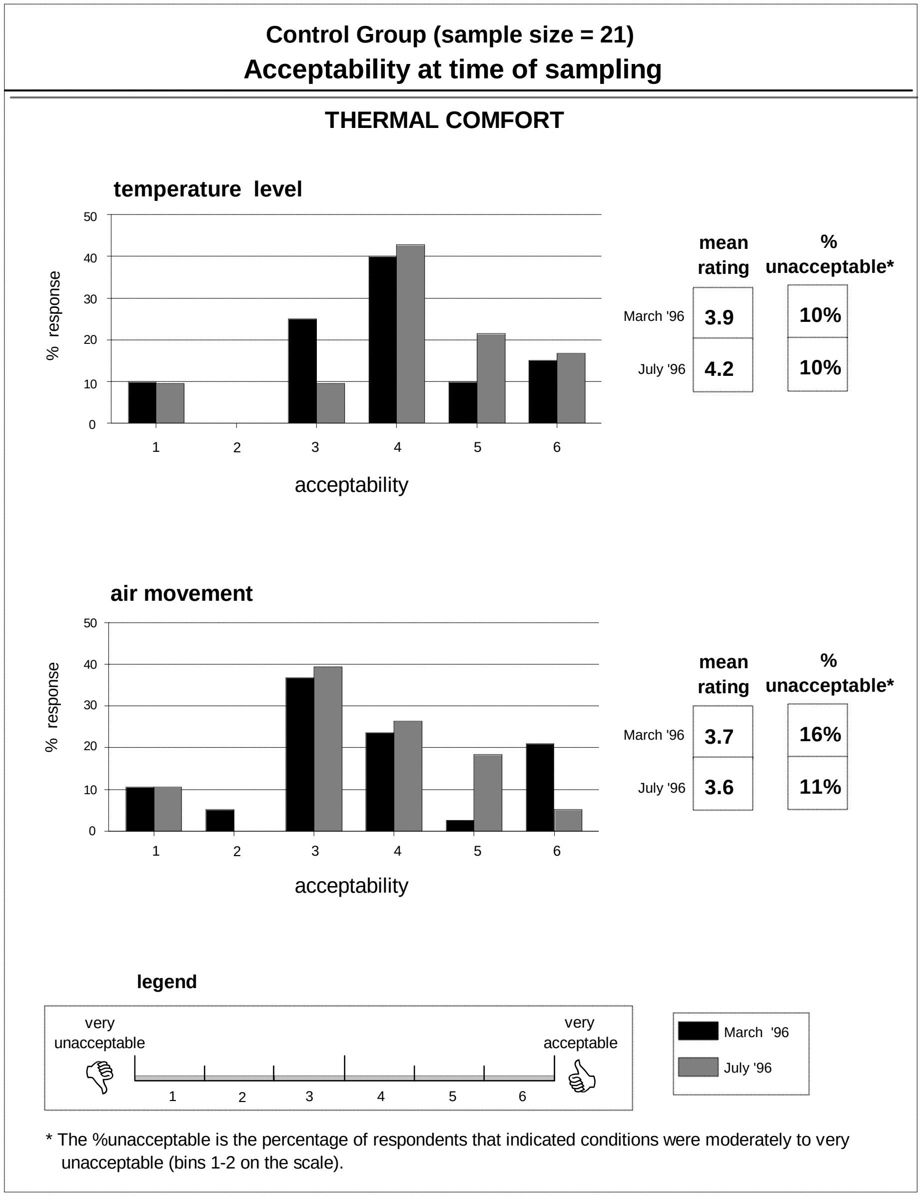


Figure 34b

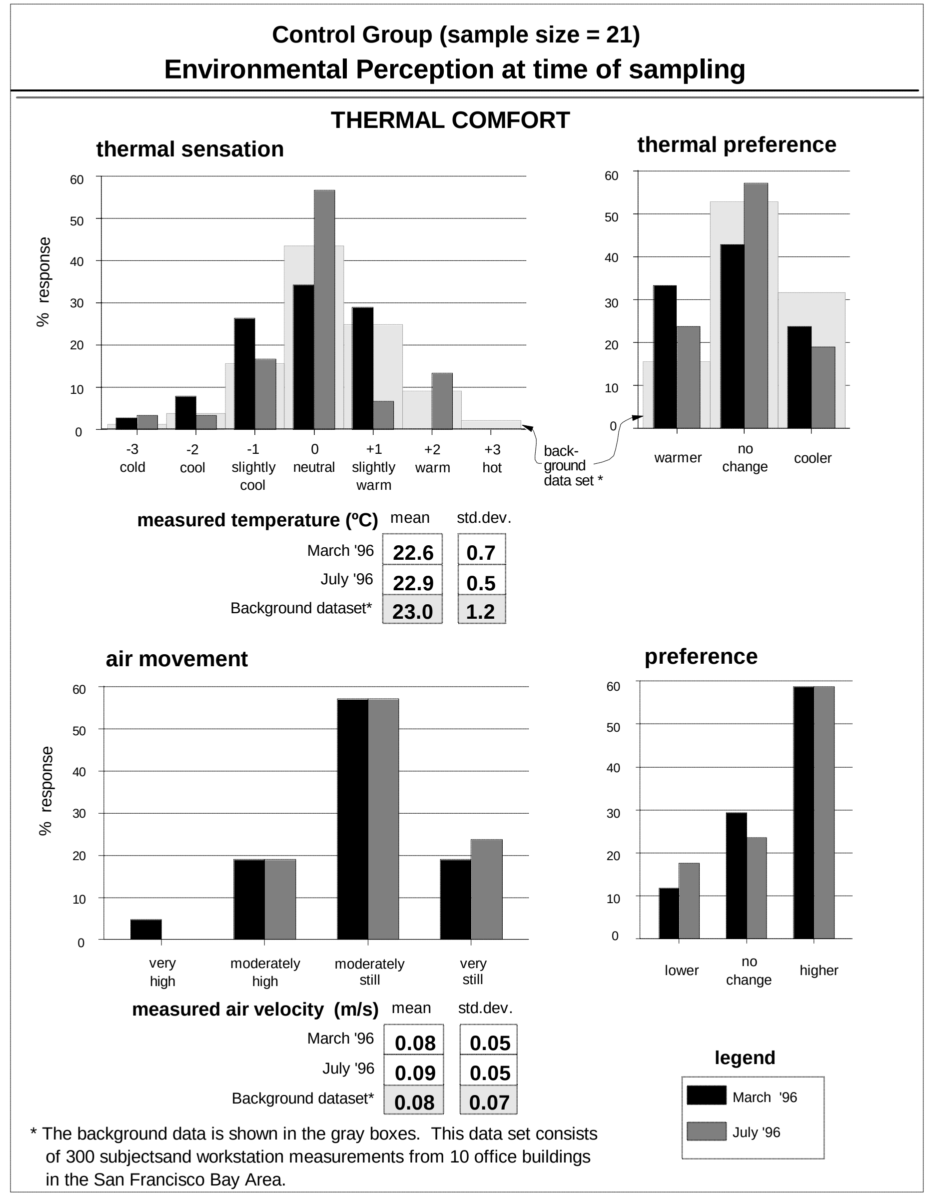


Figure 35a

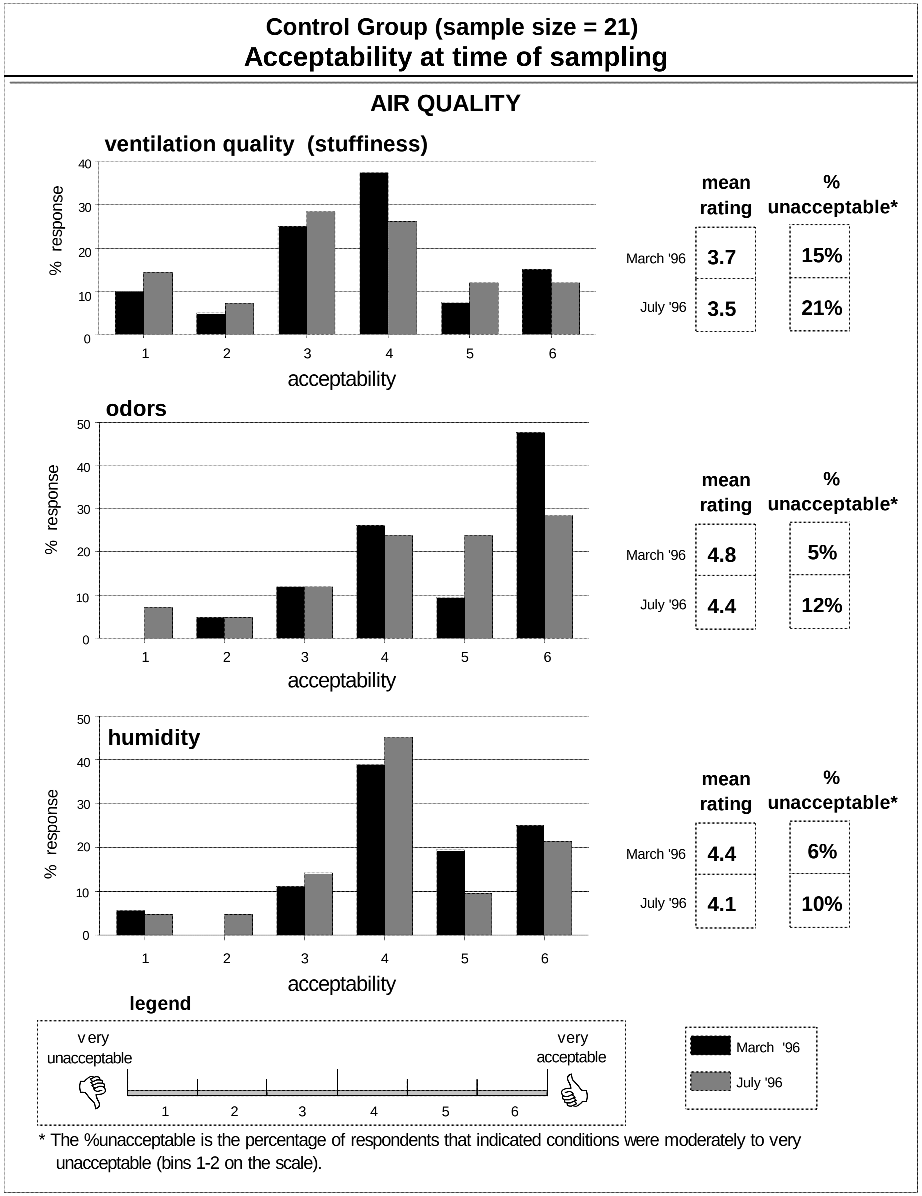


Figure 35b

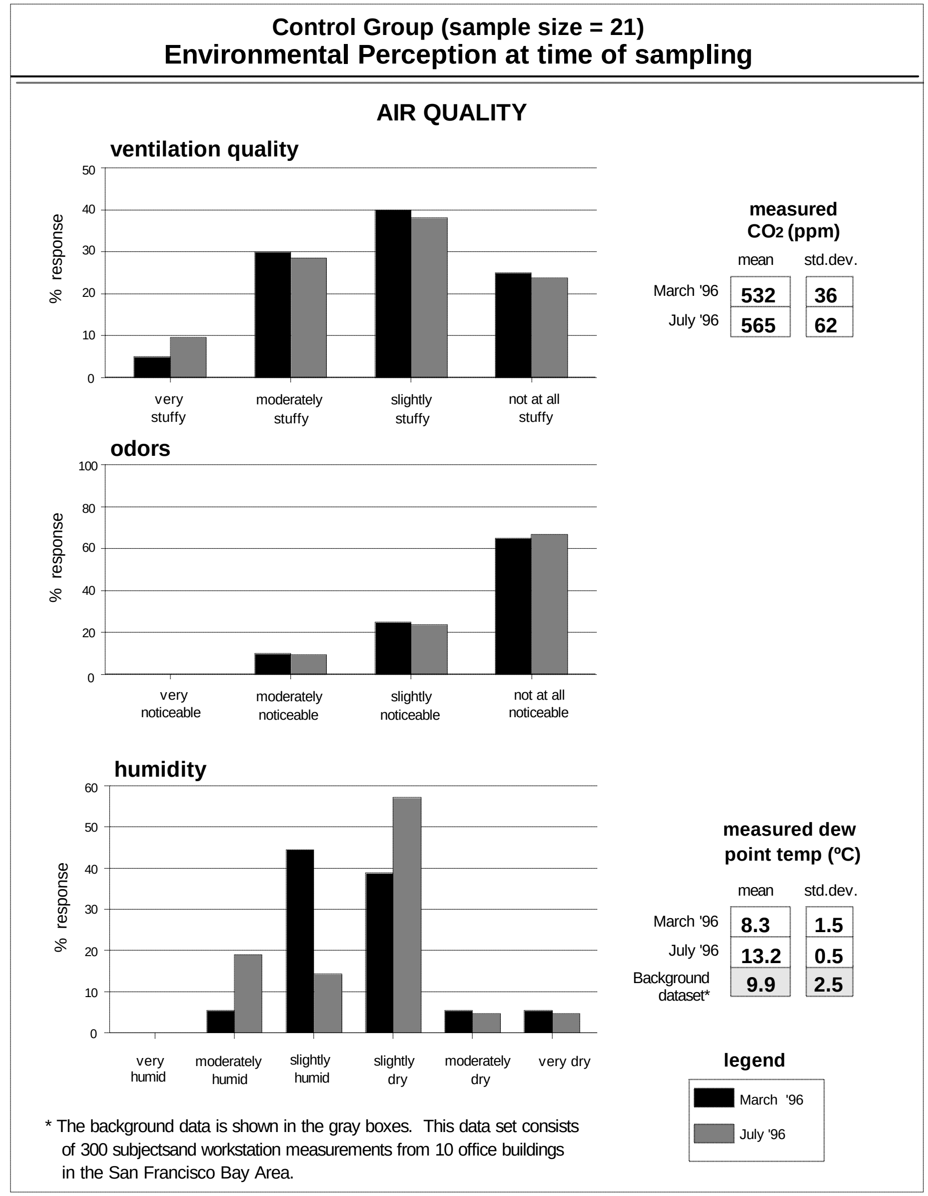
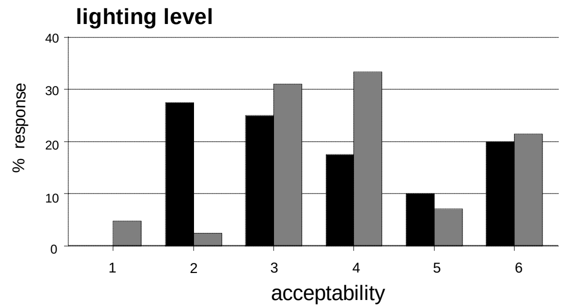


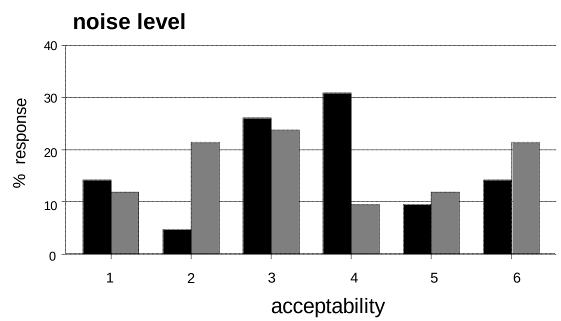
Figure 36a

Control Group (sample size = 21)
Acceptability at time of sampling

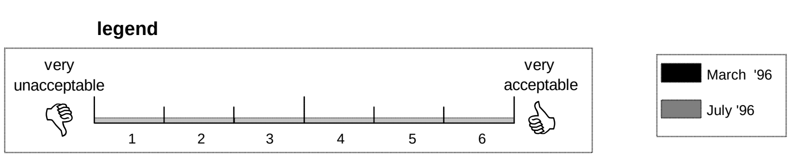
LIGHTING AND ACOUSTICAL COMFORT



	mean rating	% unacceptable*
March '96	3.7	28%
July '96	4.0	7%



	mean rating	% unacceptable*
March '96	3.6	19%
July '96	3.5	33%

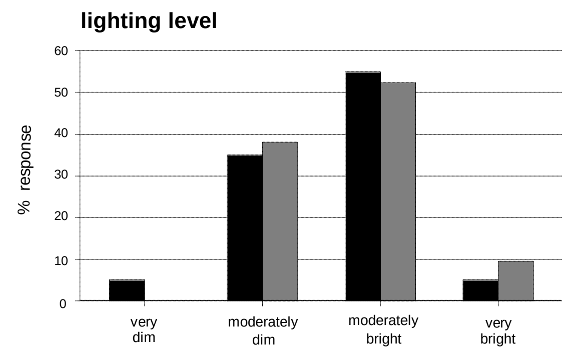


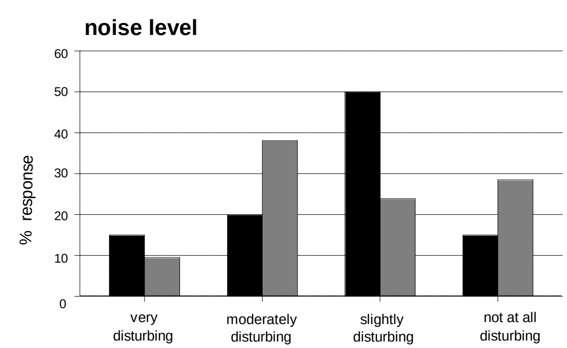
* The %unacceptable is the percentage of respondents that indicated conditions were moderately to very unacceptable (bins 1-2 on the scale).

Figure 36b

Control Group (sample size = 21)
Environmental Perception at time of sampling

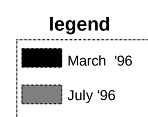
LIGHTING AND ACOUSTICAL COMFORT





measured background sound level (dBA)

	mean	std.dev.
March '96	44	2
July '96	46	4



show results for the control group. The changes observed between the baseline and post-PEM surveys are very similar to the trends found in the occupant satisfaction results (discussed previously).

PEM Group. Substantial increases in the mean acceptability rating are found for most of the seven environmental factors for the PEM group after the PEM units have been installed. These improvements take place despite the fact that the mean acceptability ratings for the PEM group during the baseline survey were actually quite good. Sixteen percent or fewer of the occupants rated the seven environmental factors as being moderately to very unacceptable (bins 1-2: defined to be % unacceptable) during the March survey. During the post-PEM July survey, however, the % unacceptable decreased to 0% (it was already 0% for odors during the baseline survey) for all environmental factors except noise level, indicating a high level of overall acceptability for most occupants.

The thermal sensation results (Figure 31b) indicate that even though there were about 10% fewer respondents in the post-PEM survey who felt their thermal sensation was neutral, about 10% more respondents preferred to have no change in their thermal environment. This thermal preference result is directly related to a larger than 10% reduction in occupants wishing to be cooler, presumably because of the increased cooling capability of the PEM air flow. The average measured temperature at the workstations was slightly cooler during the post-PEM survey (22.7°C) than the baseline survey (22.9°C) and the background dataset (23.0°C). The post-PEM air movement results show that the respondents perceive their air movement to be higher than during the baseline survey, as expected. This is reflected in the average measured velocity, which increases from 0.08 to 0.11 m/s. Air movement preference also shows a dramatic decrease in those wanting higher air movement, as it drops from 54% in the baseline survey to only 15% in the post-PEM survey.

The results for occupant perception of air quality by the PEM group are shown in Figure 32. The acceptability of the ventilation quality (perception of stuffiness) increases from the baseline to post-PEM survey due to a substantial decrease in those stating that the air is “not at all stuffy.” Average CO_2 measurements at the workstations were 543 ppm during the baseline survey and 505 ppm during the post-PEM survey, both well below the ASHRAE upper limit guideline of 1000 ppm. The local air flow from the PEMs may be responsible for the reduction in average measured CO_2 level, as well as the larger standard deviation (some PEMs may be turned on, others may be turned off or directed toward the partition, producing larger variability between workstations).

No change in the acceptability of odors was observed between the two surveys. This environmental factor was already highly rated. The acceptability of humidity conditions increases during the post-PEM survey, but the perception of what level the humidity actually is does not change between surveys. This suggests that increases in humidity acceptability may be due to improvements in the overall thermal environment.

Finally, lighting level showed some increase in acceptability between surveys, presumably due to the improved task lighting control with the PEM. Noise level also showed a slight improvement in acceptability, although the average measured background sound level (dBA) was essentially equal in both surveys.

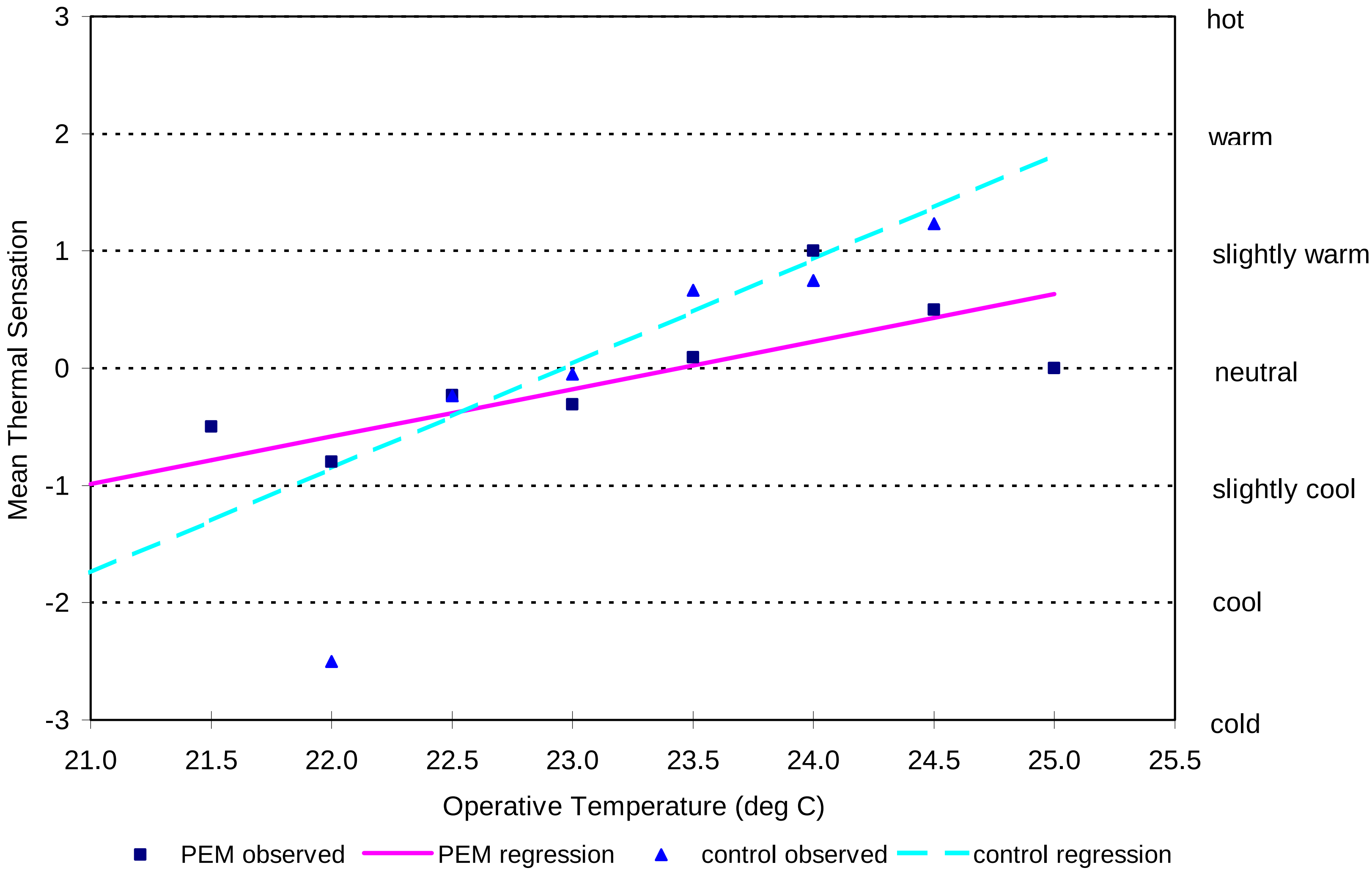
Control Group. Among the seven environmental factors considered by the control group, mean acceptability ratings increased slightly between the baseline (March) and post-PEM (July) surveys for two (temperature level and lighting level), while all others showed slight decreases (Figures 34-36). As would be expected for the control group, none of these changes were substantially large in magnitude. The % unacceptable during the baseline (March) survey ranged from 5% (odors) to 28% (lighting level), while the corresponding values during the post-PEM (July) survey ranged from 7% (lighting level) to 33% (noise level).

In Figure 34b, the thermal sensation and thermal preference results indicate that, in comparison to the background dataset, more people thought the conditions were slightly cool and would prefer to be warmer for both surveys. This finding is further supported by the average measured temperature at the workstations, which was 22.6°C during the March survey, 22.9°C during the July survey, and 23.0°C for the background dataset. For air movement, nearly 80% of the respondents in the control group perceived it to be moderately still or very still for both surveys. Unlike the PEM group, which showed a significant change between surveys, almost 60% in both surveys indicated a preference for higher air movement. With no local air supply available to members of the control group, this is not a surprising result, and is similar to findings from many other field studies in office buildings with conventional overhead air distribution systems. Average measured air velocities from both surveys were nearly identical to each other and to that of the background dataset.

Thermal Sensation Vote

Subjects were asked during the "environmental conditions right now" portion of the survey to indicate their thermal sensation on the standard seven-point scale, ranging from -3 to +3 and corresponding to the range from cold to hot (see page 10 of the survey in Appendix A). By plotting these subjective responses versus room temperature (as measured by the portable measurement cart at each subject's workstation), we investigated the sensitivity of thermal sensation to variations in temperature. These data were analyzed by grouping together individual thermal sensation votes into half-degree bins of operative temperature, and then calculating the mean thermal sensation for that group of responses. Operative temperature was used instead of simply room air temperature because it takes into account both air and radiant temperatures. A linear regression line, weighted by the number of subjects within each bin, was then fitted to these mean thermal sensation values. The results are presented in Figure 37 for all July test periods and for all three buildings. By including the normal, set-up, and setback test periods, a wider range of operative temperatures achieved during this field study were available for analysis. Individual data points that formed the basis for the calculation of mean thermal sensation in Figure 37 included all valid workstation visits

Figure 37. Mean Binned Thermal Sensation Votes:
PEM group vs. control group; all buildings; July 1996



for which there existed both subjective survey results for “environmental conditions right now,” and physical measurements of the local workstation environment. The results were separated for comparison into the PEM group and the control group. The PEM group consisted of 54 workstation visits (observations); the control group consisted of
60 observations. For each group, the mean thermal sensation values (“observed”) and the best-fit regression line are shown.

The regression lines indicate that workers in the control group were more than twice as sensitive to changes in temperature as those in the PEM group. For the control group, a 1°C change in operative temperature corresponded to nearly a one unit (0.89) change in mean thermal sensation. For the PEM group, the corresponding change in mean thermal sensation was only 0.40. These results suggest that in comparison to the control group, the individual thermal control capabilities of the PEM allow a larger percentage of the PEM subjects to maintain comfortable conditions over a wider range of ambient temperatures.

Worker Productivity

It is often assumed (largely from subjective analyses and anecdotal evidence) that improvements in worker satisfaction will lead to corresponding increases in worker productivity. The difficulty lies in defining an accurate measure of productivity and correspondingly quantifying the relationship between satisfaction and productivity. The productivity study by Kroner et al. (1992) is the most relevant to the current field study in that it investigated the impact on worker productivity of moving from an old headquarters building to a newly designed office building that included installation of PEM units in each occupant’s workstation. Through their analysis of data, they estimated that the PEMs were responsible for a 2.8% increase in worker productivity. Kroner also surveyed the occupants to determine their satisfaction level with a range of environmental factors. This allowed them to investigate the link between individual productivity measurements and individual attitude measurements. They found that there was a “statistically significant positive association between the change in productivity and change in ‘overall satisfaction with the workspace’ at the level of the individual worker.”

Although the current study did not attempt to measure worker productivity, if we make the assumption that overall occupant satisfaction and productivity are positively correlated in a similar manner to that of the Kroner productivity study, we can make a rough estimate of the impact on productivity of installing the PEMs in these three Bank of America buildings. Overall occupant satisfaction for both the Kroner study and the current study were based on survey responses to questions addressing the same environmental factors. In Kroner’s study, overall occupant satisfaction in the old building was approximately 2.6 on a 5-point satisfaction scale, increasing to about 3.9 after 4 months in the new building. This increase of 1.3 on a 5-point scale (normalized 26% increase) corresponded to a 16% increase in productivity (this increase clearly takes into account all environmental improvements in the new building, not only just the PEM units). In the current study, the average overall satisfaction during the baseline measurements was

4.05 on a 6-point scale, increasing to 4.46 three months after installation of the PEM units (Figure 11). This increase of 0.4 on a 6-point scale (normalized 7% increase) is about one fourth the magnitude of the noted increase in overall satisfaction in the Kroner study, implying a potential increase in productivity on the order of 4%. Clearly there are differences between the buildings, organizations, and type of work being performed in these two studies. But if satisfaction does correlate well with productivity, the current data do suggest that installation of the PEM units could produce improvements in productivity of a similar size (2.8%) to that found in the Kroner study.

Occupant Use of PEM Units

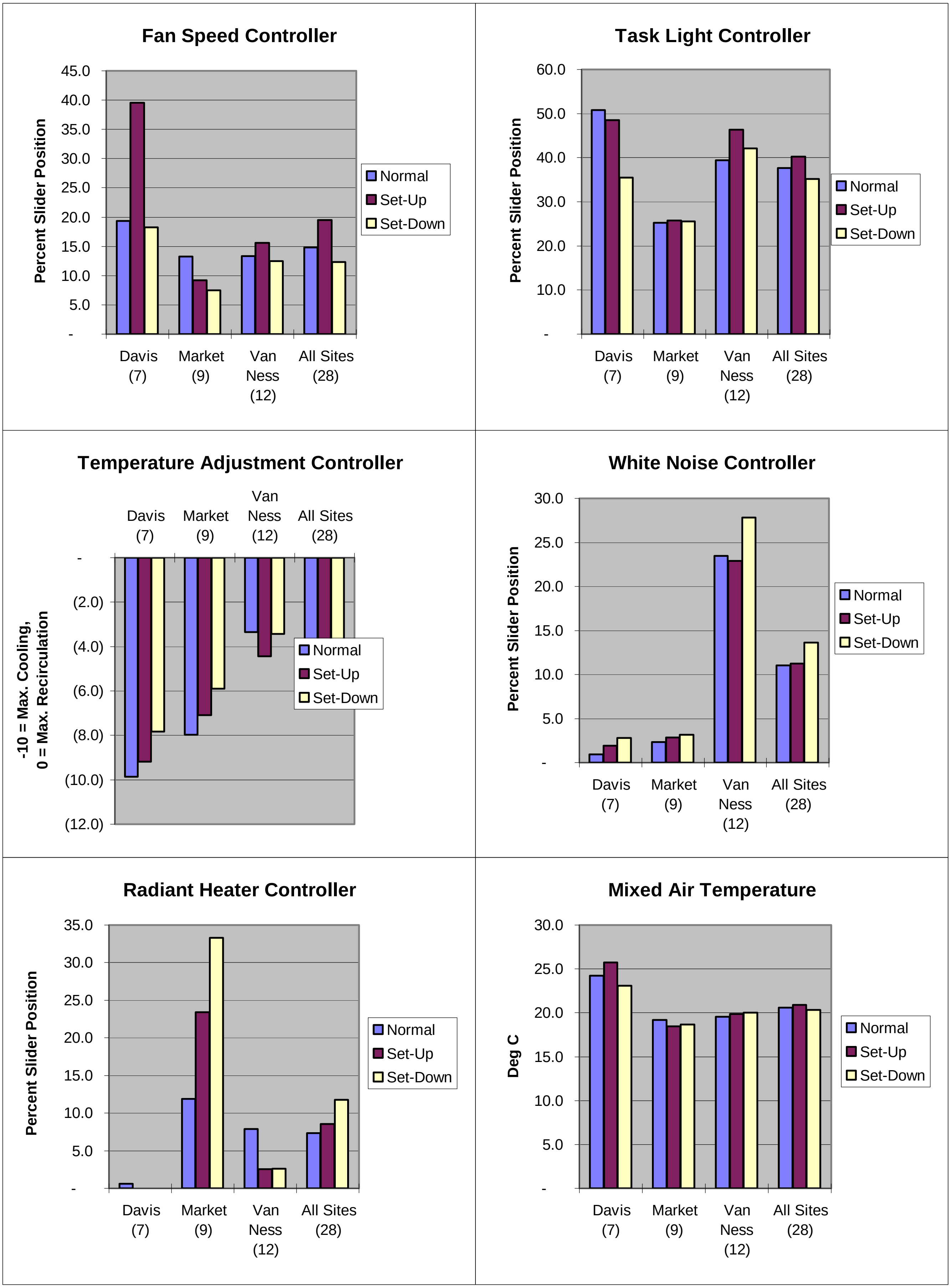
Two types of analyses were carried out on the PEM control data (occupant use patterns) collected through the PEM monitoring network. The first aggregated all data into Figure 38 comparing the average control position for each of the three July test periods by site. The second approach looked at a three week period for each PEM and observed the use patterns and identified typical examples and similarities for all PEMs. As described earlier, the PEM control results are based on data collected during the period July 8 through August 4, 1996.

Aggregated PEM Control Data

Figure 38 presents the average position of each PEM control. There are six bar graphs, each one representing one of the controls or points monitored. With the exception of mixed air temperature, all bar graphs represent occupant-adjustable controls. The three thermal controls (fan speed, temperature adjustment, and radiant heater) are located on the left side of the figure. Within each bar graph there are 4 sets of bars, one for each of three sites and a fourth for overall average. Each set consists of three bars - one for the normal period, one for the set-up period, and one for the set-down period. All data available up to July 19, 1996 was included in the normal period - approximately 12 working days. A limited amount of data is missing due to a temporarily disconnected Companion device, phoneline noise, or a PEM (connection problem?) that reported erroneous data. For the set-down and set-up periods the day of the site visit plus the preceding day were included in this figure. The bars represent averages. An average was found for each workstation and the overall average of these individual averages was found for each site. The number in brackets indicates the number of PEMs from each site selected for this analysis. Not shown is the orientation of the PEM supply vents; it is conceivable that occupants would adjust these to provide either increased or decreased cooling. The key results from this analysis include:

- The occupants in 560 Davis showed a clear response to the set-up period by utilizing the fans. The average control setting doubled from 20% to 40%. Since the PEM units at Davis used only recirculated room air (no ducted cool primary air), the occupants may have needed increased air motion to provide the necessary cooling.
- Considering that the set-up period at 1455 Market was actually a set-down and the set-down was a larger set-down, the trends in the three thermal controls indicate that occupants were adjusting their PEMs to adapt to the different environments. As

Figure 38: Aggregated PEM Use Data



space temperature decreased, fan speed decreased, the temperature slider was moved up to provide warmer recirculated air rather than cool primary air, and radiant heater use also increased. All three of these responses combined indicate that occupants were trying to create a warmer environment in response to cooler ambient conditions.

- In One S. Van Ness, moderate set-up and set-down temperatures were achieved. There are indications that occupants used all three thermal controls to personalize their environments, but the differences between the three test periods are rather small and do not follow a consistent pattern. A more obvious response in One S. Van Ness may have been observed if the set-up and set-down conditions had differed more from normal temperatures.
- The task light controls were used extensively in all three sites. The fact that an ambient lighting system which was designed to meet task needs is present in all sites and task lights are still desired suggests one of two things: the lumen maintenance of the ambient system is poor; or, the ambient system as designed is insufficient for task needs. Where PEMs are being designed into new offices, a case can be made to design the overhead lighting system for ambient needs only and install task lights for task needs. This will not only result in a more efficient lighting system, but will improve occupant satisfaction.
- The white noise generators were really only used at the Van Ness site. The workstations utilizing this control were located mostly in one area where occupants use telephones extensively.
- Overall, all five controls were utilized by the occupants with PEM units.

Individual Use Patterns

Though aggregated data such as Figure 38 are useful, it does not tell the complete story -- the individuality of occupants and their use patterns are lost. Given that the task lights were used extensively in all three sites and that the white noise generator is a control of secondary interest, the focus in analyzing the use patterns of individuals was on the thermal controls. In terms of thermal control patterns, it was difficult to find similarities between individual occupants. This was due in part to the uniqueness of the way the PEMs were installed at each site, as well as differences in the way each building was operated. Distinguishing features of each site include the following:

- At One S. Van Ness the static pressure in the duct supplying the PEMs was set too high causing cool drafts. A response to this was that several occupants turned the vents away towards the partitions and turned the temperature slider up to recirculation (warmer). Since the pressure of the room was less than that of the supply duct, this had the effect of both increasing temperature and reducing the amount of air supplied.
- At 1455 Market, the ambient temperature conditions were consistently cool leading to a higher use of the radiant heaters. In direct relation to this, the primary air tem-

perature was also very cool, leading to reduced use of the fans. Vents were also often pointed towards the partitions.

- At 560 Davis the units were not ducted to primary air, so only recirculated (room temperature) air was supplied, regardless of the temperature slider position. Thus, the only way occupants could respond to a need for cooling was to turn down the heater, increase air movement with the fan, and point the supply vents towards themselves.

Table 6 summarizes the use of the PEMs in the context of the set-up and set-down periods. A more detailed discussion by site and by PEM follows. The table indicates by site and overall the number of occupants who showed a response to the set-up or set-down periods or who used the thermal controls significantly over the three week period of study (July 15 - August 1, 1996). A response to the set-up period was defined as some response by the occupant to reduce the amount of heat produced by the PEM or to increase the amount of cooling provided by the PEM. The converse was true for the set-down period. An occupant was defined as showing some thermal response if they used any of their thermal controls over the three week period to some degree. Some degree in this context would mean for a few hours on several occasions. If an occupant used one of the thermal controls for one hour in the study period, their use would not be considered a thermal response.

Table 6. Number of Occupants Using PEM Thermal Controls (responses/PEMs)

	Van Ness	Market	Davis	Overall
Cooling Response	5/14	0/0	6/7	11/21
Heating Response	5/14	6/11	3/7	14/32
Thermal Response	12/14	10/11	6/7	28/32

The table shows that there was some type of response to the set-up and set-down periods by approximately half of the occupants. Overall, 88% of the occupants used the PEMs thermal controls to some extent over the three week period.

Observing the individual use patterns suggests that the occupants generally do not adjust their PEMs unless the ambient conditions change. The few occupants who do adjust their PEMs within a day do so only a couple of times and for the most part they adjust the controls as if it was a switch or a 2-3 position controller. No occupant fine tuned their PEM as if it was a continuous analog control. Presented below are a few examples of individual use patterns of the PEM controls for each of the three test sites. Comments and figures related to all PEMs and their observed use patterns are provided in Appendix C.

560 Davis Street. Davis provided a number of good examples of how occupants used the PEM fan to cool themselves during the set-up period. Davis was the only site in which we were really able to elevate the ambient temperatures substantially. Since there was no cool primary air supplied to the units, the air movement provided by the fan was the only control available to users to cool themselves. There was virtually no use of the white noise generator in Davis.

Of the seven workstations which were occupied and for which we have PEM data, six of them used the fan to some degree during the set-up period to provide additional cooling. Three of these workstations used reduced fan speeds to respond to the set-down period. Six of the seven occupants used controls beyond the task light substantially during some portion of the three week study period.

Figure 39 is the first trendplot discussed showing occupant use patterns of the PEMs over a three week period, it is worthwhile discussing how to read these graphs. Three of the six PEM control parameters shown on the figure use the same line type, but they appear in different parts of the chart area so they can be distinguished. The occupancy is a binary point and will always be zero (unoccupied) or five (occupied) on the left scale. The temperature slider is always less than or equal to zero - it is the only point which has negative values. Full primary air is indicated by a value of -10, which is the coolest air temperature setting, while zero indicates minimum primary air with mostly recirculated air, and is thus the warmest supply air temperature. The white noise generator is non-zero only if the workstation is occupied despite the slider position. Therefore, it jumps up and down with the exact same pattern as occupancy, but has much higher values than occupancy. The radiant heater slider is plotted with a thicker solid line and is thus unique. The two dashed lines represent the fan and the task light; the dash lengths are sufficiently different that they can be distinguished from each other.

Figure 39 shows an example of an occupant who used the fan in the 50-70% range during set-up on all days. This occupant also used the task light extensively. Figure 40 shows another occupant responding to the set-up period with an increased use of the fan. This occupant used the task light consistently and used the white noise generator on a few days to apparently mask the fan noise.

1455 Market Street. Not all occupants responded to the set-down in the same way. Some occupants reduced fan speeds, some adjusted the mixed air temperature, while others used the heater. Some used all of the above tactics. It is unclear whether occupants really understood the temperature slider as some used it as a switch. The set-up period was actually a set-down so it is meaningless to talk about a cooling response to elevated space temperatures at 1455 Market. There were 6 of the 11 PEMs with good data that displayed some form of heating response to the set down period. Overall, ten of the eleven PEMs that were occupied and for which good data were available exhibited some use of controls beyond the task light and white noise generator.

Figure 39. Individual PEM Use Patterns: Davis Example 3

July 15 through August 2, 1996

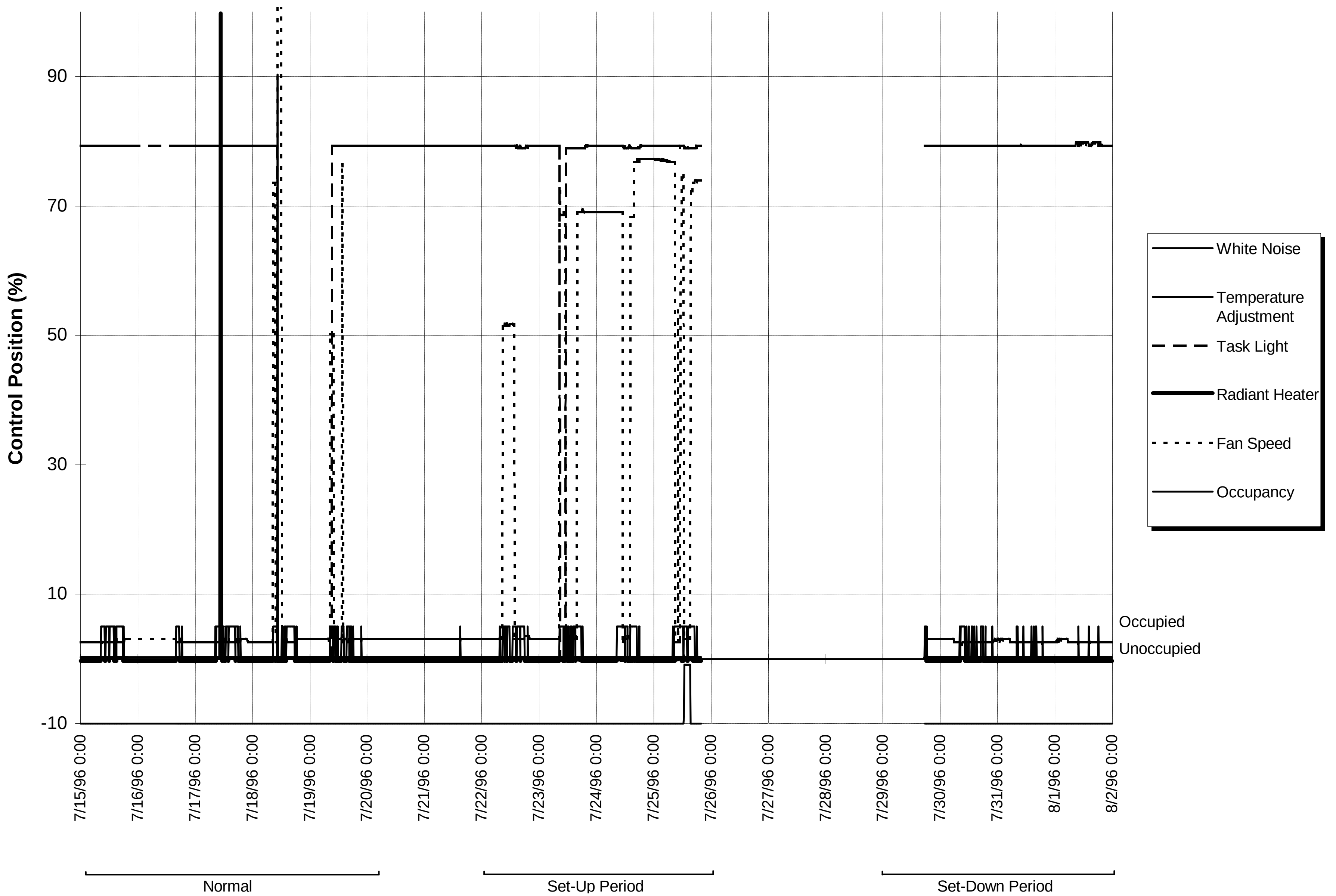


Figure 40. Individual PEM Use Patterns: Davis Example 5

July 15 through August 2, 1996

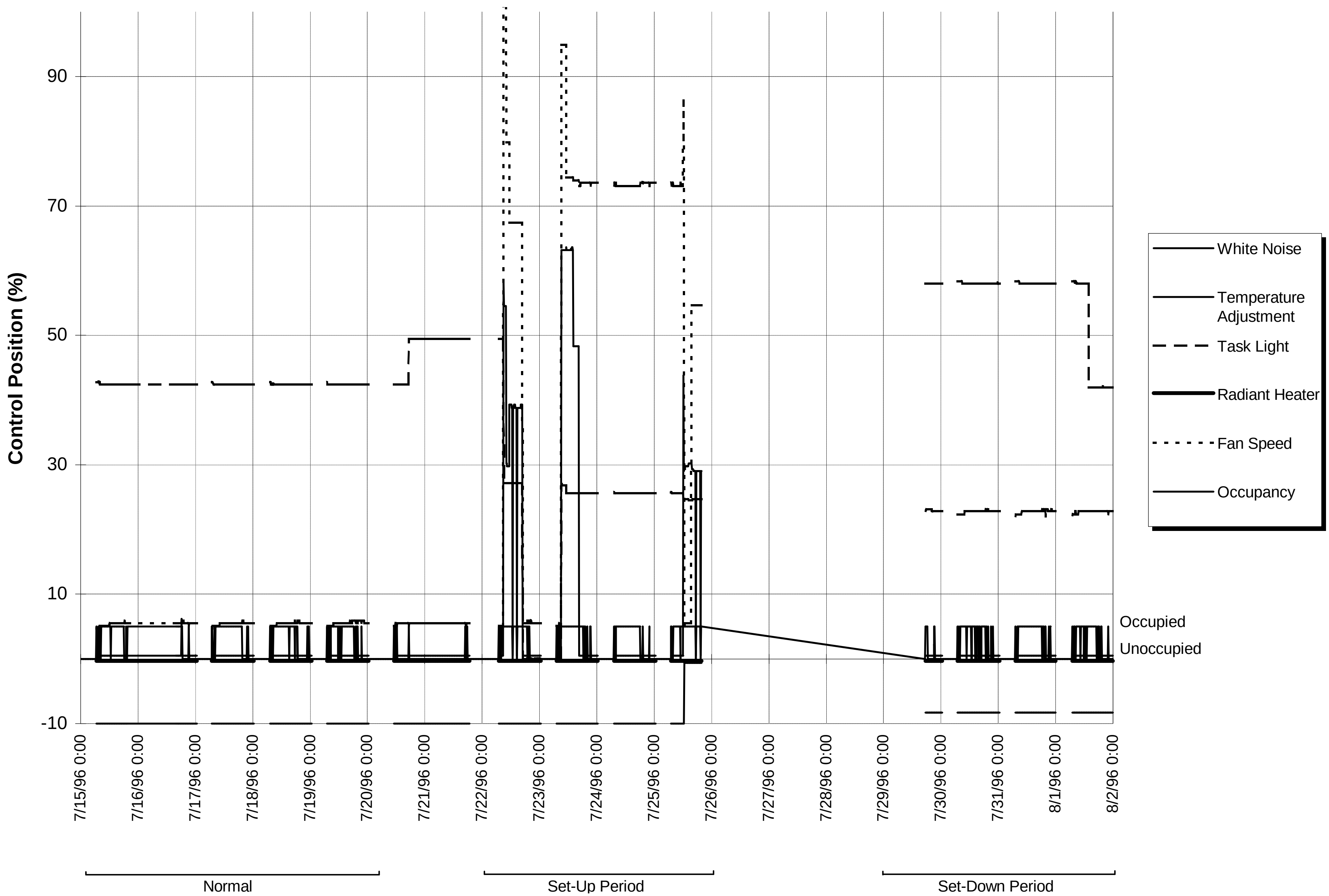


Figure 41. Individual PEM Use Patterns: Market Example 3

July 15 through August 2, 1996

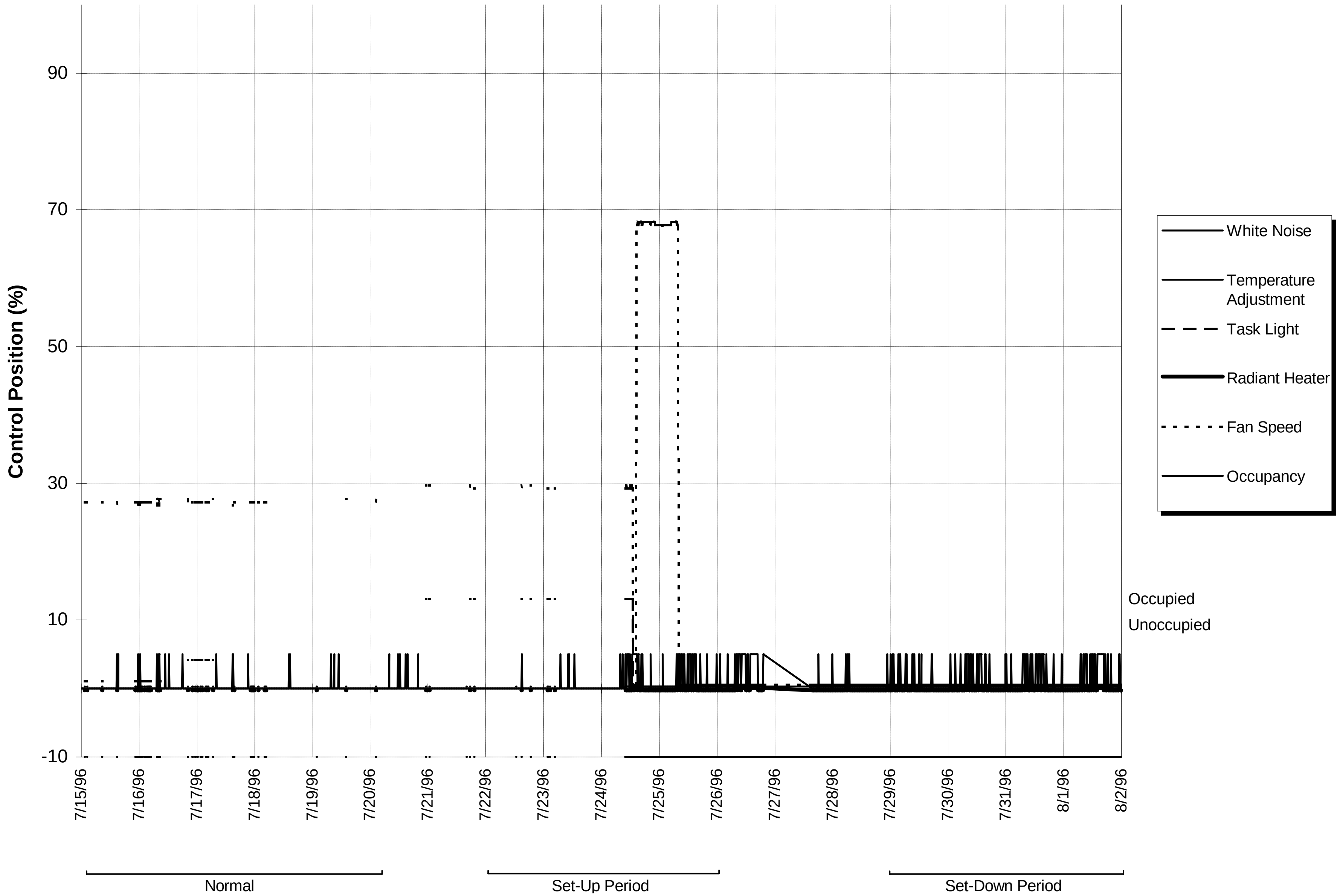


Figure 42. Individual PEM Use Patterns: Market Example 9

July 15 through August 2, 1996

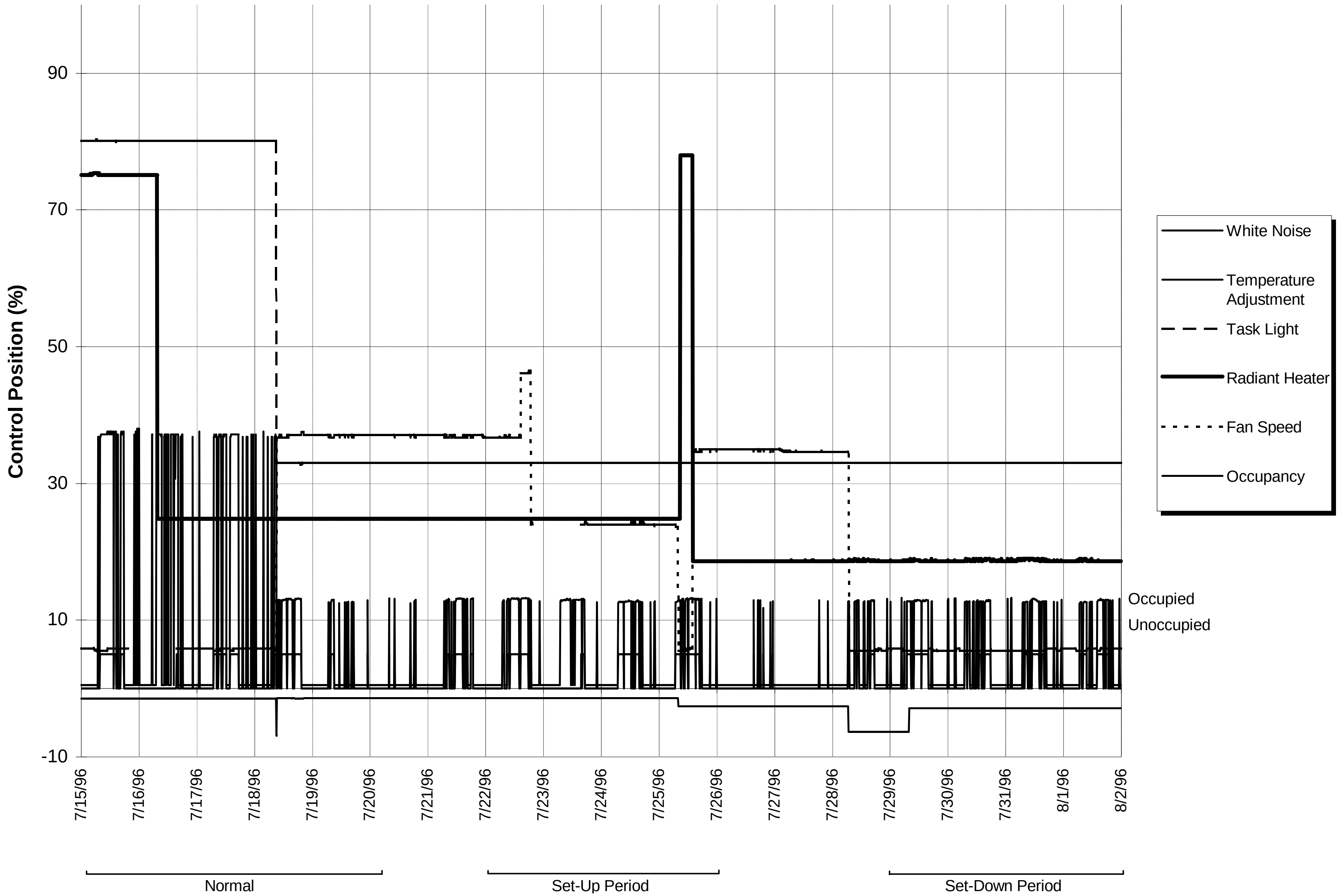


Figure 41 shows an occupant in 1455 Market who used the fan during the neutral period, but increased the fan speed during the set-up period for one day to apparently cool themselves. The fan was turned off completely during the set-down period. This occupant is one of few who did not use their task light.

Figure 42 provides a good example of an occupant who was using all three thermal controls to meet their needs. The occupant utilized the task light and was one of few who used the white noise generator in 1455 Market. The occupant used the fan the least during the set-down period.

The occupant use pattern shown in Figure 43 shows perhaps the clearest correlation with the changes in space conditions. As space temperature decreased from left to right, the radiant heater was used more and more and the temperature slider was put to full recirculation during the coldest period. The task light was also used consistently.

One S. Van Ness Avenue. Though the set-up and set-down periods at Van Ness were not that extreme, there were still indications that people were using their PEMs to respond to uncomfortable ambient conditions. Fourteen of the workstations with PEMs were occupied through the study period. The task lights and white noise generators were used extensively in many PEMs. Seven of 14 occupied workstations containing PEMs used their white noise generators extensively. These were primarily all on one side of the office. There was really only one workstation that did not use the task light control. There was only one user that did not use the thermal controls of their PEMs during the 3-week period analyzed. Five of the fourteen occupants with PEMs showed a response to the set-up period. Five occupants also showed a response to the set-down period. Twelve of fourteen occupants used the thermal controls to some extent over the three week study period.

The interesting occupant use pattern seen in Figure 44 is one of the few cases where the controls are used more like an analog control adjusted several times a day. The radiant heater is used extensively and at 4-5 different settings through the three week period. On some days the amount of heat was adjusted several times. The temperature slider was positioned at full recirculation.

One of the more active users of the white noise generator is seen in Figure 45. This occupant also used the fan extensively and increased fan speed for the set-up period. For the set-down period fan speed was reduced and the temperature slider was positioned to provide more recirculated air than had been used previously. Knowing that there were pressurization problems in Van Ness, having the temperature slider in the down position is similar to increasing fan speed so moving the slider up is like reducing fan speed regardless of air temperatures.

The final example of occupant use patterns presented in Figure 46 shows an occupant who clearly responded to the set-up period with the fan and radiant heater. Though the fan was turned down during the set-down period, the radiant heater was not re-positioned to comparable levels seen during the normal period. Note the task light is left in the same position.

Figure 43. Individual PEM Use Patterns: Market Example 10

July 15 through August 2, 1996

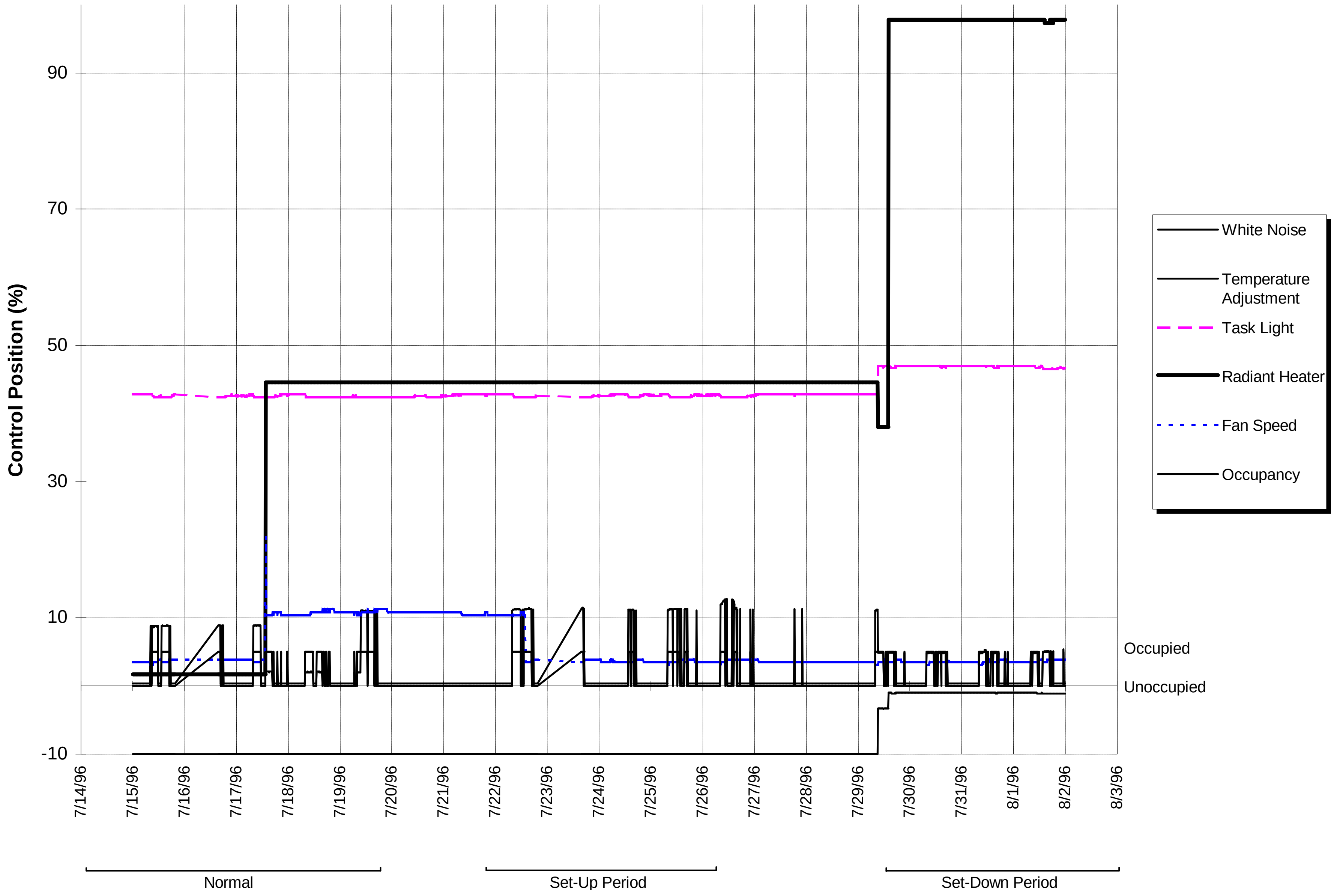


Figure 44. Individual PEM Use Patterns: Van Ness Example 5

July 15 through August 2, 1996

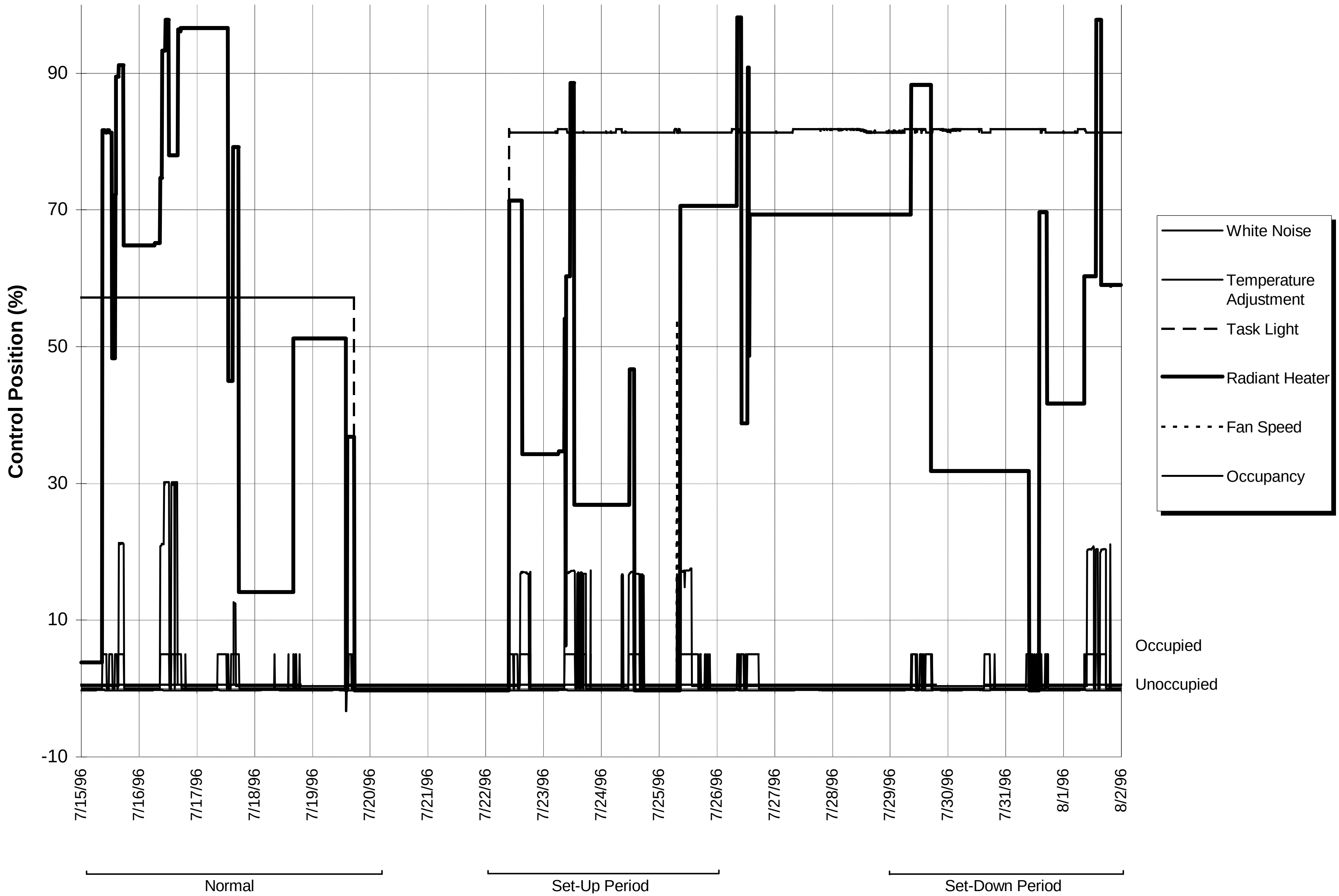


Figure 45. Individual PEM Use Patterns:Van Ness Example 11

July 15 through August 2, 1996

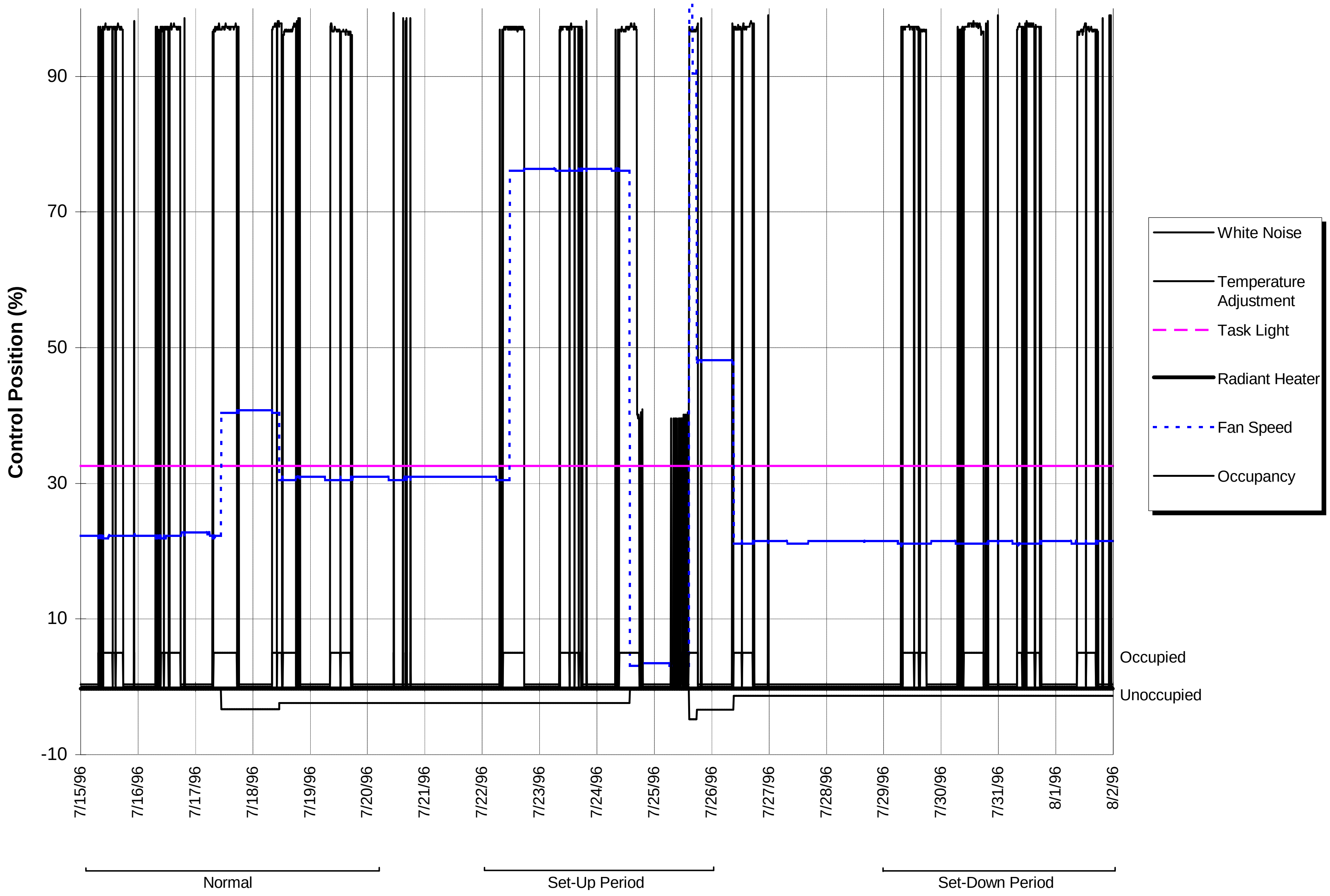
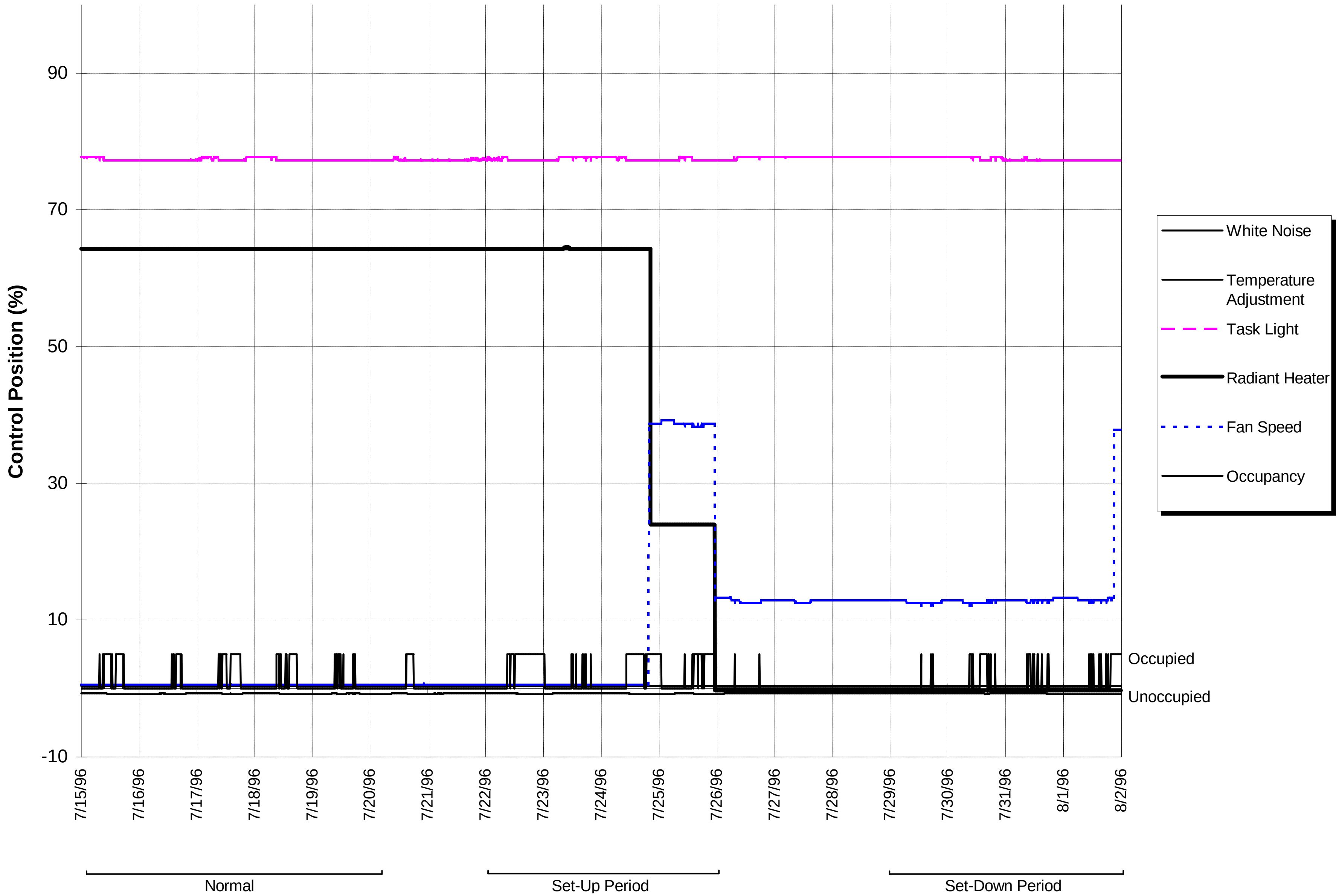


Figure 46. Individual PEM Use Patterns:Van Ness Example 13

July 15 through August 2, 1996



SUMMARY AND CONCLUSIONS

This report describes the results of a field study performed by UC Berkeley in collaboration with Bank of America Corporate Real Estate and Johnson Controls World Services. The purpose of the study was to assess the impact of installing Personal Environmental Modules (PEMs) at 42 selected workstations within three Bank of America office buildings in San Francisco. The PEM is an example of a relatively new approach to space conditioning and control in which individuals are given the ability to control critical environmental conditions within their local work area (e.g., workstation). Each office worker can adjust air flow, temperature, lighting, and acoustic characteristics to maintain their own personal comfort levels. By improving employee satisfaction and well-being, it is anticipated that the installation of a PEM system could lead to increased worker productivity and effectiveness.

The major conclusions are as follows:

1. Installation of the PEM units increased overall occupant satisfaction in all six building assessment categories studied. The largest increases occurred for thermal quality, acoustical quality, and air quality. In terms of specific environmental factors, increased occupant satisfaction levels among the PEM group were strongly significant ($p\text{-value} < 0.05$) in comparison to changes within the control group for temperature and temperature control, and were somewhat significant ($0.05 \leq p\text{-value} < 0.10$) for air movement, lighting level, visual quality of computer screen, background noise, freedom from distracting noises, and conversational privacy. Almost all of these factors are addressed by the personal control capabilities of the PEM.

2. The improvements in thermal quality and air quality produced by the installation of the PEMs is noteworthy because it runs contrary to the common trend among many recent field studies that have found thermal and air quality issues to usually be among the lowest rated categories for occupant satisfaction. In the post-installation survey, the PEM group gave these two categories their top two overall satisfaction ratings. In this same survey, the percent dissatisfied (defined as the percent of occupants indicating that they are either very or moderately dissatisfied) went to zero for all thermal quality factors, and was no higher than 6% for air quality factors. This result suggests that occupant complaints in these categories requiring response by building operators will be minimized.

3. Satisfaction ratings from both the March and July surveys were higher for all six assessment categories for the PEM group in comparison to the control group, indicating that the members of the PEM group were, in general, more satisfied with their work environment. Given this higher level of satisfaction in the PEM group, it is reasonable to assume that there would be less room for improvement after installation of the PEMs, making the findings of this study conservative. In comparison to an existing dataset based on surveys of 300 subjects in ten San Francisco Bay Area office buildings, both pre- and post-installation surveys from the PEM group had

equal or higher satisfaction ratings for all environmental factors, except background sound level. Satisfaction ratings from the control group were more comparable to this existing dataset, with some higher and some lower scores.

4. Acoustical quality was the most poorly rated assessment category in these three Bank of America office buildings. Dissatisfaction with conversational privacy was the biggest contributing environmental factor to this result. In particular, 63-64% of the control group were either very or moderately dissatisfied with their conversational privacy in both surveys. The corresponding ratings by the PEM group were 61% dissatisfied in the March survey, decreasing to 37% dissatisfied in the July survey.

5. The job impact rating results displayed similar trends to those observed for the work area satisfaction results. For the PEM group, increases in job impact rating between the baseline and post-installation surveys were strongly significant for thermal quality, air quality, and acoustical quality. There were no significant changes for the control group, suggesting that the improvements in these three environmental factors produced by the PEMs had a positive impact on the occupants' ability to work effectively that would not have occurred if the PEMs were not installed.

6. Although the current study did not attempt to measure worker productivity, a rough estimate can be made of the impact on productivity of installing the PEMs in these three Bank of America buildings by comparison with the well-known West Bend Mutual Study [Kroner et al. 1992]. The West Bend Study investigated the impact on worker productivity of moving from an old headquarters building to a newly designed office building that included installation of PEM units in each occupant's workstation. If we make the assumption that overall occupant satisfaction and productivity are correlated in roughly a similar manner to that of the Kroner productivity study, the current data suggest that installation of the PEM units could produce improvements in productivity of a similar size (2.8%) to that found in the Kroner study.

7. When responses from the PEM workers in 560 Davis Street were split out from the other buildings, the performance of the PEM in comparison to conditions prior to installation was slightly less favorable than that reported in the other two buildings. This may be due in part to the fact that the PEM units in Davis Street were only recirculating room air to the occupants -- no cooler and fresh ventilation air is provided through the PEM nozzles on the desks. However, the small number of Davis occupants (6) made the analysis statistically inconclusive.

8. Within the PEM group, the mean acceptability rating at the time of measurement ("environmental conditions right now") increased substantially from the baseline to post-PEM surveys for three factors (temperature level, air movement, and ventilation quality), and increased moderately for three others (humidity, lighting

level, and noise level). The percent unacceptable (defined as the percent of occupants indicating that they find the conditions to be either very or moderately unacceptable) decreased to zero for all environmental factors except noise level, representing a high level of overall acceptability for most occupants.

9. The increased satisfaction ratings for air movement were associated with the higher localized air movement provided by the PEM units. In general, the occupants chose to increase the local air movement. This was reflected in the average measured velocity, which increased from 0.08 to 0.11 m/s between surveys, as well as the increased perception of air movement shown in the survey results. The preference for higher air motion within the PEM group also decreased from 54% in the baseline survey to only 15% in the post-PEM survey, and 77% (up from 36%) indicated that no change was required. By comparison, almost 60% of the control group subjects indicated a preference for higher air movement in both surveys.

10. Survey results indicated that more than 80% of the PEM users adjusted the PEM controls less frequently than once each day. This suggests that it is more important for workers to have the ability to control their local environment than it is for them to actually make a large number of control adjustments. Monitored occupant use patterns found that about half of the PEM group adjusted the thermal controls in a way that was consistent with the change in temperature during the set-up and set-down periods. Overall, 88% of the PEM group used the PEM thermal controls to some extent (although rather infrequently) over the July test period. Several examples from different individual PEM users demonstrated how occupants understood quite extensively how to use the PEM to control their local environment.

11. Some problems with the PEM system causing dissatisfaction among the occupants were observed, although in most cases adverse impacts could be avoided or minimized. (1) The installation into each workstation was quite intrusive, requiring at least two large holes to be drilled through the work surface. The occupants should be well-informed of the proposed design and placement of the supply outlets and controls, to avoid unnecessarily upsetting them during installation. (2) In one of the buildings, during the first few weeks after installation, the PEM units were consistently overpressurized by the air supply coming from the main HVAC system. This problem was eventually corrected, but it did lead to initial increased dissatisfaction among some of the PEM users because they had too much air supply, even when they turned down the fan control to its minimum setting. Clearly, it is important to achieve good control of the air being supplied to the PEM users, so that the PEM can be controlled in its intended manner. (3) In the above described overpressure problem, it was possible to reduce air flows by moving the air temperature control to its warmest setting, thereby closing down the damper on the overpressurized primary air supply, and opening the damper to allow more recirculated (warmer) room air to be supplied through the PEM nozzles. Although this was a solution that was available during that initial period when problems were occurring, all of the occupants were not made aware of how these controls could be used. As with any new

technology, occupants should be properly trained to allow the operation and control of the PEM system to be optimized.

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