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Windows and Offices: A Study of Office Worker Performance and the Indoor Environment

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

This document is one of 33 technical attachments to the final report of a larger research effort called *Integrated Energy Systems: Productivity and Building Science Program* (Program) as part of the PIER Program funded by the California Energy Commission (Commission) and managed by the New Buildings Institute.

As the name suggests, it is not individual building components, equipment, or materials that optimize energy efficiency. Instead, energy efficiency is improved through the integrated design, construction, and operation of building systems. The *Integrated Energy Systems: Productivity and Building Science Program* research addressed six areas:

- ***Productivity and Interior Environments***
- ***Integrated Design of Large Commercial HVAC Systems***
- ***Integrated Design of Small Commercial HVAC Systems***
- ***Integrated Design of Commercial Building Ceiling Systems***
- ***Integrated Design of Residential Ducting & Air Flow Systems***
- ***Outdoor Lighting Baseline Assessment***

The Program's final report (Commission publication #P500-03-082) and its attachments are intended to provide a complete record of the objectives, methods, findings and accomplishments of the *Integrated Energy Systems: Productivity and Building Science Program*. The final report and attachments are highly applicable to architects, designers, contractors, building owners and operators, manufacturers, researchers, and the energy efficiency community.

This Windows and Offices Report (Product #2.6.10) is a part of the final report within the Productivity and Interior Environments research area and presents the results of a study into relationships between the indoor office environment and worker performance.

The Buildings Program Area within the Public Interest Energy Research (PIER) Program produced these documents as part of a multi-project programmatic contract (#400-99-413). The Buildings Program includes new and existing buildings in both the residential and the non-residential sectors. The program seeks to decrease building energy use through research that will develop or improve energy efficient technologies, strategies, tools, and building performance evaluation methods.

For other reports produced within this contract or to obtain more information on the PIER Program, please visit www.energy.ca.gov/pier/buildings or contact the Commission's Publications Unit at 916-654-5200. All reports, guidelines and attachments are also publicly available at www.newbuildings.org/pier.

ABSTRACT

This study reports on a statistical investigation into the influences indoor physical environment has on office worker performance, especially daylight and view, and secondarily ventilation and thermal comfort. Two different studies were conducted at the same organization, the Sacramento Municipal Utility District. The first study looked at 100 workers in an incoming call center, whose performance was continuously tracked by a computer system and measured in terms of time to handle each call. The second “Desktop” study examined the performance of 200 other office workers on a series of short cognitive assessment tests, taken at each individual's desktop computer. Extensive data was collected about the physical environment at each office worker's cubicle. The Desktop study also included a questionnaire about workers’ comfort conditions and health symptoms. Better access to views consistently predicted better performance in both the Call Center and Desktop study. Daylight levels and ventilation rates were found significant in a few of the statistical models tested. The studies have shown that indoor environmental conditions can have a measurable relationship to changes in office worker performance and have established a range of likely effect sizes that other researchers can use to refine the needs of future studies.

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EXECUTIVE SUMMARY

This study reports on an investigation into the influences indoor physical environment has on office worker performance. It is particularly concerned with the potential contributions of windows and daylight to improved performance by office workers. Two different studies were conducted at the same organization, the Sacramento Municipal Utility District. The first study looked at 100 workers in an incoming call center, whose performance was continuously tracked by a computer system and measured in terms of time to handle each call. The second study examined the performance of 200 other office workers on a series of short cognitive assessment tests, taken at each individual's desktop computer.

The study sites provided a range of daylight, view and ventilation conditions, while providing a relatively uniform environment for other potential influences on worker performance. All of the office work considered was computer-based, based on self-illuminated tasks. Extensive data was collected about the physical environment at each office worker's cubicle. Multivariate regression analysis was used to control for other potential influences, such as age or employment status. A variety of statistical models were tested to determine if any of the variations in environmental conditions, either between workers or during different time periods for a given worker, were significantly associated with differences in worker performance.

The studies found several physical conditions that were significantly associated ($p<0.10$) with worker performance, when controlling for other influences. Having a better view out of a window, gauged primarily by the size of the view and secondarily by greater vegetation content, was most consistently associated with better worker performance in six out of eight outcomes considered. Workers in the Call Center were found to process calls 6% to 12% faster when they had the best possible view versus those with no view. Office workers were found to perform 10% to 25% better on tests of mental function and memory recall when they had the best possible view versus those with no view. Furthermore, office worker self reports of better health conditions were strongly associated with better views. Those workers in the Desktop study with the best views were the least likely to report negative health symptoms. Reports of increased fatigue were most strongly associated with a lack of view.

Other variables related to view were also found significant. In the Call Center higher cubicle partitions were associated with slower performance. In the Desktop study glare potential from windows was found to have a significant negative effect on performance in three of the five mental function assessment tests. In the three tests, the greater the glare potential from primary view windows, the worse the office worker performance, decreasing by 15% to 21%, all other things being equal.

Horizontal daylight illumination levels were found to have an inconsistent relationship to performance, significant in two out of eight metrics tested. Higher levels of daylight illumination were found positive for Digit Span Backwards, a test measuring attention span and short term memory, and negative when compared to changes in daily average speed of handling calls for one of two study periods. The natural log of daylight illumination levels was found to have the best mathematical fit to the data, implying more sensitivity to changes at lower levels of illumination and progressively less sensitivity at higher levels.

Ventilation status and air temperature were also found to have significant, if intertwined and occasionally contradictory, associations with worker performance. When variation in hourly performance at the Call Center was considered, higher rates of outside air delivery were significantly associated with faster handling of calls.

Overall these potential influences on worker performance were found to have high statistical significance in the models tested. They are related to performance that is 1% to 20% better or worse than average. All together information about the physical conditions of the workers was able to explain about 2% to 5% of the total variation observed in a measure of worker productivity (Call Center study) or in performance on short cognitive assessment tests that were thought to be related to worker productivity (Desktop study).

Even small improvements in worker productivity are of great practical importance, and explaining 2%-5% of total variation is not trivial. By way of comparison, all other available information typically believed to predict performance such as demographic characteristics or employment status was able to explain about 6% to 19% of the variation in their performance. Thus the characteristics of the physical environment represent about 1/8th to 1/3rd of our entire ability to predict variation in individual worker performance.

Furthermore, changes in the physical design of a space that may influence worker performance are likely to have great persistence, continuing for the life of the building. When compared with the costs, persistence and the certainty of other methods of increasing productivity, constructing well-designed buildings may be attractively cost-effective. As demonstrated in the study site, these same features can also provide additional energy cost savings.

Both studies successfully measured variation in office worker environmental conditions and related these to measured office worker performance under actual employment conditions. The Desktop study pioneered the use of computerized cognitive assessment tools to gauge office worker performance in field conditions. The studies have shown that indoor environmental conditions can have a measurable relationship to changes in office worker performance and have established a range of likely effect sizes that other researchers can use to refine the needs of future studies. Other studies will be required to test if these findings can be replicated in other settings and to explore potential causal mechanisms between the environmental conditions and worker performance.

1. INTRODUCTION

This document reports on a field study of how office worker performance might be influenced by indoor environmental conditions. It was designed to carry forward earlier studies on the interaction of daylighting and human performance in schools and retail environments,[1,2,3] by extending the epidemiological methodologies used in those inquiries to the office building environment.

In addition to examining the basic hypothesis that daylight has a positive influence on the performance of office workers, it attempted to control for the potential influences of other indoor environmental conditions. The study used a statistical analysis technique, called multivariate regression analysis, to control multiple potential influences on office worker performance while attempting to isolate the magnitude and statistical certainty of any effect associated with specific environmental conditions, such as worker exposure to daylight and electric light illumination levels, window views, ventilation and air temperature.

Two different studies were conducted within the offices of the same organization, the municipal utility district in Sacramento, California. The first study looked at 100 workers in an incoming call center, whose performance was continuously tracked by a computer system and measured in terms of time to handle each call. The second study looked at the performance of 200 other office workers on a series of short cognitive assessment tests, taken at each individual's desktop computer.

This document reports on both the methodologies and findings of both the Call Center and the Desktop study. First the research context, key challenges and goals of the study are described below in the Introduction. Next in the sections on Site Selection and Study Site Description we describe the rationale for the selection of the study participant and provide an overview of the conditions in the buildings studied. The methodologies and findings of the two studies are presented in separate sections, first for the Call Center study followed by the related methodologies and findings of the Desktop study. Finally, the implications of the findings of both studies are discussed together in the Conclusion, along with an analysis of the potential statewide energy impacts of daylit office buildings, key findings from the study and recommendations for future research.

[1] Heschong Mahone Group (1999a). "Daylighting in Schools. An investigation into the relationship between daylight and human performance. Detailed Report". Fair Oaks, CA.

[2] Heschong Mahone Group (2001). "Re-Analysis Report: Daylighting and Schools, Additional Analysis", for California Energy Commission, Public Interest Energy Research report

[3] Heschong Mahone Group (1999b). "Skylighting and Retail Sales. An investigation into the relationship between daylight and human performance. Detailed Report". Fair Oaks, CA.

1.1 Related Research

The impact of the indoor environment on office workers has been of interest to building science researchers for many decades. Work has been pursued primarily in university-based and federal government laboratories looking at specific dimensions of worker comfort—thermal, ventilation, acoustic and lighting—and whether changes in those environmental conditions can be related to measurable changes in worker performance. Much early research was sponsored by the US Department of Defense in an effort to identify the key parameters of worker thermal comfort, resulting in the development of the "psychometric chart" which has since formed much of the basis of engineering principals for building heating, ventilation and air conditioning systems. The development of open office plans spurred an interest in acoustic environments, while workers compensation claims for back injuries and carpal tunnel syndrome drove research into office furniture ergonomics. The identification of "sick building syndrome" motivated a host of efforts to untangle the causes and effects of poor indoor environments.

The progress of current research is being tracked by the Indoor Health and Productivity project sponsored by the National Science and Technology Council.[1] Their web site currently indexes 1087 reports on the subject. The vast majority of such projects have focused on ventilation, indoor air quality, mold and related health issues. The site lists 40 experimental studies since 1990 that address sick building syndrome, 38 that address indoor air quality, 18 that address moisture issues, 12 that address electric lighting, two that address daylight and two that address acoustic issues. To help sift through this work to date, an international panel of 16 researchers selected the five most important recent projects and published these in the ASHRAE Journal in 2002.[2]

From these numbers it is clear that a relatively small number of efforts have addressed the relationship between illumination and human performance. Some of the recent laboratory and field studies most relevant to this effort are summarized in Figure 1. This chart delineates some of the worker performance (outcome) metrics that have been examined in recent office related studies along with the explanatory variables (inputs) considered.

Many studies which have focused on other aspects of the indoor environment have not controlled for potential influences from electric illumination or daylight, and visa versa. Certainly one of the challenges of field studies is accounting for all of the complexities that occur in real life situations, both in terms of the interrelationship of environmental conditions and other potential simultaneous changes in the social environment.

[1] www.ihpcentral.org

[2] S Kumar and W Fisk, "IEQ and the Impact on Building Occupants", ASHRAE Journal, April 2002

Researcher	Study type, Location	Key Inputs	Key outcome	# subjects	Findings	Comments
W. Kroner, Dept. of Architecture, RPI[1]	Field, old and new buildings, West Bend Mutual	Ventilation, thermal comfort	# insurance forms processed	300	2-3% increase due to workstations, 12-14% increase due to "improved building"	Daylight contribution in new space not accounted for
C Federspeil, UC Bekerley[2]	Field, HMO incoming Call Center	Ventilation, thermal comfort	Call handling time	100	No significant relationship to variation ventilation to performance	Variation in exposure to daylight not accounted for
D Milton, et al, Harvard School of Public Health[3]	Field, Polaroid Corp.	Ventilation	Absenteeism, health changes	501 or more	Increased ventilation associated with reduced absenteeism	
Myatt TA, et al, Harvard School of Public Health[4]	Field, Polaroid Corp	Indoor CO2 levels	Sick leave among office workers	294	No association between sick leave and CO2 differential	Follow up to Milton study above
Peter Boyce et al, Lighting Research Center (LRC), RPI[5]	Laboratory	Electric lighting conditions	Data entry and cognitive tasks, mood and alertness assessment.	15	Different light conditions have no effect on outcomes	Electric lighting considered in isolation
Aizlewood, et al [6]	Field	Ventilation, RH,	Health and comfort in an office building	Unknown	No significant effect on symptom prevalence or comfort	Only ventilation and RH considered
Boubreki M et al, Lighting Research Center, RPI[7]	Field	Window size, sunlight penetration	Emotional state of office workers, self-reports	40	Only small amounts of sunlight penetration promote positive feelings of relaxation	
J. Veitch, NRC[8]	Laboratory	Acoustics, lighting,	Reading comprehension, personality assessment	48 male and 52 female	Significant interaction between noise levels with personality assessment	
M. Figuiero et al, LRC, RPI	Field, software company	View and daylight	Occupancy rates, time spent on tasks	141	Workers in offices with views (or daylight) stay on task more	Pilot study, few controls
P. Wargocki, et al, DTI[9]	Laboratory	IAQ and ventilation rates	Performance of simulated office tasks	90	Better IAQ associated with higher productivity	Three studies, changed "pollution load"

[1] Kroner W, Stark-Martin J. *Environmentally responsive workstations and office-worker productivity.* ASHRAE Transactions, Vol. 100 (2), pp. 750-5.
[2] CC Federspeil, G Liu, M Lahiff, D Faulkner, DL Dibartolomeo, WJ Fisk, PN Price, DP Sullivan. *Worker Performance and Ventilation rate in a Call Center: Analyses of Time-series Data for a Group of Workers.* Lawrence Berkeley National Laboratory Report, LBNL-49356, Berkeley, CA.
[3] Milton DK, Glencross PM, Walters MD. *Risk of sick leave associated with outdoor ventilation level, humidification, and building related complaints*. Indoor Air, Vol. 10 (4), pp. 212-21.
[4] Myatt TA, Staudenmayer J, Adams K, Walters M, Rudnick SN, Milton DK. *A study of indoor carbon dioxide levels and sick leave among office worker* Environmental Health, Vol. 1 (1), pp. 3. s.
[5] Boyce P., Boubreki M, Hullev R. *Impact of window size and sunlight penetration on office workers*. Environment and Behavior, Vol. 23 (4), pp. 474-93.
[6] Aizlewood, CE Coward SKD, Hamilton L, Raw GJ and Wilde DJ. *The impact of humidity on health and comfort in an office building.* Proceedings of Indoor Air 2002, Vol. 4, pp. 671-6.
[7] Boubreki M, Hullev R, Boyce P. *Impact of window size and sunlight penetration on office workers* Environment and Behavior, Vol. 23 (4), pp. 474-93.
[8] Veitch. J. *Office noise and illumination effects on reading comprehension.* Journal of Environmental Psychology, Vol. 10, pp. 209-17.
[9] Wargocki P, Wyon DP, Fanger PO. *Productivity is affected by the air quality in offices,* Proceedings of Healthy Buildings `00, Vol. 1, pp. 635-40.

Figure 1: Summary Table of Related Office Studies

1.1.1 Field, Laboratory and Epidemiological Studies

Different types of studies have different advantages. Laboratory studies offer the greatest precision in isolating a given effect of interest by carefully controlling all other variation in the environment. Under the carefully controlled conditions in a laboratory, the experimenter can test for different causal mechanisms that can prove linkages between a given change in environmental conditions and a change in behavior. Given the highly constrained laboratory environment, it is often difficult to translate from lab studies to real world environments.

Field studies look for potential effects expressed in a real working environment, on people in the midst of conducting their normal workaday lives, and enmeshed in their normal organizational structure and interactions. In field studies many other influences on worker performance are in play and can potentially mask or confound results, challenging the validity of the findings. Field studies can either be observational studies, observing how performance varies with naturally occurring variation in time or space, or they can be intervention studies, where select conditions are artificially altered to test whether the change causes an observable shift in performance. This study is an observational field study. Field studies can also offer a powerful opportunity to combine observations, experimental techniques and survey techniques to enrich understanding of mechanisms and interactions. Perhaps the greatest disadvantage of field studies is that they typically look at only one or a few unique building sites, and thus it is often difficult to generalize results from one study to other conditions.

Epidemiological studies, like the *Daylighting in Schools* study cited earlier, look at large populations and use statistical methods to look for associations between physical conditions and measurable differences in behavior. Epidemiological studies generally have the advantage of being easier to generalize to larger situations, and provide useful estimates of the magnitude and certainty of effects within naturally occurring conditions. Epidemiological studies have the disadvantage, however, of not being able to test causal linkages between explanatory variable and outcome variables. They also are best at looking at broad, simply defined variables rather than precisely defined characteristics or interactions between characteristics.

As has been commonly done in the medical field, the building sciences can also use all three approaches to inform each other and build the overall knowledge base: epidemiological studies defining the scope and certainty of an effect, laboratory studies testing for specific mechanisms and linkages to explain the effect, and field studies verifying the hypothesis under real conditions and adding observational information about naturally occurring behaviors.

1.2 Measuring Office Worker Productivity

One of the key challenges of any study looking at the relationship between the indoor environment and office worker performance is finding meaningful metrics of office worker performance. While there is much discussion of the value of "productivity," the productivity of office workers is notoriously difficult to assess.

Productivity is typically defined as the ratio of inputs to outputs. In an industrial setting the definition of inputs and outputs is fairly clear: so much raw material purchased relative to so many widgets produced and sold. In an office setting, it is difficult to be precise about the definition of inputs and outputs, and perhaps even more difficult to measure them. Should input be considered number of person-hours worked? Many professional offices with salaried employees don't strictly track number of hours worked. Should output be considered profit? But profit (assuming the organization is profit-based) may often be more of a function of accounting procedures and economic climate. Given these challenges, many researchers trying to study the organizational productivity of offices have resorted to secondary measures of individual performance that are plausibly related to overall organizational productivity, such as absenteeism, or task or cognitive performance of individual workers. This type of study has a further advantage that by studying changes in the behavior of individuals it is easier to relate those changes to local variation in environmental conditions in time or space.

Clearly, an organization is only as good as the sum of its parts—i.e. each worker. However there are also structural and synergistic effects at the organizational level that may affect overall performance of the company in addition to the performance of the individuals. Thus, individual performance is not a sufficient indicator of organization productivity.

Another dimension of worker performance that is not well understood is the appropriate time period for study. While it is easy to envision that changes to the physical comfort of the worker may result in measurable changes in performance, it is also well known that humans are extremely adaptable, and will readily accommodate over time to a wide variety of conditions. Therefore, short term changes in environmental conditions, such as are typically measured in laboratory studies, may not necessarily result in net organizational productivity changes over the long term.

Observing a cross section of real workers, with real motivations, over an extended period is an extremely difficult prospect, and one that is rarely achieved in research studies. Many studies have resorted to using temporary workers as experimental subjects. However, temporary workers must be, of necessity, highly tolerant of a wide range of working conditions. Also, temporary workers are constantly exposed to new environments, and thus may even benefit from the stimulus of novel situations. Thus, they may not show the response of a long-term worker to subtle changes in environmental conditions. Furthermore, as disconnected individuals, temporary workers are the least likely to have their individual efforts contribute to a synergistic organizational effect.

In the Call Center study the linkage between individual performance and organizational productivity is fairly clear, since the Call Center's management uses metrics of individual worker performance to assess the average change in performance for the Call Center as a whole. In the Desktop study the linkage is much more tenuous since there were no measures of individual performance that were in use to assess company wide performance. The assertion is that measurable changes in cognitive performance of office workers are likely to be reflected in overall organizational productivity. We don't have specific research at this point to back up that assertion or quantify the relationship. Although at this point we can only rely on logical arguments to make the linkage, we believe that workplace managers may be persuaded.

1.3 Measuring Indoor Environmental Characteristics

This study of office worker performance attempts to untangle some of the many complex issues in indoor office design. By looking at more than just daylight, we have attempted to understand the interrelationship between multiple indoor environmental issues, such as lighting quality, thermal comfort, ventilation and acoustics.

All of these issues, at some threshold level, can plausibly be argued to have an effect on overall comfort, ability to concentrate, or performance on tasks. However, in real environments they are never fully independent of each other. For example, more daylight can also raise air temperatures or more ventilation can change the acoustic conditions in an office. Furthermore, the human body integrates the influence of all of these comfort conditions into one output—the physiological status and mental performance of the individual. These issues are clearly intertwined and work together to determine office worker comfort.

Most previous studies of the indoor environment have focused on only one or two of these physical influences, without attempting to control for variability in the others. Even though our primary objective was to understand the influence of daylight on office workers, we did not feel that we could isolate daylight from all other variation in the physical environment. Thus, we collected information about as many other aspects of the physical environment as possible.

The office study sites allowed us to control for some potential influences by simply providing an extremely uniform environment in some dimensions. In other dimensions, the study sites are extremely complex environments, with multiple interacting systems. Illumination is also provided via a variety of systems—daylight from windows and skylights, dimming electric lights and task lights—all under interactive control of automatic sensors or the occupant.

A second challenge in this type of study is the field measurement of the most meaningful dimensions of those environmental conditions which may influence worker performance. Some of these parameters, as those for thermal comfort—air movement rates in cubic volume per minute or dry bulb and wet bulb air temperatures in degrees Centigrade or Fahrenheit—have been fairly well established. Others, such as the best parameters for daylight or view, have not yet been definitively established. Some of the challenges of this data collection effort are described below.

1.3.1 Measuring Daylight Illumination

One of the more obvious qualities of daylight is that it is constantly varying. It varies in intensity by time of day and season, as the sun moves through the sky and with atmospheric conditions. It varies with location within a building and relative to the perspective of the viewer. It also varies in spectral composition throughout the day and season.

In order to understand what to measure, one needs to understand the expected effect on humans. Are we looking for an instantaneous visual effect? A delayed emotional or morale effect? A physiological circadian effect, which might be most evident on a daily or weekly performance scale? Or all of the above? Thus, should we look at average annual, daily or hourly exposure? Or perhaps peak exposure, or measures of degree of variability, such as standard deviation? How do we account for duration and frequency of exposure?

The time function of a daylight effect should also influence the physical location of where daylight illumination measurements are collected. For example, the most common assessment of illumination in an office space is made by measuring the average horizontal illuminance at the desk (as was done for most of the illuminance measurements in this study). This metric was developed decades ago when the typical office task was reading or writing on paper. However, in computerized offices the most common visual task is now viewing a vertically-mounted self-illuminated screen, changing the issues of visibility of task dramatically. Alternatively, if the key issue of interest is circadian stimulation, then total daily (or perhaps peak) illuminance received by the eye of the worker may be a more important dimension of illuminance to measure.

There is also the question of how to quantify daylight intensity by wavelength. Standard light meters (illuminance meters) measure the intensity of visual spectrum of wavelengths weighted according to the visual sensitivity of the eye, using the photopic or V-lambda curve. However, if exposure to daylight in an office space also has a circadian or physiological function, then an illumination measurement weighted to the wavelength sensitivity of the biological system would be more appropriate. Not only are such devices not available at this point in time, but the biologically active spectrum has not been fully defined.

Considering all of these issues together makes it clear that we really are only beginning to sort out the critical issues in measuring the presence of daylight relative to human performance. This study is part of early efforts to try to hone down the set of issues.

1.3.2 Other Characteristics of Windows

Windows are perhaps one of the most complex aspects of the office environment. They can provide an office with daylight, views, ventilation and a communication conduit with the outside world. They can also allow thermal discomfort, glare, noise and distractions into the workplace.

In the Desktop study, we attempted to isolate the effects of daylight from the other characteristics of windows by including a wide range of conditions with combinations of view and daylight exposure. These included lots of daylight with no view, lots of view with no daylight, and a variety of conditions in between.

To further control for the potential complexities of how window characteristics might influence workers, we considered a number of ways of describing a worker's relationship to a window. We collected information including measured horizontal daylight illumination at the workplane, distance to a window, orientation of nearest window, ability to control blinds at the window, sun penetration, glare potential from the window, and size and content of view. We also measured temperatures at the workstation that might be partially a function of daylight illumination levels.

Throughout this study we have used standard illuminance measuring devices (hand held light meters and Hobos), weighted to the eye's visual sensitivity. We have taken most of our measurements in the horizontal plane, with a modest attempt to correlate those measurements to vertical readings. We have looked at illuminance averages, peaks and variation over one hour, one day and multi-week periods. We also tested whether a one hour or a one day time lag provided a better fit in predicting performance. We have accounted for glare and view as qualitative categories, rather than measured data. We have made no attempt to account for peoples' exposure to light outside of their workstation. We believe that we have a few interesting answers, and certainly many new directions and questions.

1.3.3 The Importance of View

Of all of these characteristics of windows perhaps the most interesting and most controversial is the importance of view. In office buildings, it has long been a truism that the senior executives are rewarded with corner offices, with the biggest boss getting the best view. The real estate market also clearly attaches monetary value to nice views. Given the value people normally place on a good view, researchers have sought to understand what constitutes a "good" view and how such a view might positively impact workers.

The most widely acknowledged positive contribution of a window view involves contributions to eye health. Ophthalmologists, concerned about the prevalence of eye strain the in the modern work environment, have stressed the importance of frequent changes in eye focus distance to give the eye muscles a chance to relax momentarily. Computer based workers often develop eye strain or dry eyes from looking at their computers for extended periods without a break. Distant views provide an attractive alternative focus for eyes, helping to prevent eye strain.[1]

Some researchers have postulated that views of nature potentially improve people's health and well-being[2]. For example, prisoners with windows facing the surrounding hills instead of the interior prison courtyard visit the infirmary less frequently and report fewer stress-related ailments.[3,4] A famous study of heart surgery patients found that patients whose window overlooked a field edged with trees healed faster and required less pain medication than those with a view of a brick wall.[5] Substitutes for views of outside nature have also studied, suggesting that people have a "hunger" for views of nature. One study found that office workers without a view to the outside were more likely to post posters of natural scenes in their workplaces.[6] A Norwegian researcher found that placing plants in offices reduced reported health symptoms for workers by 25% over a one year study.[7]

Others interested in landscape and the natural environment have postulated theories that views of nature reduce stress or improve attention. One theory to explain the importance of views to nature suggests that natural elements trigger quick, positive emotions that help reduce physiological stress. This theory, bolstered by various laboratory and field studies, suggests that urban dwellers might constantly be experiencing low-level stress reactions which impact their physical health and behaviors, and that might be alleviated by exposure to natural scenes.[8]

Attention Restoration Theory offers a different mechanism to explain the benefits of exposure to views of nature. This theory suggests that views of natural scenes have the potential to restore the directed attention capabilities of the brain after

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[1] Recommendation from American Academy of Ophthalmology, http://www.pp.okstate.edu/ehs/kopykit/eyestrain.htm

[2] This summary draws from C Knecht "Urban Nature and Well-Being: Some empirical support" Berkeley Planning Journal, 17, 2003. in publication.

[3] West, M.J. (1985). Landscape and stress response in the prison environment. M.L.A. thesis. Department of Landscape Architecture, University of Washington, Seattle, WA.

[4] Moore, E.O. (1982). A prison environment's effect of health care service demands. Journal of Environmental Systems, 11, 17-34.

[5] Ulrich, R.S. (1984). View through a window may influence recovery from surgery. Science, 224, 420-421.

[6] J Heerwagen and G Oriens "Adaptations to Windowlessness: A study of visual décor in windowed and windowless offices, Environment and Behavior, 1986, 5, 623-639

[7] T Fjeld, Indoor Plants Reduce Office Worker Health Symptoms, SCIC News, October 2001, European Commission, http://scic.cec.eu.int/scicnews/2001/010228/news14.htm

[8] Ulrich, R.S., Simons, R.F., Losito, B. D., Fiorito, E., Miles, M. A. and Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. Journal of Environmental Psychology, 11: 201-230. The overall theory is explained in Ulrich, R. S. (1983). Aesthetic and affective response to the natural environment. In I. Altman and J. F. Wohlwill, Eds. Human Behavior and Environment: Advances in Theory and Research, 6, 85-125. NY: Plenum.

extended cognitive activity has drained a person's ability to focus and concentrate. Once the mind's ability to suppress distractions and impulses has become exhausted, people perform more poorly on tests requiring concentration. It also impacts people's ability to suppress urges for inappropriate behavior in favor of thoughtful consideration. Finally, this capacity affects emotion; people whose attention is exhausted show irritability and impatience. In various studies, natural window views have been shown to restore or maintain peoples' ability to concentrate over extended periods.[1]

Natural window views appear important in restoring or maintaining this ability to concentrate. Empirical tests have found that university students with more natural window dormitory views perform better on many (non-academic) tests of concentration, such as repeating a long series of numbers (Digit Span Backwards).[2] Most recently M Figueiro, M Rea, et al reported that computer workers with view offices spent 15% more time on their primary task of programming computers, while equivalent workers without views spent 15% more time talking on the phone or to each other.[3]

Given this body of research on the potential importance of view, we decided to include information about the availability and content of view of the workers in our two office studies. We considered a variety of options of how to categorize view, from highly detailed to very simplistic, and settled on a middle ground that captured some but not all possible characteristics of the types of views we found in the SMUD office buildings. This included assessment of size (viewing angle), content and glare potential. In addition, we asked participants in the Desktop study to make their own assessment of their personal view, providing us with detailed self-reports for correlation to the surveyor assessments.

1.3.4 Other Indoor Environment Issues

In addition to illumination and view, there are many other characteristics of the office environment that should be disentangled in a field study such as this. The discussion below quickly summarizes the approach used in this study.

Ventilation, temperature and air quality: Ventilation rates, air temperature and air quality have been some of the most studied characteristics of the office environment. We attempted to control for these conditions with direct measurements that could be used as control variables in our statistical models. We were not completely successful in isolating these influences, partly due to

[1] Kaplan, S. (1995). The Restorative Benefits of Nature: Toward an Integrative Framework. Journal of Environmental Psychology, 15, 169-182.

[2] Tennessen, C. and Cimprich, G. (1995). Views to nature: effects on attention. Journal of Environmental Psychology, 15, 77-85.

[3] M Figueiro, M Rea, A Rea R Stevens (2002) Daylight and Productivity: A Field Study. in proceeding of 2002 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy.

incomplete data and partly due to the inter-relationships among all the environmental characteristics of the workers' environment.

Furniture and Ergonomics: Ergonomics of office furniture and computer equipment is a key concern in office worker performance and health. We controlled for this issue by selecting a study participant who had remarkably uniform standards for both office furniture and computers for all their employees. We specifically excluded workers with exceptional conditions such as larger or private offices, temporary workstations or unusual computer setups.

Acoustics: The acoustic environment is another very important potential influence on office worker performance. All of the participants in both studies were situated in an open office environment, where they could not physically exclude noise by closing a door. While we were able to control for the type of office environment, we were not able to control for local or intermittent variations in acoustic conditions since we did not have access to acoustic recording devices which could be distributed throughout the study spaces.

Occupant Control: Some researchers have hypothesized that the ability to control and customize one's own environmental conditions will directly contribute to worker productivity, either through more tailored environmental conditions or perhaps as a morale booster giving the worker a sense of "empowerment." While one of the study site buildings had many options for user control of local comfort conditions, we were not able to control for the presence or use of these features independent of other aspects of the building.

1.4 About Statistical Analysis

Lastly, in our discussion of challenges of this type of research, there is the question of how any findings of a statistical model that combines these two types of information—worker performance and environmental conditions—should be interpreted and might be used to inform decisions about office worker environments.

We have made an effort to make the findings of the statistical analysis accessible to the average reader. A glossary is provided in the Appendix defining statistical terms. Statistical analysis provides enormous power in understanding huge trends in the world that are beyond our perception as individuals.

The specific statistical tool used in this study, multivariate regression analysis, allows the analyst to isolate the certainty and magnitude of a given effect, while simultaneously controlling for competing influences that inevitably occur. Statistical methodologies are designed to be intrinsically conservative. A common standard (and used in this report) is that a statistician must be 90% certain that a finding is true (p-value < 0.10) in order for it to be reported as a finding. There are many dimensions to statistical analysis. The two most commonly reported findings are the magnitude of an effect (B-coefficient) and the certainty of that effect (p-value).

This study relies on statistical analysis of the performance of a hundred or two office workers to detect very subtle effects of the physical environment on worker performance. However, individual human behavior is not highly predictable. The models in this study generally can explain less than 25% of the influences on how well a worker is performing on the various measures considered. The other 75% or more of variation in performance remains unexplained by the models, and could be a function of variables for which we had no information, such as a given individual's abilities or motivation on a given day, what they had for breakfast, or may be influenced by outside random events. Finding any variable that reliably explains variation in human behavior is indeed an achievement.

1.4.1 Statistical Power, Effect Sizes and the Validity of Models

The statistical power of a model is somewhat equivalent to the resolution power of an optical lens. A lens with poor resolution power can only resolve the presence of very large or high contrast objects, while a lens with higher resolution can allow the observer to detect finer details and objects with lower contrast. Higher resolution provides clarity for objects that might otherwise appear indistinct.

In a similar fashion, "statistical power" is a term describing of the resolution power of the statistical model. The greater the statistical power of a model, the smaller the "effect sizes" it can decisively resolve. Statistical power is typically provided by having large study populations. The more natural variation in the outcome variable being studied (as in human behavior), the larger the population needed to confirm the certainty an effects. Epidemiological and field studies, with a great deal of natural variation, typically require greater statistical power than laboratory studies that can artificially reduce variation by simplifying the experimental conditions. The more subtle a potential effect under consideration, the more statistical power is needed to resolve the certainty of that effect. The effect sizes found in this and other field studies of the influence of the physical environment on human performance tend to be very small. The question should be raised; at what point does an effect become too small or weak to be of interest?

The use of radar has also been used as an analogy to statistical analysis, as a similar process of trying to detect events which are beyond our normal perception:

> *"There are many ways to miss what is really there and 'find' what is not there. With radar, for example, the equipment may not be looking in the right direction or switched on at the right time. It may not be sensitive enough to detect craft bellow a certain threshold size or it may be so sensitive to background noise that real signals are difficult*

> *to pick out. Additionally, it may respond to extraneous objects (e.g. clouds, weather balloons) as if they were craft of interest or fail to respond to some craft that are of interest (e.g. those in the wrong orientation or construction of non-metallic materials)."[1]*

If the task is to detect any incoming aircraft, no matter how fast or how small or how low flying or strangely shaped or flying in a dust storm, then the instrument needs to be very sensitive. Expanding the study population is the statistical equivalent of adding sensitivity and resolution power to the radar instrument. Greater sensitivity provides greater resolution power.

In order to compare the relative statistical power of different statistical methods, Jacob Cohen[2] pioneered the discussion of the importance of "effect sizes" in the behavioral sciences. He defined the term as the percentage of unexplained variance in the model that was explained by the addition of the variable of interest (see f^2 in the glossary) and set up a protocol to gauge small, medium and large effect sizes.

One way to think of the effect size is that it represents clarity of the signal-to-noise ratio between the variable of interest and the data. According to Cohen, a large effect size explains more than 25% of the remaining variance, or there is a 1:4 signal to noise ratio. A small effect size explains at least 2% (signal) of the remaining variance (noise). Since more subtle or less distinct effects have a lower signal to noise ratio, greater statistical power is required to detect them. This greater statistical power is generally best provided by a larger study population that makes it easier to achieve statistical certainty. In our radar example, more information makes it easier to be certain that the little blip on the screen is indeed a real object to worry about and not just dust or some other atmospheric anomaly.

Mark Lipsy[3] continued the discussion of effect sizes and statistical power by pointing out that most behavioral science studies did not have sufficient statistical power to detect the effects that they were interested in. He further pointed out that findings with effect sizes far below Cohen's threshold levels could still have very important consequences. Lipsey was concerned that too many studies were failing to find any meaningful effects simply because they did not have sufficient statistical power to do so. As a result, researchers were coming to the erroneous conclusion that there was no effect, rather than the more proper conclusion that their research instruments were not sufficiently powerful enough to detect such an effect.

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[1] Lipsey, Mark W. *Design Sensitivity: Statistical Power for Experimental Research*. Newbury Park, CA: SAGE Publications, 1990.

[2] Cohen, Jacob. *Statistical Power Analysis for the Behavioral Sciences*. Hillsdale,N.J.: Lawrence Erlbaum Associates, Publishers, 1988

[3] Lipsey, Mark W. *Design Sensitivity: Statistical Power for Experimental Research*. Newbury Park, CA: SAGE Publications, 1990.

Thus, the key need for understanding effect size is determining appropriate sample size. If the approximate effect size can be anticipated, researchers can determine in advance the most cost-effective format for a study that still has a good chance of detecting the effect of interest. Subtle effects require bigger sample sizes, while obvious effects can get by with smaller sample sizes.

Once a study has been completed and a significant effect has been found, does it matter how big the effect size was for the variable of interest? Yes, and no. Yes, because the effect size is an indicator of how easy or difficult the effect will be to verify in a replication study. The bigger the effect size, the more likely it is to be found again, and the smaller the study population that might be needed to detect it a second time. No, because effect size does not necessarily determine the importance of an effect. Even a very small airplane may be very important to detect if it is an enemy carrying a bomb. Likewise, a subtle effect (small effect size) may be very important in the behavioral sciences if it has important social consequences.

1.4.2 Judging the importance of an Effect

Ultimately, the importance of any effect should be primarily evaluated by its social utility. Once we know the certainty (p-value) that it is a true effect and the magnitude (B-coefficient) of the effect, then we need to assess the usefulness of that knowledge. For example, if we determine that the presence of windows is likely to influence the performance of students or office workers, even if that effect is small or subtle, is that likely to change how we design our buildings? Is this something that is relatively easy (cost effective) to do, given the expected impact, or is it vastly more expensive than other alternatives that are likely to have bigger or more long-lasting effects? And are there other costs or benefits associated with this action?

In the case of windows in offices, adding view windows during the design phase of a building is relatively inexpensive and is likely to have a very long lasting presence (for the life of the building). Real estate agents have known for a long time that attractive view windows can raise the rental value of an office space. Adding windows that optimize the use of daylight can also have predictable energy savings that reduce the operating cost of the building (see discussion on energy saving potential in Section 6.1).

Given all of these costs and benefits, developers and owners inevitably must make their own decision if it is an attractive proposition to construct a new office building with more windows. This cost and benefit calculation will vary with each project, and it is beyond the scope of this document to try to quantify any of these values. In reality, most building owners make decisions based on preconceived assumptions about the value of different design characteristics of buildings.

It is the intent of this research to try to provide information that might influence the discussion on the value of design and operating decisions for office buildings that affect the quality of the indoor environment for office workers. This is a very young and imprecise science, in which we are just beginning to achieve definitive results. However, building owners continue to make mega-million dollar decisions on new buildings, and they are clamoring for certainty and reliable decision criteria.

1.5 Goals for this Study

There were a number of goals defined for this study at the outset. Roughly in order of priority they included:

- Test the hypothesis that daylight may have a positive effect on office worker performance
- Consider and control for other potential environmental influences on worker performance such as electric light, ventilation, view, acoustics and thermal comfort
- Develop a methodology for measuring worker performance in a field study of an office environment
- Determine the energy implications of greater use of daylighting techniques in office environments in California
- Compare results of this study to other related studies in offices, schools and retail environments
- Make recommendations for future progress in this field

2. SITE SELECTION

The site selection process was an important factor in the structure and outcome of this research project. Prior to beginning the search for a participant office, we determined a set of ideal characteristics that we would use to evaluate and qualify the candidate office. The following criteria guided our selection process. The criteria were intended to maximize the potential significance of the study and to minimize the effort required to account for confounding factors.

2.1 Selection Criteria

At a minimum, the office selected for this study would:

- Be a **large organization/large population** that would provide us with a diversity and more data points for a statistical analysis.
- Have **some daylit and some non-daylit** departments/buildings so that daylighting effects could be compared between otherwise identical environments. It would be ideal to have a continuous range of daylighting conditions so that a dose-response relationship between daylighting and office worker performance could be studied.
- Have **little variation between daylit and non-daylit** work environments across the population other than the amount of daylight available. This would minimize the number of other factors that needed to be controlled for.
- Maintain electronic **demographic database of employees** to control for other factors affecting employee performance other than their physical environment.
- Maintain a **performance database** on the performance of employees. If the participant could provide data on the characteristics of the individual performance, we would be able to conduct a more precise analysis and invest project resources in other types of data collection.
- Be **located in California.** The goal of the PIER program is to fund research that will enhance overall energy efficiency and quality of life in the State of California. Research on in-state buildings was most likely to be persuasive to state policymakers, and was more cost effective for the research project.
- Be **willing to participate**. The research could not proceed without the organization’s permission to utilize their employee information data and to allow us to physically inspect their buildings. Enthusiasm for the study was likely to facilitate and expedite such access.

- Be willing to allow the **study results to be published publicly**. As a project funded with public goods moneys from the State of California, we are obligated to make our findings public. If the participant preferred to remain anonymous, we could potentially accommodate this request with careful attention to confidentiality issues, but the results would be published.

2.2 Participant Search

The above selection criteria provided us with a basis for deciding the appropriateness of various candidate office participants. Our search for participants involved reviewing library information, searching web-based resources and conducting interviews with architects and potential candidate organizations. We researched case studies and interviewed other experts involved in daylighting design to identify as many possible subject sites as possible. Our research identified a handful of office buildings as potential study sites. For each potential site we first identified the key contact, usually the business owner or company director, then interviewed each about their interest in participating in the study.

We eventually identified three potential sites. All were large organizations with multiple buildings. One was a private company: two were public. Each of these was visited to assess the range of daylighting conditions, the uniformity of other conditions and the availability of performance data on the employees. The selected study participant, Sacramento Municipal Utility District (SMUD), presented the greatest range of daylighting conditions and the potential for pre-existing metrics in at least one department of the organization. SMUD management agreed to assist in the study and offered a high level of cooperation and commitment to the study. We were granted extraordinary access to the site and its employees. In return, we endeavored to minimize our intrusion into everyday work activities and promised confidentiality to all individual participants.

2.3 Selection of Participant

The Sacramento Municipal Utility District is a large publicly owned utility company in Sacramento. It operates about two dozen facilities around the county of Sacramento. Of these about a dozen buildings exist at one central campus, and about half of those include some office functions. We selected three for our study which would allow a comparison to workers in the same company who are working in the same location and climate, but different interior environmental conditions.

SMUD's most recent building, the Customer Service Center (CSC) completed in 1995, is a four story office building, with exemplary daylighting features and many other innovative design features intended to promote both worker comfort and energy efficiency. The Headquarters building, completed in 1960, was also an exemplary building of its time. Also four stories, it features expansive views out into a botanical garden setting, with movable sun shades on the exterior walls. Floor to ceiling tinted glazing allows ample views but restricts the amount of daylight that enters the building. A third building, the Distribution Center completed in the early 1970s, is a two story office building that was recently renovated. It has wide supporting columns outside of each window that block both the sun and views and allow minimal daylight into the building. All three of these buildings support a large population of office workers housed in nearly identical workstations. Corporate standards provide ergonomic furniture, medium height partitions, and up-to-date computers at each workstation. (A detailed description of each building is provided in Section 3. In addition, a photo-tour of each building is provided in the Appendix.)

2.4 Decision to Pursue Two Studies

These three buildings provided the potential for a good range of daylighting, electric lighting, view and ventilation conditions for our study. They did not, however, offer a set of pre-existing individual worker performance metrics that we could analyze. We addressed this challenge in two ways.

To study worker performance in the range of conditions in the three buildings, we decided to administer a set of brief performance tests that could gauge aspects of worker performance, such as speed, accuracy, attention and memory, similar to tests that had been used in other related laboratory studies on office worker performance. While these performance tests would not achieve our objective of measuring organizational productivity, they might provide insight into some of the discrete mechanisms that contribute to individual performance. In particular, they were chosen to capture effects of visual fatigue and mental fatigue.

We also had the opportunity to study one department within SMUD that did have individual and organizational performance metrics—the Call Center, which handles incoming service requests and any customer question about the utility's programs. In the SMUD Call Center over 100 workers are doing similar tasks, have similar levels of education and experience and are monitored for their performance objectively through the use of automatic tracking software.

However, there were two limitations to the Call Center for our purposes. First, the range of daylight conditions was limited, since all of the workers were located in the same daylit space. Second, performance in a call center is a highly specialized subset of office work and cannot necessarily be obviously translated into more generalized office or professional work.

We hoped to be able to overcome this limited range of conditions in the Call Center by introducing a few interventions that would change conditions temporarily for the workers, by artificially restricting or increasing the amount of daylight or ventilation for a short time period. We also hoped that the rare opportunity of conducting two concurrent studies on related office spaces, even with very different outcome metrics, would potentially increase the validity and value of both studies.

Thus, we decided to pursue two related studies simultaneously, one looking at how worker performance in the Call Center varied with exposure to light and ventilation over time, and the other measuring differences in worker performance across the range of conditions at their workstations in the three study buildings. We called the first the Call Center study, and the second the Desktop study.

3. STUDY SITE DESCRIPTION

The SMUD buildings provide a unique opportunity for a study of this nature because one of its buildings features exemplary daylight conditions for its workers. The central SMUD campus consists of a variety of buildings, which include about a dozen locations. This study involved three of the major office facilities:

- The Headquarters building, a four story building from the 1960s with a deep floor plate and heavily shaded and tinted windows resulting in very little daylight penetration. The windows provide primarily a near view of surrounding mature trees and vegetation.
- The Customer Service Center (CSC) building, a four story building finished in 1995 and designed for maximum daylight, with a narrow floor plan and high performance windows and skylights. The building features near and far views of the surroundings and sky through its large windows.
- The 59th street building, a two-story office building built in the 1970s with minimal daylight. Narrow windows are almost completely obstructed by exterior columns, allowing very limited views.

All of the buildings are in the same location in Sacramento, California, and thus share an identical climate. Workers in all three buildings perform a variety of professional and clerical tasks, and work in very similar furnishings, including modular workstations with acoustic partitions, similar vintage chairs and computers. SMUD makes considerable effort to accommodate the ergonomic needs of its workers, and so workstations and chairs have frequently been adjusted to accommodate the specific preferences or needs of individual workers.

Thus, these three buildings presented us with an opportunity to study office workers in the field under very similar organizational, environmental and physical conditions, while varying the worker's relationship to daylight. The following sections describe in detail the layout and features of the three SMUD buildings selected for this study.

3.1 Customer Service Center

The Customer Service Center (CSC) building is the most recent building and the only one among the three buildings explicitly designed for daylighting (shown in Figure 2). It houses a variety of departments primarily focused on customer services—the Call Center, the billing group, residential and commercial customer outreach services—along with other internal services departments.

Figure 2: Customer Service Center (CSC) building

The building is a 184,000 sq. ft. facility, with four wings linked by a central lobby hub. Each wing is a rectangular plan, about 70’ deep and running east to west. The ceiling height is about 11’. Figure 2 provides an aerial view of the building. The front wings to the southwest and southeast are two stories tall while the back wings to the northwest and northeast are four stories tall. The top floor of each wing includes skylights, and the windows of the south façades include shading devices.

Figure 3 shows the layout of the 2^{nd} floor northeast wing (top plan) and 4^{th} floor northwest wing (bottom plan) of the CSC building. This has mostly open offices on each floor, along with a few closed offices for senior managers. Typically there are six workstations across the width of a wing, with two corridors. In a few wings one internal corridor is arranged with seven workstations across the width. The partitions are light gray in color (40% visible light reflectance), while the carpet is a darker gray (15% reflectance). The ceiling is off-white with acoustic tiles forming square patterns. Desk surfaces are white (80% reflectance). Employees work flexible hours, but most are at their desks from about 8:00 AM to 4:00 PM and spend a large part of their day working on computers. SMUD is in the process of changing regular CRT monitors to 17” flat-screen LCD. Hence, there are monitors of both types in the CSC building.

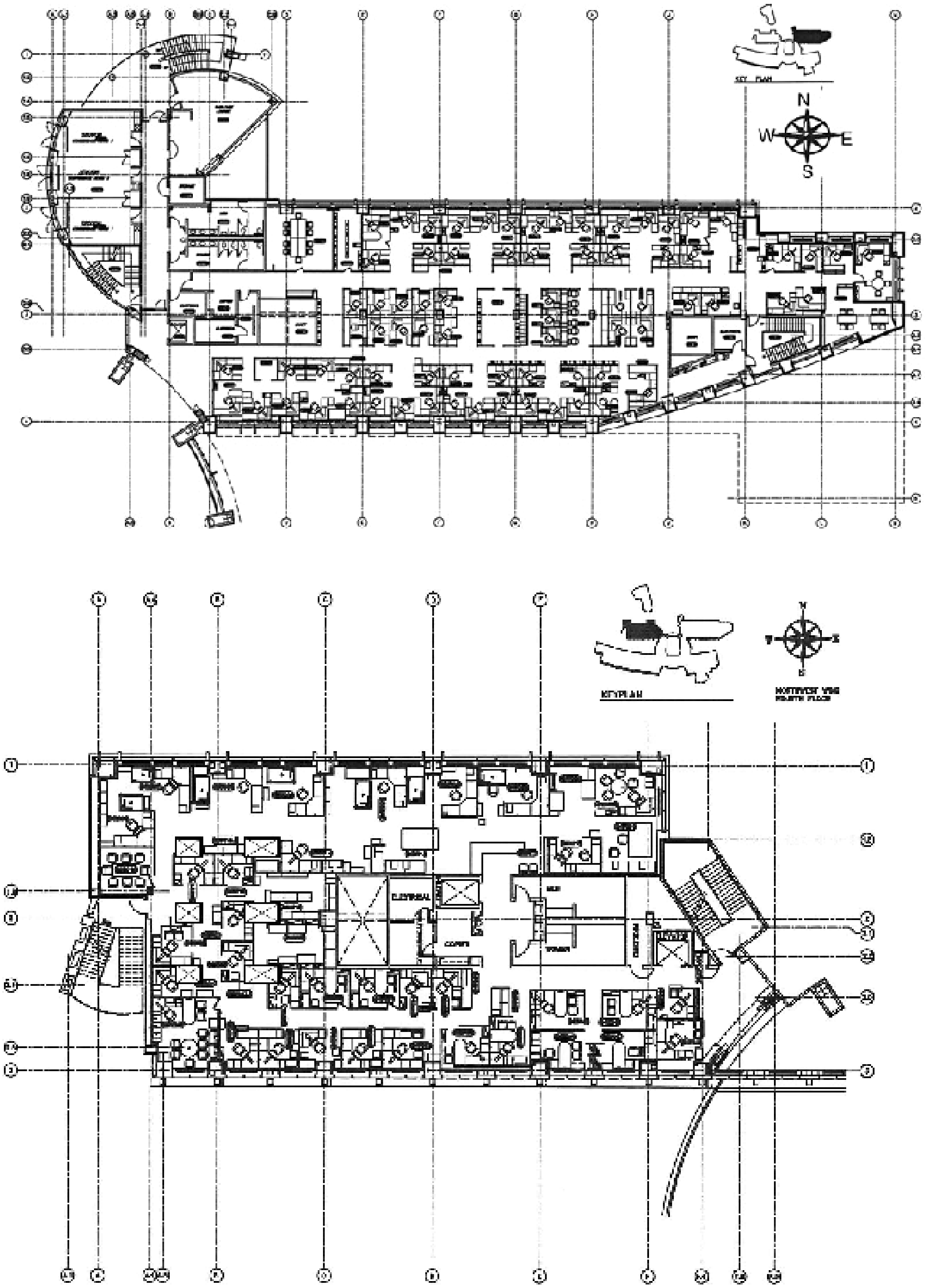

Figure 3: Plans for 2nd floor NE wing and 4th floor NW wing of CSC building

3.1.1 Electric Lighting

The electric lighting system uses linear pendant-mounted luminaires for primary ambient lighting. The direct/indirect luminaires (70% up / 30% down, one lamp in cross section, with specular parabolic louvers) are suspended 28" from the ceiling, and spaced eight feet on center (shown in Figure 4).

These fixtures are typically arranged in rows running along the length of the plan parallel to the windows in the east-west direction. On a few top floors and the Call Center the fixture arrangement is perpendicular to the other floors. Here the fixtures run in the north-south direction perpendicular to the windows. During daylight hours, a combination of controlled daylight and electric lighting provides 30 to 90 footcandles (fc) on the work plane, depending on proximity to windows (see Figure 7). The T-8 florescent lamps are on automatic dimmers controlled by photosensors mounted on every third fixture.

The CSC was the subject of a detailed study of its lighting system when it first opened for occupancy. This study was published as a Delta Report by the Lighting Research Center in 1997. Many of the graphics from that report have been borrowed to illustrate the configuration of the building for this report. The Delta Report found extremely high levels of satisfaction with the lighting conditions among the employees that were surveyed,[1] especially on the top sky-lit floors.

Figure 4: Direct/indirect luminaire and recessed downlights in CSC building

[1] DELTA Portfolio Lighting Case Studies, Volume 2, Issue 2, Lighting Research Center, 1997, Rensselaer Polytechnic Institute, Troy, NY

In addition to the primary luminaires, there are a variety of other fixture types used throughout the building, such as louvered fluorescent luminaires above the south view windows, as shown in Figure 5. Some of these are only switched on at night, to supplement the lighting when daylight is no longer present. Electric illumination levels during daytime (with blinds closed) vary from 20 to 30 fc. After dark the electric lighting alone provides between 15 to 50 fc on the work plane.

Figure 5: Light shelf with louvered luminaire at south window in CSC building Note partial view through perforated blinds.

Figure 6: Luminaire arrangement on top floor of CSC building with skylights Note luminaires perpendicular to windows, top floors only.

3.1.2 Daylight

The daylight system in the CSC building includes windows, light shelves, vertical blinds and skylights. The north and south facades of each wing are designed to maximize daylight penetration into the office space, while minimizing solar heat gain. The north facing walls of the building have large windows with no external shading, while the south walls have smaller windows with both vertical and horizontal shading (see Figure 7). All south and east facing windows have a clerestory. The windows above the shelf are clear; the lower windows are tinted low-e (low-emissivity) glass, with a measured visible light transmission of 37%. The north windows have a transmission of 49%. The light shelves extend inside the glass and are white to maximize the reflection of daylight onto the ceiling.

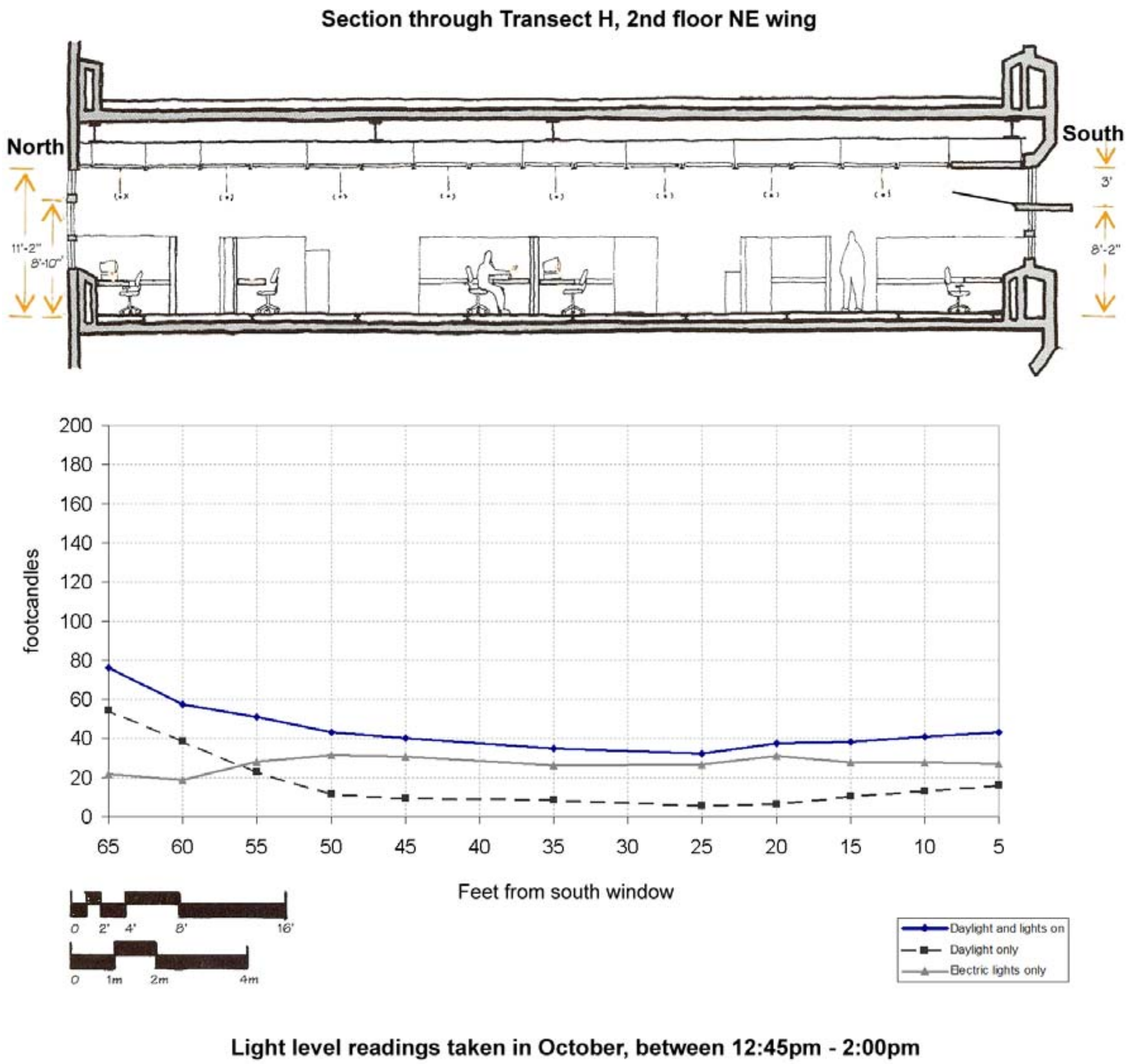

Figure 7: Illumination cross-section, 2nd floor NE wing, CSC building

All windows have movable vertical blinds. The light-colored, perforated vertical blinds block 95% of the daylight, allowing employees to eliminate glare while retaining the view. While these blinds can theoretically be adjusted by the occupant of the nearest workstation, often the controls are very difficult to reach, given the distance between the desk and windows. In general, we observed about 80% of the blinds along the north walls to remain fully open and about 80% of the blinds along the south walls to be partially or fully closed. Even with the blinds fully open, daylight levels on the north side are higher than the south side, as shown in the illumination cross-section shown in Figure 7.

Figure 8: Skylights above work spaces in CSC

On the top floors of each wing, daylighting from windows is supplemented by 4' x 6' skylights (shown in Figure 8) spaced on a 24' x 20' grid. The translucent skylight material is a triple layer of acrylic with two prismatic layers below a milky white layer. Each skylight distributes daylight to many workstations below. They feature splayed light wells below a four foot deep vertical shaft. Movable, opaque louvers are also provided inside the skylight well to allow control of the daylight levels; but these seem to be rarely used.

Figure 9 presents a measured illumination cross section for the second floor of the southwest wing while the blinds were fully open. The cross section through the wing was taken between skylights, rather than directly under them, at midday on a clear day in October. The electric lights are seen to be dimming in response to daylight illumination levels, and vary from 1-2 fc to about 35 fc. Daylight illumination in this toplit space varies from 40 to 110 fc.

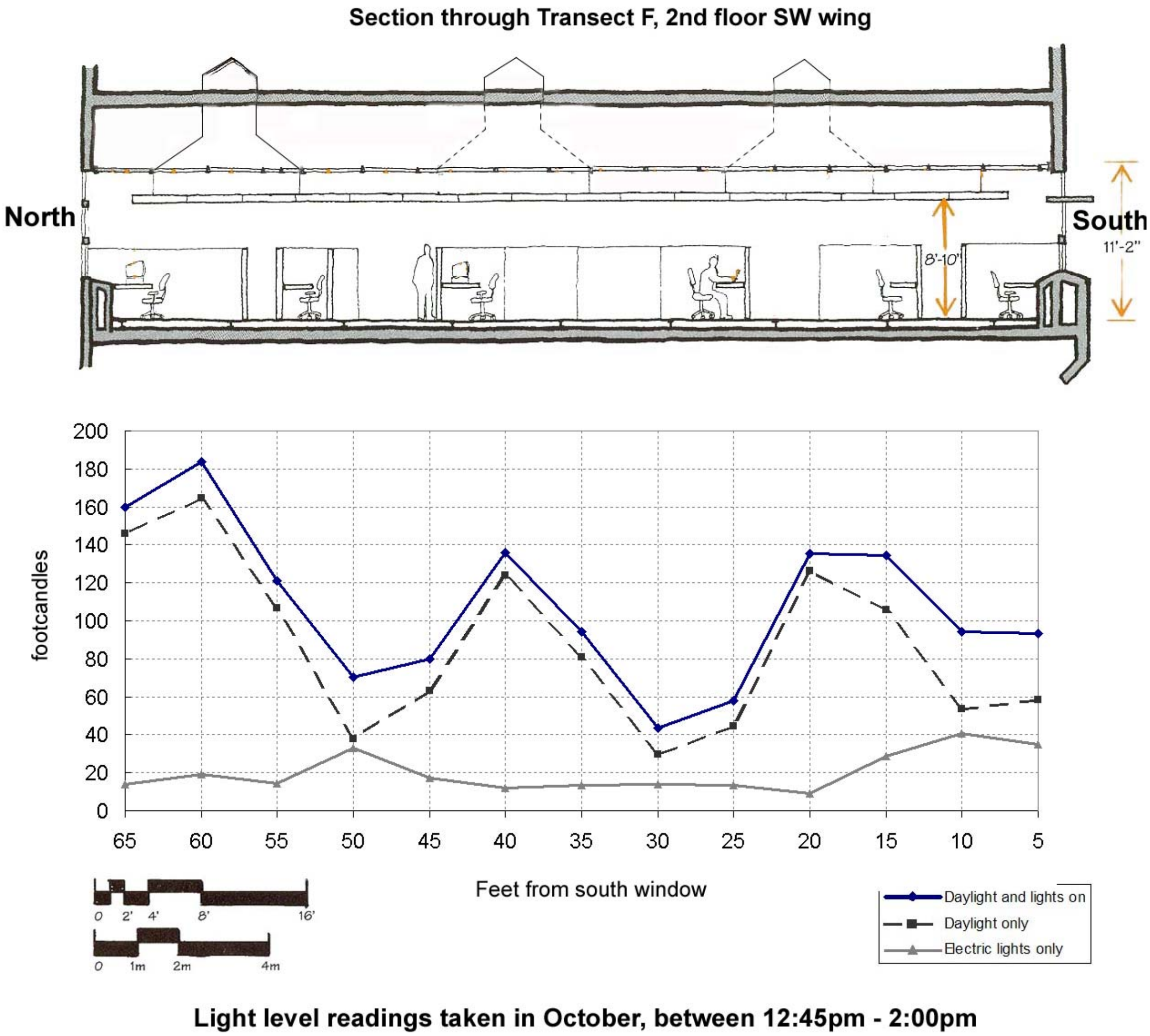

Figure 9: Illumination cross-section, 2nd floor SW wing, CSC building
Skylit floor, daytime illuminance readings

3.1.3 HVAC Systems

The CSC building has the most complex HVAC system of all three buildings, and offers the occupants a great deal of control over their ventilation. On each floor there are two separate HVAC systems serving the space, plus the option of opening windows. Each of the systems is served by dedicated air handlers located in penthouses on the rooftop.

Under-floor system: SMUD has an innovative under-floor constant volume air supply system. The primary air supply for each wing is through floor vents via displacement ventilation. Each cubicle typically has one supply register, and the occupant can adjust the amount of air flow by turning the position of the circular basket under the vent, shown in Figure 10. Each under-floor delivery system is divided into multiple thermal zones. Some air handlers can handle multiple zones for more than one floor. Thus, for any given floor there are up to three air handlers for the under floor system, and for every air handler there are up to three floors served.

Perimeter system: Each floor is also supplied by a perimeter dual-duct VAV system. The perimeter zones have separate air handlers for heating and cooling, while the core zones are served by air handlers that can provide both heating and cooling. The perimeter supply registers are located along the wall next to operable windows. These vents were originally designed to shut off air supply when a nearby operable window was open, though this system is not used.

For both the under-floor and perimeter systems the return is through the ceiling plenum. There are economizers on all the air handlers, which increase the proportion of outside air provided by the system when the outside air temperature can help cool the building.

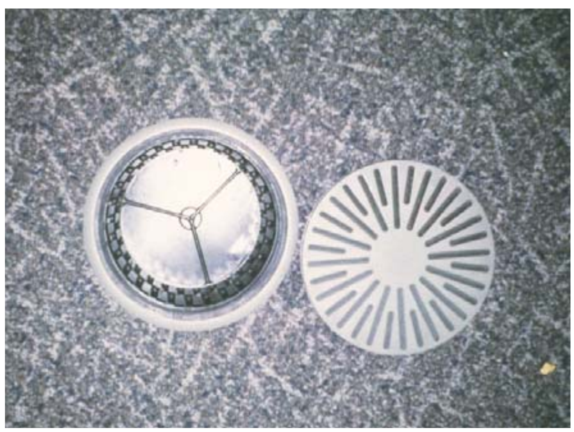

Figure 10: Floor registers for under-floor ventilation system in CSC Building Top grill is lifted off and set to the right side to show control "basket" underneath that allows employee to select amount of air exiting vent.

3.1.4 Personal Control and Variability

The Customer Services building was explicitly designed to maximize personal control and responsiveness to climatic conditions. As a result, it is an enormously complex building.

Daylight and Electric Light Controls: The daylight design includes vertical blinds that can be adjusted by the occupant to control sunlight, daylight and view. The electric lighting system includes a photosensor controlled dimmer that can be locally adjusted, each controlling three luminaries (i.e. every twelve linear feet), if needed. Indeed, our observations suggest that the dimming system has been adjusted fairly frequently over time, given the variation in electric illumination readings. In addition, each worker is assigned at least one multi-arm task light that can be maneuvered in three dimensions. We observed that about 10% of the workers have two task lights at their desk, and about 10% have none. We did not attempt to formally assess the use of the task lights, but informal observations during occupied periods suggest use of the task lights is fairly low, with no more than 20-25% turned on at any given time.

Ventilation Controls: The ventilation system similarly allows local occupant control. The windows have about one operable section per workstation along the perimeter. We observed about 15-20% of the windows were open throughout the CSC during the workday, with the exception of the Call Center, where it tended to be less than 10%. The building is supposed to be pressurized, so that opening a window will cause a net air flow outwards. However, employees have told us that they do feel a breeze inward when they open their window.

In addition, the under floor air supply plenum is fitted with floor registers that can be adjusted by the occupants. Most workstations have a floor register somewhere within their area. About 10% have no floor register and about 10% have their access blocked by furniture. We observed that in the accessible floor vents there is a range of settings maintained, from fully closed to fully open. In addition some floor vents have been intentionally blocked with paper or foil inserts and in some the baskets have been removed, perhaps to increase airflow even more. We observed that after one month about 25% of the floor registers had changed their settings, either increasing or restricting air flow. This is consistent with the findings of an earlier U.C. Berkeley survey of employee satisfaction with the CSC building.[1]

[1] E Ring and G Brager, "Summary Report of Indoor Environmental Quality Assessment" prepared for SMUD by The Center for the Built Environment, U.C. Berkeley, Dec 1999.

3.2 Headquarters

The Headquarters building is a four story building from the 1960s. The building is a 134,440 sq. ft. facility with a north and a south wing. A service core, with elevators and stair cases, connects the two wings. It houses a number of administrative departments, such as accounting and human resources, along with some specialized engineering and information technology departments. The north wing has a square plan 124'. by 132'. The south wing has a rectangular plan that runs 280' east to west and 63' north to south. The third floor plan for north and south wings is shown in Figure 11, and Figure 12 shows the typical cubicle layout for the Headquarters building.

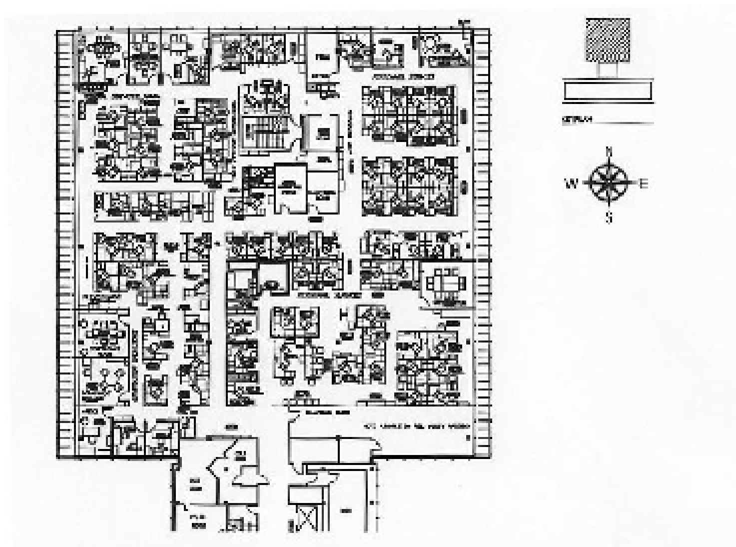

Figure 11: Plan of 3rd floor north wing, Headquarters building

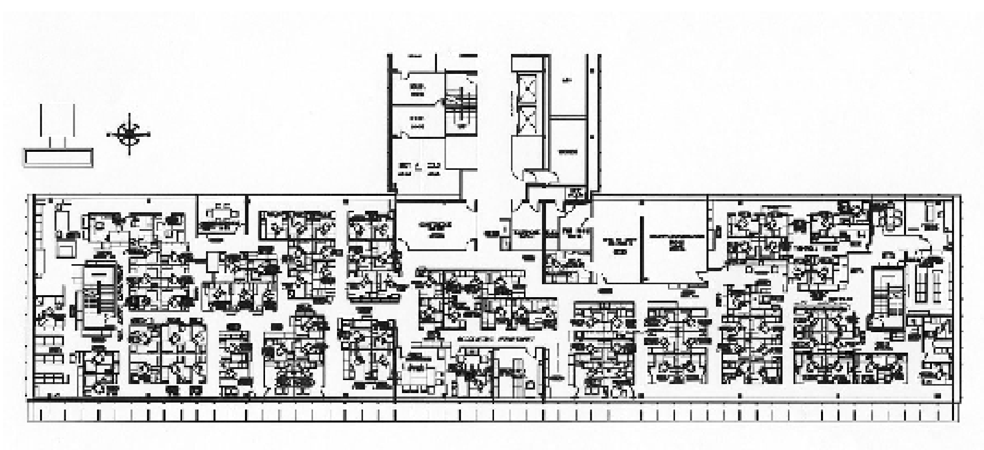

Figure 12: Plan of 3rd floor south wing, headquarters building

3.2.1 Daylighting

The building has large floor to ceiling windows with heavily tinted, single pane glass, with a visible light transmittance of 10% for the south, east and west windows. In the north wing, the east and west walls have vertical external shading fins that are motorized to gradually move over the course of the day to block direct sunlight. In the south wing, the large south wall has fixed vertical external fins and two sloped horizontal fins to shade the glass from the south sun. The external fins are shown in Figure 14 and Figure 15. The north windows have no external shades and more lightly tinted glass. The windows in Headquarters do not have any internal blinds or shades (Figure 13).

Figure 13: North windows and view, Headquarters building

In addition to the architectural shading, the windows of the Headquarters building are heavily shaded by mature evergreen and deciduous trees. The windows generally look out onto beautiful near-views of fairly thick vegetation. These large trees also block views of the sky, and thus greatly reduce the amount of daylight that reaches the interior spaces.

Daylight in the Headquarters building is restricted to the light coming in from the heavily tinted glass on the external walls. In most places near the windows the daylight illumination was negligible, rarely above five footcandles. At one cubicle's distance in from the windows, the daylight drops to one footcandle.

Figure 14: External fins (movable) on east wall of Headquarters building

Figure 15: External fins (fixed) on south wall of Headquarters building

3.2.2 Electric Lighting

Headquarters is illuminated with parabolic louvered luminaires using T-12 florescent lamps with magnetic ballasts recessed mounted in the 9 ft. high ceiling. These are arranged eight feet on center in a pattern where every other luminaire is perpendicular to the next, as shown in Figure 16. At some point every third luminaire was disabled in order to save energy. As a result there are some very dim pockets and non-uniform illumination patterns throughout the Headquarters. The lighting system typically provides 35 to 60 fc of illumination on the workplane. Workers are also provided the option of having one or two task lights at their desk.

Figure 16 : Cubicle and ceiling in Headquarters, looking south

3.2.3 HVAC System

The building is served with a constant volume dual-duct system, and is served by multiple air handlers. Each floor is divided into multiple thermal zones by orientation, and each of the thermal zones is served by a separate air handler. Some air handlers serve zones across multiple floors, in which case, the zones are oriented in the same direction–for example, one air handler serves the south facing thermal zones on three floors of the south wing. The interior supply registers are located in the ceiling while the perimeter supply registers are located in the floor next to the floor-to-ceiling windows. The return is through the plenum. Users in the space have no direct control over the HVAC system operation. While there is no economizer operation on this building, the dual duct system maintains the mixed air temperature between 72-78°F, and adjusts the amount of outdoor air accordingly to maintain the mixed air temperature.

3.2.4 Personal Control

Other than task lights, the Headquarters building has no personal controls for electric lighting, windows or ventilation.

3.3 Distribution Services Building

The two story Distribution Services Building was built in the early 1970s and has been recently renovated. It houses the distribution services department, which consists mainly of engineers, and has a total area of 25,525 sq. ft.

3.3.1 Daylighting

This building has very little daylight. The east and west windows have visible light transmittance of 36-40%. Deep roof overhangs are supported by wide columns with perforations, as shown in Figure 18. These are placed directly in front of the windows so as to also function as vertical sun-shades for the northeast and southwest facing windows. Occasional narrow shafts of sunlight make it past the columns and momentarily brighten the space. At some angles within the space employees can see a slice of the sky or view, but these perspectives are rather limited. Daylight occasionally reaches 10-15 fc in small areas near a window, but generally is negligible in the space.

Figure 17: Cubicles and ceiling in Distribution Services building

Figure 18: Wide columns blocking view in Distribution Services building.

3.3.2 Electric Lighting

This building has been recently retrofitted with new parabolic luminaries using T-8 fluorescent lamps with electronic ballasts. The luminaires are recessed in a new white acoustic tile ceiling located at 9 feet above the floor. Employees have access to the same task lights available in the other buildings.

3.3.3 HVAC System

The distribution service building has two floors, and each of the two floors is served by a different system. The first floor is served by a dual-duct VAV system, while the second floor is served by a single duct VAV system with electric reheat. The second floor system has an economizer that operates based upon the outdoor dry bulb temperature. The supply registers are located in the ceiling system, and the return is through the plenum. Users in the space have no direct control over the HVAC system operation.

3.3.4 Personal Control

Other than task lights, this building has no personal controls for electric lighting, windows, HVAC system or ventilation.

4. CALL CENTER STUDY

Call Centers are a rapidly expanding type of office work, as more and more industries find ways to market to or serve their customers over telephone lines. Examples of industries that use call centers include banking, financial services, credit cards, insurance, healthcare, airlines, computer technical support, retail catalog sales, telecommunication, public safety, market research and various business services and communications. Many of these operate 24 hours a day, 7 days a week.

Two million people work in call centers in the United States and a total of ten million work in call centers internationally. The call center workforce is expected to expand by 50% over the next decade.[1]

Call center work is highly dependent upon both acoustic conditions, since agents are talking to customers on the phone, and visual conditions, since they are typically entering and processing information on computer screens. Since call center workers are using electronic equipment, primarily telephones and computers, it is easy and common to closely monitor their work performance with computerized tracking systems. Often workers are provided with instantaneous feedback on their performance and the call center group as a whole. This feedback, along with incentive programs based on performance metrics, creates pressure for ever better performance. A wide variety of metrics of performance are used in the industry, and it is rare to be able to compare performance between call centers as the metrics and criteria of service change between centers.

4.1 Description of SMUD Call Center

The SMUD Call Center handles all incoming calls from residential and commercial utility customers who have service requests, questions about billing or want information about utility programs. About 100 Customer Service Representatives (CSRs) have been trained to handle any customer question or request. Call Centers are typically categorized by whether they are inbound, i.e. receiving incoming calls, or outbound, i.e. placing outgoing calls, or a combination of the two. The SMUD Call Center is strictly an inbound center.

Over the years, the SMUD Call Center has become increasingly computerized, giving CSRs the opportunity to resolve issues directly on integrated computer software, rather than referring a matter to another department via a paper or electronic request. As the center has evolved, success as a CSR has favored

[1] Industry Report 2000, Office of Occupation Statistics and Employment Projections, Bureau of Labor Statistics, US Department of Labor

younger workers with sophisticated computer skills over older workers who developed extensive experience with the internal workings of SMUD departments over time.

Employee turnover within SMUD is traditionally very low, as the public utility provides excellent wages and job benefits. The Call Center also traditionally had a very low turnover rate, and had many CSRs who had worked there for their whole careers. Recently, however, the Call Center has been viewed as a training ground for promotion within the company. As a result, turnover has increased as CSRs move on to other jobs within the company, and new CSRs are trained to replace them. During our study there was a 10% annual turnover rate.

4.1.1 Physical Layout

The Call Center is located in the southwest wing of the CSC building, a space 65' wide and 117' long, with the long dimension oriented east-west. Along the north and south walls there are large windows designed to maximize daylight penetration into the space. An internal central aisle runs down the length of the Call Center, allowing entry into various subsections of cubicles.

Customer Service Representatives sit at uniform cubicles, typically seven feet square. SMUD pays a great deal of attention to ergonomics, and each employee has a chair and keyboard customized to their size and preferences. The cubicles are separated with three, four, or five foot high acoustic partitions. The five foot high partitions delineate boundaries between groups within the Call Center.

Each worker has a computer with a flat panel 17" screen and a telephone with a headset. Workers take calls, search for information on computer screens, enter data into forms on the computer screens and also refer to printed materials on paper. With increased reliance on computerization, the visual tasks at the Call Center have changed from primarily paper based to primarily a self-illuminated task managing files on the computer monitor. Glare on computer screens became an increasingly important concern, and largely motivated the recent change to flat panel screens.

As described earlier, workers in the Customer Services Center building are provided with a variety of individual lighting and thermal comfort controls. Each workstation is provided with a mobile compact fluorescent task light. Some workers request two and some none. There are also operable vents in the floor, which allow each worker to control the amount of ventilation provided near their desk. By lifting up the round floor register, the worker can open or close the vent fully or partially. Workers who have a workstation located near a window have two additional controls available. They can control the setting of vertical blinds at the windows, over about a six foot distance near their desk, to regulate the amount of daylight and view provided by the window. They also have the ability to open a small awning window to increase ventilation. Security protocols for the Call Center ask employees to close their blinds and windows every evening before leaving the building, thus if the worker desires them to be open they must be re-opened again in the morning.

Lighting conditions in the Call Center differed from other areas of the Customer Services Building in two ways. First, the interior light shelf was removed a number of years ago and then the upper clerestory windows along the south wall were blocked off with opaque blinds. Apparently workers felt that the light shelf was a safety hazard. Without the light shelf, the upper windows needed to be blocked to reduce glare problems. Secondly, we were told that the electric lights had been set at full light output, so that they no longer dimmed in response to daylight. (Ultimately, based on comparative measurements, we determined that some of the luminaires still retained some dimming function.)

4.1.2 Shifts and Group Assignments

The Call Center is organized in five shifts covering a twelve hour service period from 7 AM to 7 PM. Each shift is served by two groups, for a total of ten groups. The ten groups are distributed across the following shifts: 6:45 AM to 3:45 PM, 7:45 AM to 4:45 PM, 8:15 AM to 5:15 PM, 9:15 AM to 6:25 PM and 10:15 AM to 7:15 PM. The shifts overlap so that there is the highest population of CSRs in the middle of the day when there tends to be the greatest number of incoming calls, and the lowest population at the beginning and end of the day (see Figure 19).

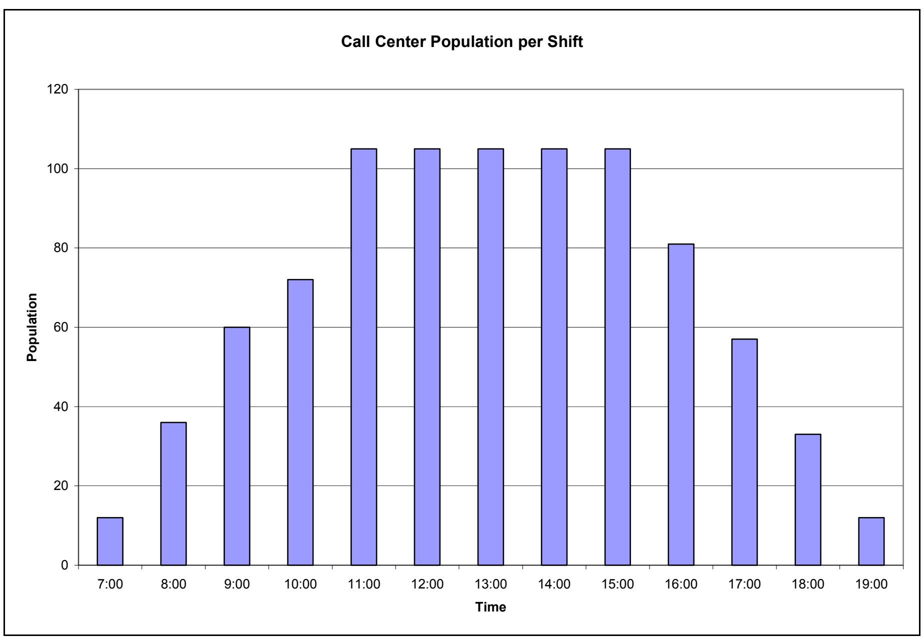

Figure 19: Population of Call Center by hour of the day.

Employees are organized by their workgroup and their shift. Each workgroup consists of nine CSRs who share a shift, along with a team leader and a supervisor who sits with them. Generally, an employee sits in an area with other members of his or her workgroup, surrounded by five foot high partitions to denote the “workgroup neighborhood.” Thus, people who sit near each other most often share the same shift and team identity. In general, we were told that the early shifts are considered most desirable and tend to be selected by the employees with the longest tenure. The two workgroups with the earliest shift, starting at 7 AM, are located along the north windows.

The Call Center has a system of “rovers,” employees who do not have a permanent seat assignment, but rather sit in workstations temporarily vacated by other employees who might be on leave, vacation, sick or at a training assignment. The roamers are given temporary seat assignments that might vary from one day at a minimum to up to a month or more. There are also a handful of employees who have decided to change shifts but remained in their old location or with their former supervisor. Thus, while cubicle location in the Call Center tends to denote which shift and group an employee belongs to, there is some diversity created by these two exceptions to the rule.

4.1.3 Management

The SMUD Call Center is very tightly managed. Supervisors have access to real-time performance metrics on all of their employees. Each worker typically handles six to eight calls per hour, which includes both time talking with the customer (Average Talk Time) and time spent completing the necessary forms or reports (Average Work Time). Together, these two metrics are combined as Average Handling Time (AHT), which is the bottom-line measure of individual, group and department performance. The SMUD Call Center typically has daily AHT ranging from six to eight minutes per call.

Employees are given continuous and instantaneous feedback on the performance of the Call Center via animated LED signs posted around the work area that report on the current call wait time and other metrics of group performance. Thus, they can gauge their actions based on the current status of incoming calls. When the number of incoming calls is very low, or the wait time very short, there is less pressure on the group, and individual CSRs are more likely to take breaks or engage in catch-up work. When the number of calls increases and/or the wait time increases, CSRs are urged to pick up the pace to help keep the wait time within management goals. CSRs are judged by their AHT on a daily, monthly and yearly basis, and given rewards for faster overall performance, including both immediate prizes and long term salary increases. Both individuals and groups with the best or most improved performance metrics are given public recognition for good performance.

In addition to the full time CSRs, the Call Center has a number of strategies to bring in additional resources when the number of incoming calls is especially heavy. This includes asking employees to work overtime on days with expected heavy call rates, such as the first of the month; having supervisors and assistant supervisors leave administrative tasks to help out with the extra call load when needed; and using supplementary employees on other assignments to help fill in during heavy periods. Schedulers predict heavy call periods and bring in extra staff as anticipated.

In addition to speed, the SMUD Call Center also monitors quality of service in a number of ways. CSRs are given training on an almost monthly basis in new methods and procedures. Supervisors selectively monitor calls and also are available to help out with difficult calls. All CSRs are given a quality performance review at least annually, based on a sampling of their recorded calls, so that they are also getting continuing feedback on the quality of their performance.

4.2 Selection of Study Population and Period

The Call Center had a total of 129 employees located in the first floor of the CSC building during our study period. Out of these, a total of 100 full time Customer Service Representatives were selected for our study population. The total Call Center is divided into 10 teams, consisting of one supervisor, one assistant supervisor and 10 Customer Service Representatives (CSRs). The final population included:

- All regular Customer Service Representatives (80)
- All assistant supervisors (10), since they spend about 50% of their time acting as a CSR (called "team leader" later in this report)
- All rovers (10), who do not have a permanent desk, but work at desks vacated by other absent employees.

4.2.1 Two Phase Study

We undertook the study of the SMUD Call Center in two phases, an initial pilot study of the daily performance of Customer Service Representatives (CSRs) during September of 2002, and a more detailed hourly study during November of 2002. We scheduled our study periods to avoid disruptions to the workflow expected by the Call Center management. The September study period was treated as a pilot. The data was collected and analyzed quickly in order to inform the data collection efforts for the second, more detailed phase.

In October of 2002 the Call Center was scheduled to make an upgrade in tone module of the information software that CSRs used, along with rotating training sessions planed to bring all of the CSRs up to speed in using the new module. Thus, we avoided studying the Call Center while this transition was in progress. We were also told that the nature and intensity of incoming calls and employee performance were likely to change during the holiday period between Thanksgiving and New Years, so we also wanted to avoid that time period for our study. Thus, we ultimately collected data for two time periods, four weeks in

September 2002, hereafter referred to as Phase 1, and three weeks in November 2002, called Phase 2.

We were further informed that Mondays, the first and fifteenth of the month and the day after holidays tended to have heavier loads, and additional staff was often assigned to handle these conditions. Therefore, we set our study period to avoid these times. We processed data for Tuesday through Friday, avoiding Mondays. The two study periods also managed to miss holidays and the 1st and 15th of the months. By avoiding studying Mondays we minimized our intrusion onto the Call Center during its busiest time.

4.2.2 Employee Data

The Call Center management gave us access to information on the daily (September) and hourly (November) performance of CSRs, along with some basic information about the individuals. This was provided in either paper or electronic formats. Identification numbers were used to preserve employee confidentiality. The Call Center management specifically did not give us detailed demographic information, such as sex, age or education level, in order to further preserve employee confidentiality.

We were provided with the following information about each employee:

- *Hire Date*, the date each employee was hired as a Customer Service Representative, as a measure of experience with the job.
- *Job Status*, team leader, rover, full time or part time
- *Group*, indicating to which group and shift each employee belonged
- *Location*, cubicle location in the call center.

4.2.3 Performance Metrics

Performance metrics were derived from a report called a Daily Agent List. The report details an individual Customer Service Representative's performance on a daily or hourly basis, as recorded by the computerized monitoring system.

- *Average Talk Time (ATT)*, the time spent by the agent talking to the client on the phone. This information is reported per individual per hour per day.
- *Average Work Time (AWT),* the time taken to wrap up the call or do paper work related to the call after the call is over. It also includes time a caller is put on hold and the agent is working on information for the caller. This information is reported per individual per hour per day.
- *Average Handling Time (AHT)*, the total of the average talk time and average work time. This information is reported per individual per hour per day. It is generally considered the most important metric in

evaluating individual performance. It is also summarized for the group and the Call Center as a whole.

- *Total Handling Time*, the sum of total Talk Time and Work Time per person per day. It indicates the number of hours an employee worked as a Customer Service Representative for a given day. It excludes lunch and break time, training time, time spent on administrative tasks and time away from the Call Center on other assignments.
- *Total Number of Calls Answered (ANSW)*, the number of calls answered per person and by the Call Center per day. It serves as a measure of intensity, and is used to forecast future load on the center according to daily and seasonal patterns.
- *Average Speed Answered (ASA)*, the average time in seconds it took for the center to answer an incoming call for a given hour. This information is collected for the Call Center per hour and per day. It serves as a measure of work intensity relative to worker density. It is also a very important performance goal for the Call Center as a whole to keep the hold time below a maximum threshold.

4.3 Environmental Data Collection, Phase I

The Phase 1 data was collected between September 4, 2002 and September 27, 2002. Our data collection effort was limited by the usual constraints of time and budget. In addition, we wanted to find the least intrusive methods for observing environmental changes in the space so that our study would not disrupt Call Center operations and so that we would minimize the possibility of influencing our study subjects' behavior.

Our goal was to collect information that would reflect the variation of indoor environmental conditions that workers were exposed to during the study period. We were interested primarily in how light varied in time and space, along with concurrent changes in view, temperature and/or ventilation. While we believe that acoustic conditions are likely also very important to worker performance, we did not have any instruments available to directly measure changes in acoustic conditions over time.

We settled on two primary methods of data collection: observations of the space while it was not occupied and on-going data collection via miniature data loggers. The observations during the non-occupied periods would allow us to assess variation in space under different daytime conditions. The miniature data loggers would allow us to record variation over time. In addition, SMUD agreed to make facilities records available to supplement the analysis.

We spent one intensive Saturday before the start of the study period collecting information about the physical conditions in the space. During this Saturday, we observed static conditions at all of the cubicles and took light level readings throughout the day under different blind conditions. We also installed the Hobo miniature data loggers. The details of our data collection methodology are described below.

4.3.1 Saturday Observations and Measurements

During the initial data collection surveyors from HMG collected preliminary site level data that could not be collected during the regular work hours. A team of five surveyors collected the following observations and measurements:

Horizontal Illuminance Readings

To assess daylight, we measured horizontal illumination levels along transects across the building, perpendicular to the windows. Measurements were taken every five feet, at four feet above the ground, using a handheld Minolta digital illuminance meter. Transects were taken approximately five feet apart along five column lines, indicated by letters D,F,H, J and K (see Figure 20, which also notes data logger locations by number).

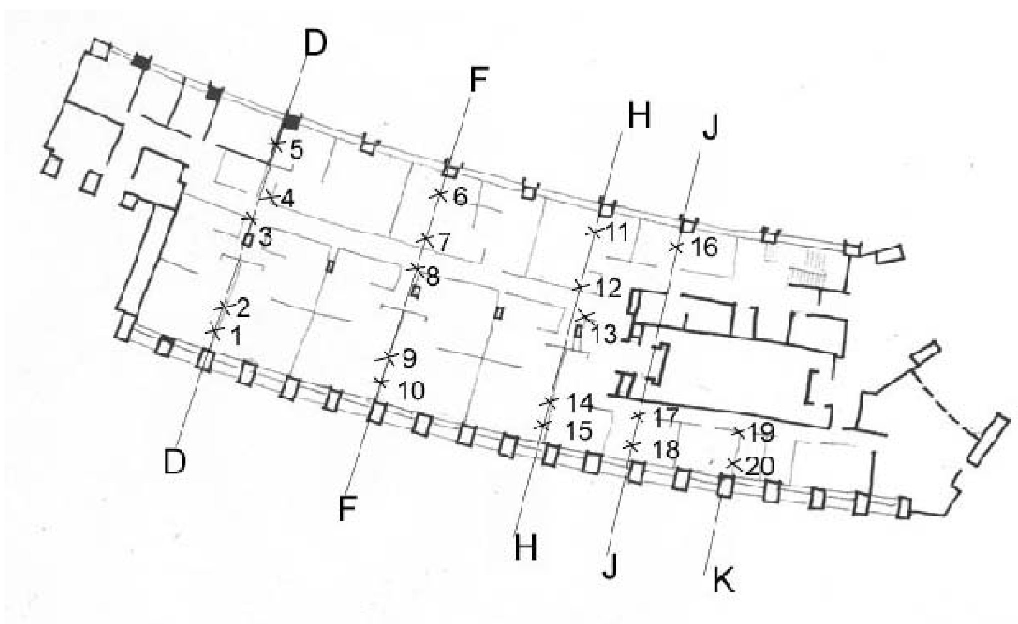

Figure 20: Call Center transects and Hobo locations, Phase 1

Data for these transects were collected under four lighting conditions and three time periods, morning, midday, and afternoon. The four lighting conditions were:

- Lights off, blinds closed
- Lights on, blinds closed
- Lights on, blinds open
- Lights off, blinds open

The overhead lights were turned on and allowed to warm up for ten minutes before readings were taken. By subtracting the readings with the lights off from the readings with the lights on we were able to derive the electric and daylight illumination levels for the various blind conditions and times of day.

Subsequent analysis of this data showed that electric lighting peaked in the middle of the space and dipped at the perimeter. The daylight levels were generally highest along the north wall, quite low in the middle of the space and rose again near the south windows. These illumination patterns are illustrated in Figure 21 below.

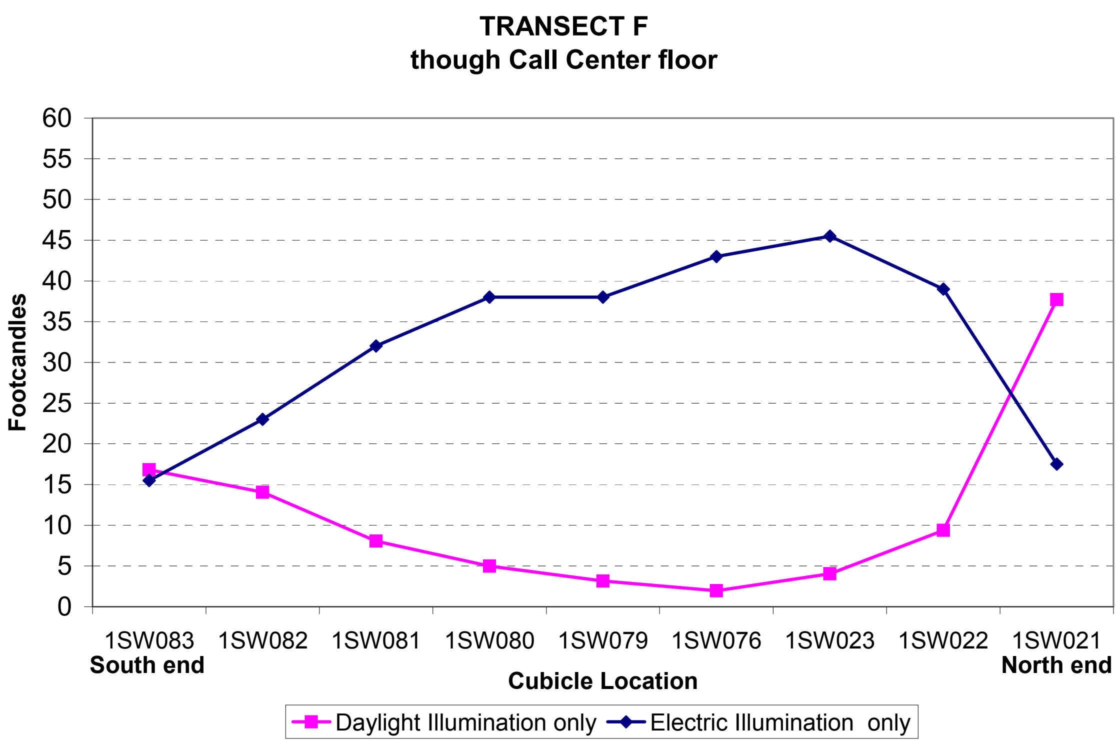

Figure 21: Daylight and electric illumination transect in Call Center

The Call Center illumination patterns, however, were not as uniform between transects as we expected. While some variability can be attributed to the variation in survey readings, there was considerable variation in both electric and daylight illumination patterns for different transects. Given this evidence of variability, we decided to collect a much finer grain of illumination data for the second phase of the study.

Vertical Illumination

In addition to the horizontal illumination transects described above, we took “cubic illuminance” measurements at points along three transects. These cubic illuminance measurements involved six readings around a hypothetical cube, one up, one down and one vertical facing in each of four cardinal directions taken at four feet above the floor level.

These readings were used to assess the differences between horizontal and vertical illuminance, and specifically the different contributions of daylight and electric light to each component. As expected, electric light was clearly strongest in the horizontal illumination readings, while daylight component was strongest in the vertical direction facing the window.

A comparison of the readings with ‘lights on’ versus ‘lights off’ revealed that the horizontal measurement of daylight was essentially the same as the average of the four vertical readings of daylight (Figure 22). This observation gave us the confidence to use horizontal measurements to represent daylight intensity throughout the rest of the study.

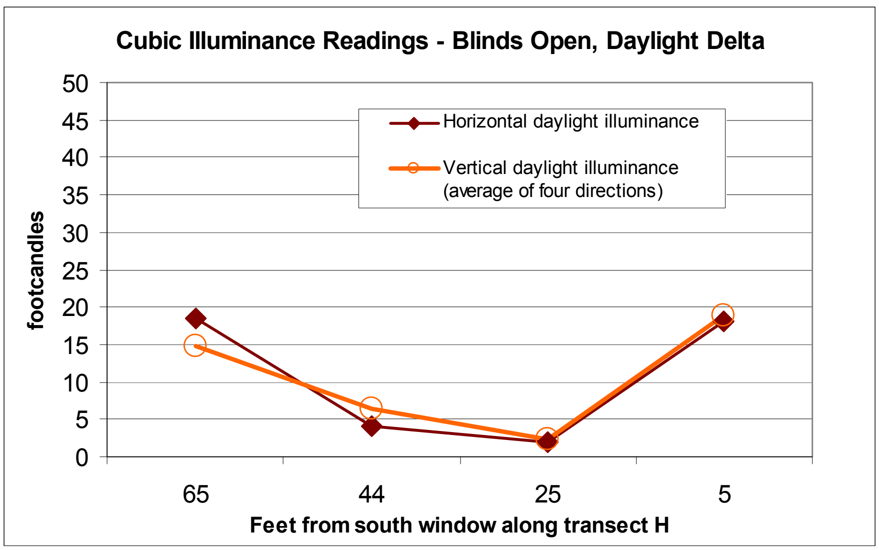

Figure 22: Horizontal versus vertical daylight readings at the Call Center

Nighttime Illumination Readings

In deriving the electric light levels by subtracting the lights off from the lights on readings, we observed more variation than could be attributed to measurement error. While we had been assured by facility management that the lamps in the Call Center were all set to maximum output, this variation suggested that some luminaires were indeed responding to the photosensors and dimming the lamps in response to daylight illumination levels. However, this variation was not uniform, as there was the potential for a different dimming setting along every 12 feet of the pendant luminaires. To establish a maximum electric illumination level we returned at night and took readings after dark. At this time all of the electric lights were on in the space, including the louvered fluorescent fixtures mounted along the south windows which were only turned on after sunset. As a result, the nighttime electric light levels were slightly higher than the daytime levels. We used these nighttime readings to calibrate the Hobo readings in order to determine an approximate electric light level per cubicle under daytime conditions.

Radiant Temperature Readings

Radiant temperature readings were taken during the transect readings at the same locations as the illuminance readings. At each location, using a Raytek Raynger Infrared Thermometer Model No. MX4, we recorded the following temperature values – ceiling, floor, desk surface, four walls or partitions around the location and windows. The radiant readings were extremely uniform throughout the space, with the exception of the window surfaces, which tended to be 2-10°F degrees warmer on the south and 1-2°F warmer on the north. Our original goal was to calculate the impact of radiant effects from the windows based on the measured glazing temperature. However, due to the modest ranges observed and the complexity of the number of possible blinds positions and seating arrangements that affect the radiant exchange between windows and people, we abandoned this effort.

View Factor

Two types of views were assessed for each cubicle location, the *Primary View* and the *Break View*. We were interested to see if the influence of view changed depending upon whether it was a constant or occasional event during the workday.

The *Primary View* was rated by sitting in the chair in each cubicle facing the computer monitor. The amount and quality of view visible within a 90 degree cone of the monitor was rated from 0=none to 5=largest, based on the methodology described below. This *Primary View* represented the view that most employees would have while working on the phone or computer. The surveyor then moved away from the desk, still sitting in the workstation chair, and rated the amount of *Break View* available from all other seated positions within the cubicle. This would be the view that the employees would get when they wished to take a break from regular work for a few moments, by turning their head or moving their chair, while remaining seated.

We did not assess a view based on standing position, as all workers in the Call Center had access to uniformly large pleasant views when standing. The highest partitions in the space are five feet high, thus even the shortest workers can still see over the top of the partitions to the high windows when standing throughout the wing.

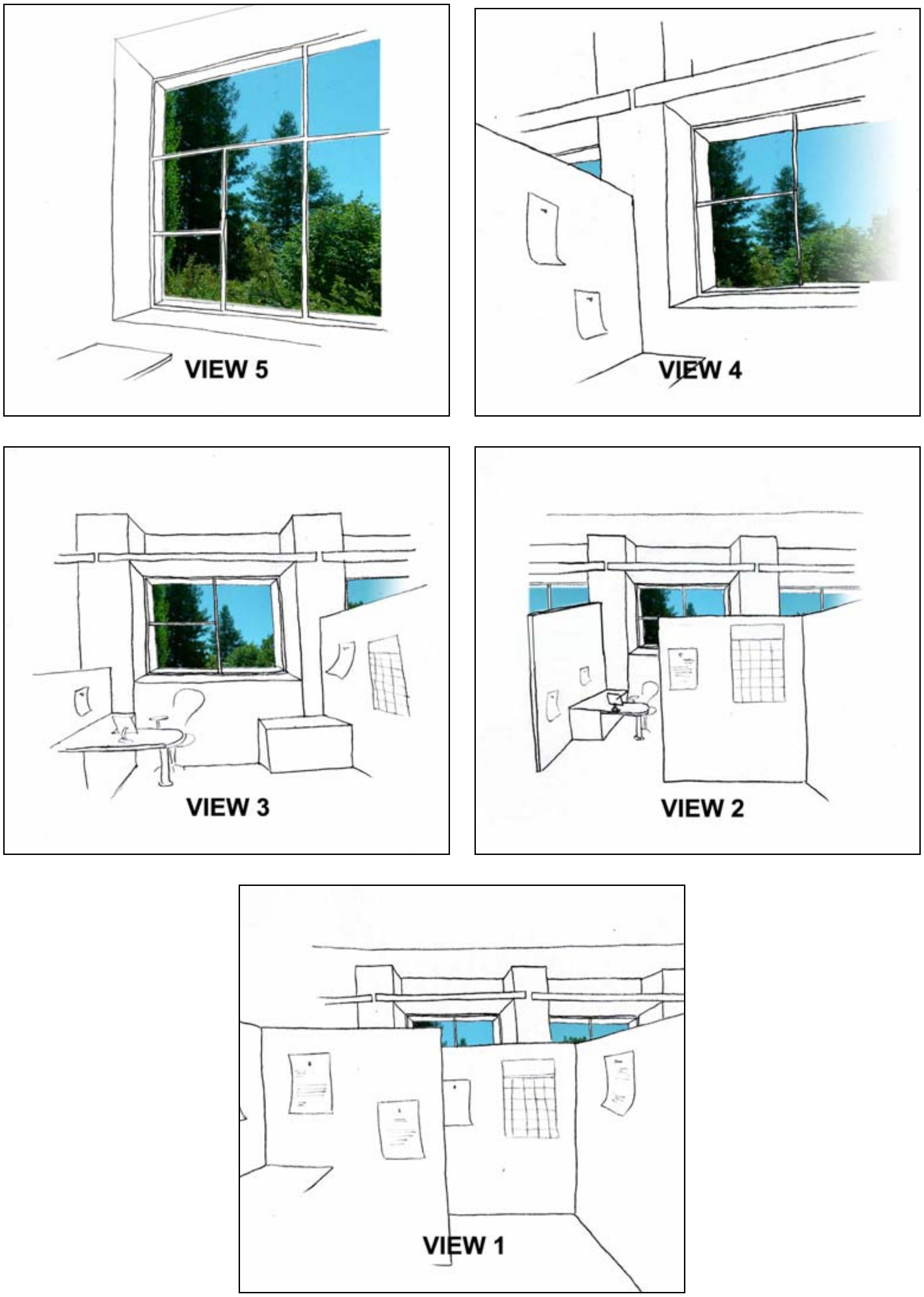

Figure 23: Examples of view ratings 1-5

Figure 23 presents images that visually represent the scale used to assess the view in this study. A view rating of 5 almost completely filled the visual field of the observer seated at the cubicle. A view of 4 filled about one-half of the visual field. A view of 3 represented about one-half the size of a view 4, but still with a coherent view. A view rating of 2 represented a narrow and typically fractured view. A view rating of 1 represented a glimpse of sky or sliver of the outside environment.

We used a single surveyor for view rating in this study, in order to insure internal consistency. However, we also tested the inter-rater reliability of the view rating process and developed a more precise metric for guidance on view rating. It was noted that the tendency of the novice raters was to rate views based on a normal curve distribution rather than absolute sizes. A viewing angle criterion was developed to insure consistency across raters. With the establishment of this viewing angle criterion, we found 90-95% consistency among the three raters tested.

The largest view rating of a 5 was defined as filling the observer's field of view. This was empirically determined to be at least a 50 degree viewing angle. Each subsequent lower category represented about one half of the previous angle. Both the vertical and lateral view angle from the point of view of the observer were considered, as shown in Figure 24.

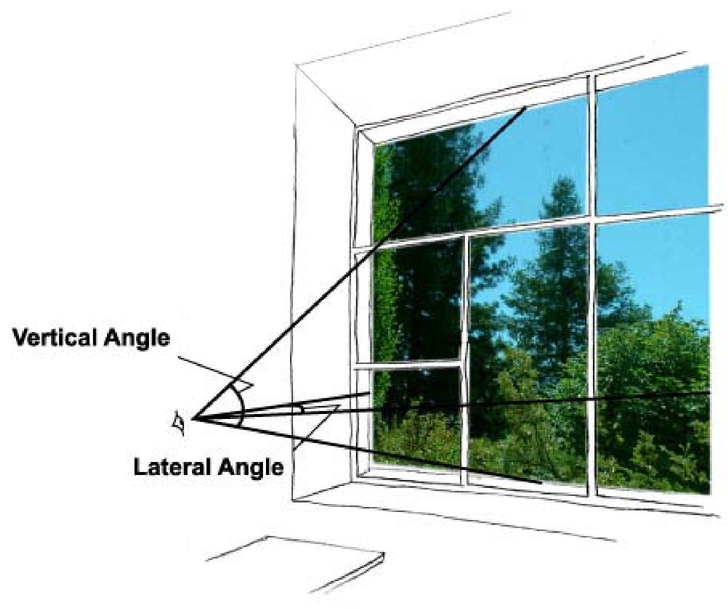

Figure 24: View angle, lateral and vertical

The smaller of the two view angles became the threshold determinant of the size of the view. This threshold view angle was used to assess the Preliminary View Rating from the table given in Figure 25. In between each clear size category was a gray zone where a view might be rated either higher or lower, depending on the content of the view.

Prelim. View Rating	View Angle	
	Min - Max (degrees)	Gray Zone Range (degrees)
1	1 - 4	
1 or 2		4 - 5
2	5 - 9	
2 or 3		9 - 11
3	11 - 15	
3 or 4		15 - 20
4	20 - 40	
4 or 5		40 - 50
5	50 - 90	

Figure 25: View rating table based on view angle

A view falling within the gray zone would be rated up a level if it had very high vegetation content and down a level if it had no vegetation content. Examples of the two extreme conditions are given in Figure 26.

Figure 26: Views with (left) and without (right) vegetation

The greatest potential view rating discrepancy was due to the height of the rater. Very short raters could see less than very tall raters, when seated in the cubicle chair. Obviously employees come in different heights also, and so their height also influences what they can see from their cubicle. We addressed this consistency issue for our data collection by sitting in the employee's chair, at whatever height it was set at, in order to partially account for employee height and preferences. We also used only one rater to maintain a consistent viewing height. Alternatively, a consistent vantage point, set at perhaps four feet above the floor, or at the center of the computer monitor for each cubicle, could also address this viewpoint consistency issue.

Cubicle Observations

In addition to taking light level readings and assessing the view, the surveyors also collected information about each cubicle to assess the micro-environmental conditions at each worker's desk. Only one surveyor assessed any given variable in order to ensure consistency. We collected more information than we ultimately used in the analysis. Much of the information, such as chair orientation, was used to cross check other information.

We noted the following information at each cubicle, based on direct observation:

- *Floor Register Status*, position of floor vent, on a scale of 0-4, where 0=missing or blocked, 1=closed and 4=fully open (as shown in Figure 10)
- *Task Lights*, number of task lights at workstation, 0,1, or 2
- *Fan*, presence of personal fan. We also noted presence of a sweater left in the cubicle for countering excessive cooling, or a local heater.
- *Partition Height*, height of partition around workstation, 0= none, 1= below eye level while seated in both directions, 2= below eye level in one direction, 3=above eye level in both directions.
- *Orientation*, of chair (NW, NE, SW, SE, or N, S, E, W). This information was collected to cross check the view and glare ratings.
- *Glare from Windows*, potential for glare from the windows at the normal working position, 0=none, 3=most. This was assessed by the surveyor while seated at the cubicle chair. A direct view of a potential bright sunlit surface (given the movement of the sun throughout the year) or sun reflecting off of cars was considered a potential glare course. Though not used in the Call Center analysis, this rating was refined and used in the Desktop study described in Section 5.3.3.
- *Glare on Screen*, potential for glare on the computer screen, yes/no. This was assessed by the surveyor looking for potential glare sources while seated at the cubicle chair, including lights, windows, or reflections of white objects. Given the flat screen monitors and shielded lighting system, there was very little glare noted on the monitors.
- *Clerestory Glare*, potential for glare from the clerestory windows, 0=none, 3=most. If the clerestory windows were in the normal field of view while seated at the computer this was assumed to be yes. This information was collected primarily to cross check the assertion that the Call Center needed to block the clerestory windows for glare protection. It was determined that approximately 1/3 of the employees

had the clerestories within their field of view and that about ¼ would be negatively impacted by glare if the blocked clerestories were re-opened. Hence, we decided not to consider altering clerestory conditions in later parts of the study.

4.3.2 Hobo Locations

The data loggers selected for collecting environmental data were small matchbox sized Hobo data loggers type H08-004-02 from Onset Technologies. These loggers have the primary advantage of being very small and economical, making it possible to record data from many points in the building over long time periods. They have other disadvantages that are discussed later in the discussion of calibration of data.

The loggers automatically collect illumination, temperature and relative humidity data at a user specified time interval. This data gets recorded on the in-built memory of the logger, and the memory capacity of the logger along with the time interval between readings determines the number of data points stored on each logger. For our study, we decided to use 15-minute time intervals between readings, in order to accommodate the four week monitoring period. The 15-minute interval also allowed us to average four readings per hour (our smallest time measure for study), thus potentially reducing data errors. Data was downloaded to a computer once during the study period, and then at the end of the study.

Figure 27: Hobo placement on a partition.

We had thirty six Hobos available during this period. The Hobos were installed along the top of the 5' high partitions in the space, as shown in Figure 27, creating a set of transects of the Call Center wing, illustrated in Figure 20. The Hobos were held down with Velcro stickers and tape. A brief introduction to the Hobos was provided on the chair of each employee near by, explaining that they only collected environmental conditions and that they needed to remain undisturbed for a few weeks. In addition, five hobos were placed on north and south window sills to collect light level readings inside of the windows, but outside of the blinds. The specifics of the Hobo data collection, calibration and analysis are provided in the Appendix.

4.3.3 Daily Observations

Since we had not verified the reliability of the data that could be collected with the Hobos under these conditions, nor proven that they would not be disturbed during the study period, we decided to also make daily observations of daylight levels and blind positions. We reasoned that if the Hobo data collection failed that we would still be able to derive daylight illuminance levels if we knew the outdoor illuminance and the blind position at each window, which could then be related to morning, noon and afternoon illuminance readings taken during the Saturday observations for a range of blind conditions. Thus, a surveyor was sent to make daily observations of blind positions.

Throughout Phase 1 of the study, one surveyor visited the Call Center each day around 1 PM during the peak population period, after all shifts had started, and before any shifts had gone home, to observe daily blind positions. The positions of the blinds at each window per day were later used to calibrate the daylight illumination levels derived from the Hobo data loggers for the Phase I analysis. In addition to the observation of blind position, the surveyor also recorded outdoor illumination levels at a set of fixed positions outside of the Call Center.

A paper-based survey form was used that noted blind position at each window, both percent drawn to fully open, and the blind angle from closed to perpendicular. This non obtrusive assessment took about 15 minutes to compete, walking down the center aisle of the Center. The Call Center employees did, however, come to notice the surveyor and were told that we were doing a “lighting study.” We hoped to minimize the novelty of the surveyor’s presence by constant repetition throughout the four week study period.

Early in the study period the surveyor spent one entire day onsite to observe all changes made to the blinds during the day. We noted that about 80% of the window blinds were adjusted twice during the day—once when the nearby worker arrived for work and once when they left for the day. (The Call Center requests that workers close all blinds at night for security reasons.) About 20% of the blinds in the Call Center were never adjusted, either left open or closed. Most likely this was because occupants could not physically reach the blind’s controls, which might be blocked by furniture, or secondarily because the mechanism was stuck. Only 2 out of 34 window systems were observed to have blinds adjusted more frequently, presumably in response to sun penetration. Thus, we judged daily observation to be a reasonable approximation of blind position.

4.3.4 IAQ Data Collection

Over the course of one day we recorded the carbon-dioxide (CO_2) levels inside the call center using a handheld CO_2 monitoring meter attached to a data-logging device. We also recorded the volatile organic compounds (VOC) in the air using another meter attached to another data-logging device for the same day. The process was rather intrusive, since the shoe-box sized assembly of equipment needed to be located on an empty desk in a central location with power outlets available and so tended to attract attention. Furthermore, due to constraints on equipment availability, we could only collect a few days of hourly data in that one location. The CO_2 values were well below the ASHRAE specified maximum CO_2 value of 1000 ppm, and varied between 400 ppm to 550 ppm over the day; with the highest values occurring between 8:00 AM to 11:00 AM.

Given the small range of variation observed, and the limitations of IAQ data collection, we abandoned an attempt for on-going monitoring of IAQ metrics in the Call Center.

4.3.5 Facilities Data

SMUD has an automated environmental management system (EMS) which is used to log and control the performance of the air handling units serving the CSC building. SMUD actively tracks numerous performance variables for the air handlers serving the Call Center. SMUD provided us with the following data for the two study periods:

- Outdoor dry bulb temperature – Hourly averages
- Air handler supply air temperature – Hourly averages
- Air handler return air temperature – Hourly averages
- Air handler mixed air temperature – Hourly averages
- Air handler supply air volume (CFM) – Hourly averages
- Call Center zone air temperature – Hourly averages
- We supplemented this information with local weather data for outside air and insolation conditions.

4.3.6 Phase 1 Interventions

This study is primarily an observational study, observing naturally occurring changes to behavior relative to normal changes in the environment. The Call Center provided a considerable range of daylight conditions between employees located near the windows and those in the core of the space, as represented in Figure 21. However, we wanted to make sure that we had sufficient variation in daylight conditions both within and between subjects for successful analysis. We were concerned that the weather in Sacramento in September was so consistent that we would not capture sufficient variation in daylight conditions between different days. The weather in Sacramento in September is typically a stable condition of clear skies with hot, sunny days. We watched the weather forecasts to see if any natural variation in day to day illumination levels might occur due to variable cloud cover. However, we received only very occasional high cirrus clouds

We were also concerned that daylight exposure would be confounded by a seating assignment bias, where workers with more seniority were more likely to be located near the windows. Thus, we sought to artificially increase the daily variation in daylight illumination levels, so that all workers near the windows would have at least a few days with little daylight exposure.

We received permission for a simple intervention in the Call Center: requesting employees to open or close their blinds for set periods. After two weeks of observing “baseline” conditions, where the employees operated their blinds according to their normal preferences, we asked the employees along the south wall to keep their blinds closed for four days, from Tuesday through Friday. Employees along the north wall were asked to do the opposite and open their blinds fully for this period. The following week, we reversed the pattern, with north blinds closed and south blinds open. This request was transmitted to the employees via the Call Center management on our behalf, as part of the “lighting study,” and, of course, compliance was voluntary. About 80% of the employees indulged our request and closed or opened their blinds for the period requested. Interestingly, we got more complaints about closing blinds from those who normally left them open than visa versa.

This intervention provided us with at least four days of data with reduced daylight levels for those employees who normally had the highest daylight levels, and higher illumination levels for those near the windows who normally left their blinds closed.

4.4 Environmental Data Collection, Phase 2

The initial data collection from September was run through a preliminary statistical analysis. Our initial findings suggested that ventilation was very important for worker performance, as indicated by the strength of the floor register status variable in predicting faster performance (see discussion in Section 4.6). We knew from our evaluation of the EMS system that the percentage of outside air delivered to the Call Center varied considerably by time of day. We also knew that our primary explanatory variable of interest, the daylight illumination, also varied considerably by time of day. Thus, we resolved to increase the level of data collection for the second phase of the study to support more detailed hourly analysis of worker performance.

The automated data collection in the Phase 2 of the Call Center study used the same environmental data and instrumentation method to record the data. We returned to the Call Center for more Saturday observations in mid October and at the end of the study period in mid November. We collected automated data at a stretch from the end of October to the end of November. However, a few modifications were made to the Phase 2 data collection based on our experience from Phase 1. The changes to Phase 2 are described below.

4.4.1 Phase 2 Saturday Data Collection

The Saturday data collection in this phase was quite similar to the Phase 1, with illumination readings taken with lights on and off, blinds closed and open, except we took handheld horizontal illumination readings at every cubicle and Hobo location, rather than just along the transect lines. This approach allowed us to calibrate each cubicle illuminance level more closely to the nearest Hobo reading.

We also noted the floor register setting to calculate the rate of change over time. We observed that about 25% of the floor vents had changed their setting, and that these were balanced between those that increased versus those that decreased the setting. About 10% of the population of the center had also changed their cubicle location between the two periods and one area of the Call Center had been rearranged to add about three more workstations.

We did not repeat all of the other workstation observations such as view and partition heights, since they were presumed to be static over time, with the exception of the few cubicles that were rearranged in one section of the Call Center.

4.4.2 Phase 2 Hobo Locations

The Hobo logger locations were changed to represent more accurately the cubicle conditions. We decreased the number of Hobo data loggers to twenty five but located more at cubicle locations near the windows, so that we could capture the variation in daylight due to individual blind position. Illuminance data collection through Hobo calibration and the calculation procedure for illuminance is described in detail in the Appendix.

We decided to record the outdoor illuminance data for this study period to capture the weather conditions across the study days and as a back up in case we lost any of the interior Hobo readings. This was done by placing two Licors (light instruments- Li-210 sa) on the roof above the Call center and connecting them to a Campbell data logger (CR-10) to record the illuminance every fifteen minutes across the study days. An average of the two Licors was taken as the outdoor illuminance every fifteen minutes, and calibrated to both Minolta and Hobo readings taken in the same location.

4.4.3 Phase 2 Interventions

In Phase 2 we also wished to conduct interventions similar to Phase 1, in order to ensure a substantial range of variation in the explanatory variables.

For daylight illumination we had more natural variation in daylight illumination in this period for two reasons. One, we were comparing hourly illuminance and performance data, which allows a greater range rather than just averaged daily data. Secondly, the weather in Sacramento in November is more variable than in September, so we were more likely to have intermittent cloud cover. Mother Nature complied and provided us with a few cloudy and one stormy day during the first two weeks of the study period. However, to ensure a range of conditions, during the final week of the study we once again also requested employees to close or open their blinds, but this time only for one day each. Again, about 80% of the employees complied with our request.

In addition to variation in daylight illumination, we were also interested in variation in ventilation, since our Phase 1 preliminary analysis had pointed to the strong influence of ventilation on worker performance. Determining the rate of ventilation air in the Call Center, or the Customer Services Building as a whole, is an enormously complicated issue, given the complexity of the HVAC system and the number of options of direct occupant control. Ideally, we could have measured air quality over time at many cubicle locations, as we did with illumination and temperature. However, we did not have miniature air quality data loggers available for this task. Our attempt to measure air quality over time (see Section 4.3.4) was limited by the constraints of having only one fairly large piece of equipment.

We decided that the most useful ventilation metric available would be the rate of outside air delivered per hour by the HVAC system. To ensure a range of conditions in outside air delivery which would not be collinear with outside weather conditions (time of day, outside air temperature, and thermal load created by the sun) we requested that the facilities department disable the Call Center economizers for two days at the end of the study. When they did this, the outside air delivered was reduced to the base levels maintained by the system at all occupied times.

4.5 Variable Definition and Statistical Methodology

The information that we collected from the Call Center and from our various on-site investigations was then transformed into outcome and explanatory variable that could be used in the regression analysis. The outcome variables were all based on Average Handling Time (AHT). The explanatory variables can be classified into three basic types:

- **Demographic variables**, which described the status of the individual employee. These are reported as Personal Status and Group Assignment in the results tables.
- **Performance variables**, which describe conditions in the Call Center, such as number of incoming calls and the number of staff working at a given time. These are termed Call Center Status in the results tables.
- **Environmental variables**, collected onsite, which described the physical environment to which the employees were exposed. These are grouped into the categories Light, View, and Temperature and Ventilation in the results tables.

In transforming the raw data into variables for consideration in the models we had a number of choices to make, as described below.

4.5.1 Daily, Hourly and Lagged Variables

We received both individual and Call Center performance variables in hourly and daily values. For the September analysis, which only looked at average daily performance, we used the daily performance data received from SMUD. For the November analysis that looked at both daily and hourly performance, we calculated daily averages based on the shift of each individual. Thus, rather than using the 12 hour daily average for Average Speed Answered (ASA) provided to us by SMUD, we calculated the individual's daily average based on the 8 hours of their shift, so that for the same day, workers in the early morning and late afternoon shifts could have slightly different daily average values.

Similarly, for both the September and November Daily analysis, we calculated individual daily averages for the physical variables that varied by hour, such as daylight illumination and outside air in cubic foot per minute per square foot (CFM/sf). Thus, we created daily averages for the 8 hour shift that an individual worked.

In the November analysis we were interested to see if the model showed a better fit if we used daylight illumination of the time under study, or the illumination from the previous time period, either the hour before the measurement of performance or the day before. Thus, for the November analysis we also created "lagged" variables that described the illumination levels of the earlier time period, either the hour before or the day before.

4.5.2 Choice of Linear versus Logged Variables

We had a choice of using linear or logged variables for both the outcome and the explanatory variables. Regression models try to fit lines that best describe a plot of data points. Multivariate models consider more than one dimension at once.

Linear models fit straight lines through the data. It is also possible, but more complex, to consider curved, or non-linear, relationships. The most common way to do this is to redefine a variable as a natural log[1] function. This can be done with an outcome variable, an explanatory variable, or both.

Log variables have often been found to be highly appropriate for models dealing with variables likely to have diminishing effects as their size increases. A logarithmic function requires that the variable be defined on a continuous scale, and also that it does not include any values less than or equal to zero, since the natural logarithm function is only defined for positive numbers. Thus, only some variables can be converted to natural logarithms. In addition to meeting the mathematical criteria for taking the log of a variable, a logged variable should also have a logical explanation for why a diminishing effect might be expected as the scale of the variable increases. Candidates for logged functions can also be tested by looking at the spread of their data. When the data distribution is skewed with the highest density of data in the lower values and increasing fewer data points out at the higher values, then a logged function is likely to be appropriate.

Candidates for logged variables in the office studies are timed functions, such as Average Handling Time (AHT). The assumption is that if there is a problem with a one minute call that might make it take twice as long, it is more comparable to a problem with a 10 minute call that makes it take twice as long, at 20 minutes, than to a problem that adds only one minute to the handling time.

Other candidates for logged variables include descriptions of illumination levels, since the eye basically responds to light intensity on a log scale, with a very narrow range of sensitivity at a low light level (such as at night) and a huge range of sensitivity at high light levels. Typically, people will not perceive 100 footcandles as ten times as much light as 10 footcandles, as the footcandle measurement scale implies, but closer to two times as much light, per a log response. Thus, taking the natural log of the footcandle readings creates a scale closer to human visual perception.

In the Call Center data we found a number of variables that met these criteria, and we tested those variables both with and without the logged function. We also tested alternative forms of other variables, looking for the format of the variable that most accurately captured a relationship to the outcome variable. For example, we considered models with both *View Factor* (total view rating form desk) versus its component parts *Primary View* and *Break View*.

4.5.3 Outcome Variables

The outcome variables for the Call Center models were all based on the Average Handling Time (AHT), which is the most fundamental measure of performance

[1] A logarithmic function based on the natural number “e”

for the SMUD Call Center. The AHT is the hourly average handling time per call in minutes, or the sum of the average talk time and wait time per call. It is used to evaluate worker performance on an hourly, daily, or monthly basis. It also serves as the measurement of how well the shift groups and the Call Center as a whole are performing. The AHT for the SMUD Call Center for all of 2003 averaged at about seven minutes. The distribution of the hourly data was fairly strongly skewed, with more calls in the short range. Ten percent of all calls were shorter than four minutes, while at the other end of the scale, another 10% of the calls were longer than 11.5 minutes. This distribution is shown in Figure 28.

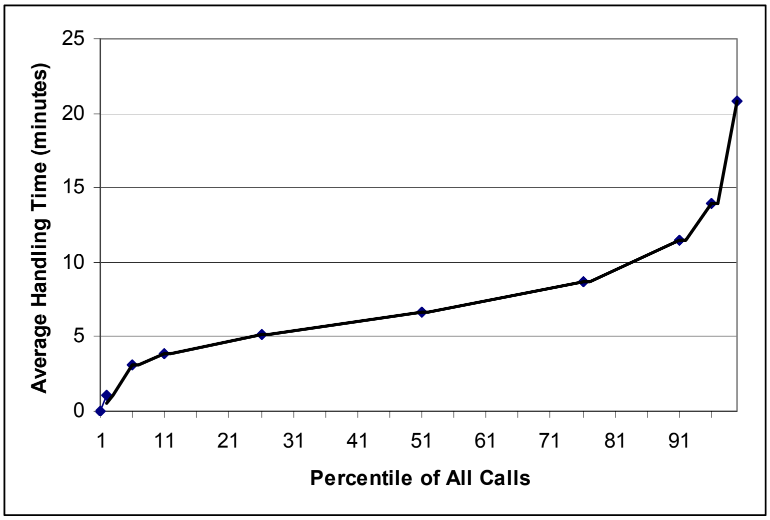

Figure 28: Hourly Average Handling Time, cumulative percentiles

Upon examination of the data, and in consultation with the Call Center we removed hours at the extreme end of the data to obtain an average AHT for the study period of around 7 minutes. Hours with an AHT longer than 9.33 minutes were assumed to represent "problem" hours, needing higher level resolution often with the assistance of a supervisor. Hours with an average talk time shorter than 1 minute and hours with an average work time of 0 minutes were assumed to represent partial work hours involving only single calls that were wrong numbers or hang ups. The exclusion of the extreme hours gave us a more normal distribution of the data and allowed us to analyze a more typical range of calls that involved CSR skill.

The distribution of the daily data was much less skewed, since the more extreme conditions had been blended into the daily averages. Thus, we hypothesized that we should use the logged AHT for the hourly models but stay with the linear version for the daily models. We tested our hypothesis by comparing the fit for the logged and linear AHT for each of the daily and hourly models. It is not possible to directly compare the mean squared error (MSE) and the R-square between models with logged and linear outcome variables, so we used the Box-Cox transformation for this comparison. Using this comparison, for the daily model, the linear average AHT model indeed had a better fit than the logged average AHT model. For the hourly model, the logged AHT model had a better fit. Therefore we concluded that we should use the linear average AHT for the daily model and the logged AHT for the hourly model.

4.5.4 Explanatory Variables

Below, we list all of the explanatory variables considered in the Call Center analysis. Our primary variable of interest was the amount of daylight each worker was exposed to on either an hourly or daily basis. In addition, we were also interested in exploring the effects of variation in temperature and ventilation. In order to properly control for these variables of interest we added other information about each employee's workstation conditions including the quality of their window view, their employment status and the overall condition of the Call Center in terms of population density and number of incoming calls.

While all of these variables described below were tested at some point in the preliminary models, not all of them were selected for consideration in the final models. For those that were dropped we offer a brief explanation why. When data has multiple forms, the more general format is listed first and the alternative formats which were considered are indented.

Lighting

The environmental variables describe the range of illumination, temperature and ventilation conditions that were observed in the Call Center. These were formatted separately for the daily and hourly analysis.

A number of variables were created to describe the amount of daylight and electric light that each worker was exposed to, since we wanted to test the most appropriate way to model exposure to the intensity and variability of the lighting conditions. These included both linear and logged versions of the variable average, range and standard deviations and a lagged version that described the employee's exposure to light in the previous day or hour. A detailed description of the calibration and calculation procedure for illuminance variables is given in the Appendix.

- ***Daylight Illuminance*** (*DI*) the average horizontal daylight illuminance for a single hour. It was created by subtracting the estimated electric illuminance from the total calibrated illuminance reported by the Hobos. We tested a variety of formats of the Daylight Illuminance variable, including linear and logged version, concurrent and lagged versions, and both the average reading and the standard deviation for a given time period.
    - ***Log Daylight Illuminance*** (*log_di*) the natural logarithm of *DI*

- ***Lag Daylight Illuminance*** (*lag_di*) the daylight illuminance for the previous hour
  - ***Log Lag Daylight Illuminance*** (*log_lagdi*) the natural logarithm of *lag_di*
- ***Standard Deviation of Daylight Illuminance*** (*DI_std*) the standard deviation of hourly *DI*
  - ***Log Of Standard Deviation of Daylight Illuminance*** (*log_distd*) the log of standard deviation of *DI*
- ***Average Daily Daylight Illuminance*** (*DI_avg*) the average daylight illuminance for the time period of the shift to which the employee belongs
  - ***Log Daily Daylight Illuminance*** (*log_diave*) the natural logarithm of *DI_ave*

- ***Total Illuminance*** **(TI)** the horizontal illuminance in footcandles recorded by the Hobos, which includes electric and daylight illuminance
  - **Log Total Illuminance** (*log_ti*) the natural logarithm of *TI*
  - **Lag Total Illuminance** (*lag_ti*) the total illuminance for the previous hour
    - **Log Lag Total Illuminance** (log_lagti) the natural logarithm of lag_ti
  - **Average Daily Total Illuminance** (TI_ave) the average total illuminance for the time period of the shift to which the employee belongs
    - **Log Daily Total Illuminance** (*log_tiave*) the natural logarithm of *TI_ave*
- ***Range of Illuminance*** (RI) the range in footcandles that a certain cubicle is exposed to over the course of a day. It is another measure of the variability of daylight conditions, similar to the standard deviation of DI, but using minimums and maximums rather than a normal range. It was used for the September study period. To calculate RI, minimum and maximum hourly average hobo readings of total illumination were identified between 7:00 AM to 7:00 PM for all the study days.
  - ***Log Range of Illuminance*** (*log_ri*) the natural logarithm of the RI
- ***Electric Light Illuminance*** (*TImin*) the horizontal illuminance in foot candles from the electric lights in the building.

- ***Log Electric Illuminance*** (*log_timin*) the natural logarithm of *TImin*

View Characteristics

See Section 4.3.1 for a discussion of the rating procedure for views.

- ***View Factor*** (*VF*) 0-10, the size of view of the outside that the employee has from anywhere in his or her workstation. It is the sum of *Primary View* and *Break View* described below.
  - ***Primary View*** (*VP*) 0-5, the view of the outside that the employee has when s/he is seated at his/her desk and looking directly at the monitor
  - ***Break View*** (*VB*) 0-5, the maximum view of the outside available when the employee is seated anywhere within his/her workstation and looking away from the monitor

Distance from a window was created as an alternative variable to descriptions of view or illumination levels.

- **Location on North or South Side** (*LocationN/LocationS*) two yes/no variables to identify if the cubicle is located within the first two cubicles from the north wall or the south wall. The default was cubicle located in the core, three or more cubicles from a window.
  - ***North Feet to Window*** (*North_fttowin*) the distance in feet of the cubicle from the nearest window, for those employees seated on the north side of the building wing
  - ***South Feet to Window*** **(***South_fttowin*), the distance in feet of the cubicle from the nearest window, for those seated on the south side of the building wing

Temperature and Ventilation

- ***Temperature*** (*Temp*) the hourly average value of air temperature in deg F recorded from Hobos. Comparison of temperature readings between Hobos in a uniform environment showed their readings to vary within a tightly constrained range, thus we considered them reliably calibrated.
  - ***Average Daily Temperature*** (*temp_ave*) the average temperature for the time period of the shift to which the employee belongs
- ***Relative Humidity*** (*RH*) the average relative humidity in percent. This variable was later dropped from the analysis, as the calibration variation was bigger in magnitude than variation recorded between days

- **Outside Air CFM** (*CFM_Metric_sf*) the rate in cubic feet per minute of outside air introduced into the space via the HVAC system, per square foot averaged for a given hour,. This metric was only available for the November study period.
  - ***Average Daily Outside Air CFM*** (*cfmsf_ave*) the average outside air CFM for the time period of the shift to which the employee belongs

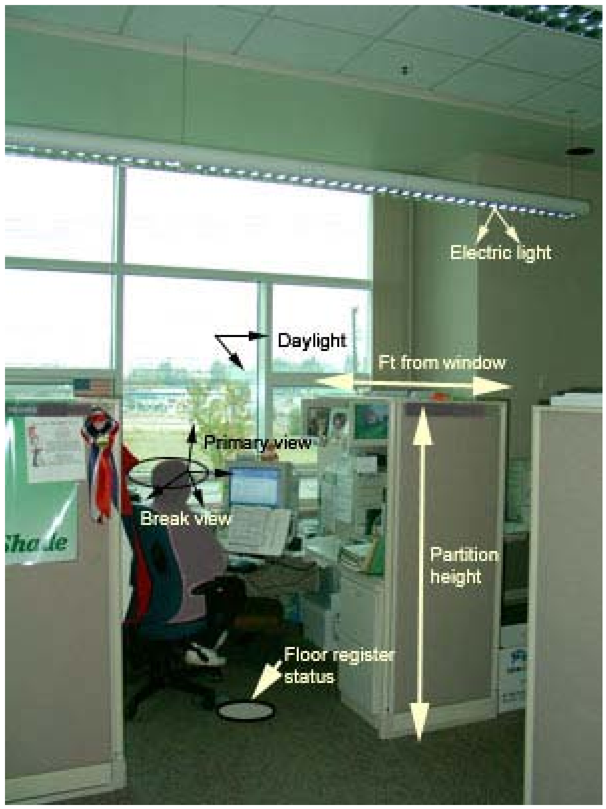

Figure 29: Diagram of the workspace environmental variables

Other Workstation Characteristics

Data for each of the workstations for the employees in the Call Center were recorded on Saturday site visits to SMUD. These variables give a description of the condition we observed at each workstation (see Figure 29).

- ***Number of Task Lights*** (*TaskLts*) 0-2, the number of task lights we found at the employee's workstation
- **Personal Fans** (*Fans*) a yes/no indicator if we found a personal fan at the employee's workstation
- ***Status of Floor Register Vents*** (*FlRegStat*) 0-4, an indicator of the position of the vent on the floor register at an employees' workstation,

with 0 = missing or blocked, 1= completely closed, 2 = 10-40% open, 3 = 50-80% open, 4 = fully open

- ***Partition Heights*** (*Partitions*) 1-3, an indication of height of partitions surrounding a cubicle. 1= low, all below sitting eye level, 2 = one-half low, one-half high, 3 = high, all above sitting eye level

Personal Status

We were given limited demographic information about individual Customer Service Representatives in order to preserve their privacy. We were able to create the following variables describing the status of individuals:

- ***Number of Days on Job*** (*Daysonjob*) the number of days since the date the employee began work as a Customer Service Representative
    - ***Log Number of days on Job*** (*log_daysonjob*) the natural logarithm of *Daysonjob*
- ***Part Time Status*** (*WkStatusPT*) a yes/no variable indicating employees who normally work less than 40 hours per week
- ***Team Leader Status*** (*WkStatusSen*) a yes/no variable indicating an assistant supervisor, typically an employee recognized as experienced and highly productive who splits their time about 50/50 between taking calls and doing administrative work
- ***Groups*** (*Group A-Group J*) the shift group to which the employee was assigned. This also included the roamers in the group. The Call Center tracks and reports performance by groups. We renamed the groups in order to preserve confidentiality.

Call Center Status

Call Center status variables were created from the performance data provided to us by SMUD. This data was collected from the Call Center's automated performance monitoring software. The software continuously logs information about the status of incoming calls. The information was reported to us in daily averages for September and one hour averages for November. For November we created individual daily averages for each worker based on their shift times.

- ***Hourly Population*** (*hourpop*) the count of the number of employees logged into the system available to take a call at a single hour
    - ***Average Hourly Population*** (*hourpop*) the population per hour of the call center
    - ***Daily Population*** (*hourpop_avg*) the average daily population during a given work shift. Morning and evening shifts have lower daily averages than shifts in the middle of the day

- ***Average Time to Answer*** (*Answ*) the number of calls answered (Hourly Total for Call Center)
    - ***Hourly Answ*** (Answ_ave10) the daily average "*Answ*" for each person's shift. This was then divided by 10 to reduce the scale of the variable.
    - ***Daily Answ*** (Answ_10) the total number of calls per hour for call center divided by 10
- ***Average Speed Answered*** (*ASA*) the average time in seconds it took for an incoming call to be answered. We ultimately used the natural log of these values as they produced better fit in the models.
    - ***Log Hourly ASA*** (*log_asa*) the natural logarithm of the hourly *ASA*
    - ***Log Daily ASA*** (*log_asa_ave*) the natural logarithm of the daily ASA,.
- ***Hourly Indicators*** (*hour1 to hour12*) twelve yes/no variables indicating the hour from 7:00 AM to 6:00 PM. We tested these hourly indicators in preliminary hourly models, but found that they were confounded with too many other variables that also varied by hour, such as population and CFM/sf. Thus they were dropped in favor of the two variables below:
    - ***Not Present on Previous Hour*** (*prevmissing*) the employee was not logged into the system on the previous hour. This could be the case when the employee starts work, hence the first hour of the day, or the hour right after a break such as lunch. It was used to indicate an employee returning to the Call Center from outside.
    - ***Last Hour*** (*lasthour*) an indicator of the last hour that the employee was logged into the system for a given day. It often represents only a partial hour of work, and so the values of AHT tended to be exceptionally short or long.

4.5.5 Statistical Methodology

All of the analysis was pursued using multivariate regression models run in SAS statistical analysis software. The analysis used $p \leq 0.10$ as the threshold criteria for inclusion of explanatory variables in the models, meaning that for a variable to be considered significant, there must be no greater than a 10% chance of error in making this decision, or 90% certainty. All statistical terms are explained in the Appendix.

Preliminary analysis of the data was performed to test for heteroscedasticity and collinear variables. Alternate forms of both outcome and explanatory variables were considered, such a linear versus logged versions, as discussed above. Models were judged based on their R^2 (the percentage of variation in the data explained by the model), the parsimony (minimum explanatory variables for maximum explanatory power) and consistency between the models.

4.5.6 Variable Selection Method

There are 3 stepwise variable selection procedures that are often employed in linear regression: forward selection, stepwise selection and backward elimination. The forward selection procedure starts with an equation that contains only the constant term and successively adds explanatory variables one-by-one, until the last variable added to the model is insignificant. Stepwise selection is essentially a forward stepwise procedure, with the exception that at each iteration, the possibility of deleting a variable is also considered.

The backward elimination method first calls for fitting a model using all potential explanatory variables and calculating the t-statistic associated with each variable. The explanatory variables are then deleted from the model one-by-one, until all variables remaining in the model are associated with a significant t-statistic. During each iteration, the variable with the least explanatory power is identified and deleted from the model.

The RLW variable selection method,[1] used in this study, is a variant of the backward elimination method. Similar to the backward elimination method, the RLW variable selection method begins with calculating a model using all potential explanatory variables and the associated t-statistics. However, the RLW method allows for the deletion of multiple variables during each iteration, whereas the backward elimination method does not. This procedure helps to identify collinearities between insignificant variables, which might otherwise be dropped without first understanding how such collinearities could potentially influence results. Specifically, the RLW method consists of the following steps:

1. Calculate a “full” linear regression model including all potential explanatory variables.
2. Identify all insignificant variables from the model resulting from step 1.
3. Perform an F-test to test whether the set of individually insignificant variables are statistically significant as a group. Specifically, the null hypothesis of the F-test is that the beta coefficients of each of the variables in the group are zero, while the alternative hypothesis is that there is at least one variable in the group for which the beta coefficient is not zero. If the F-test shows the set of variables are not statistically significant as a group, all variables identified in step 2 are also identified

[1] The RLW variable selection methodology was developed by Dr. Roger Wright, lead statistician of this study.

for deletion. If the set of variables tested is statistically significant as a group, this indicates there is a collinear relationship between the variables that is affecting the model. In this case, a reduced set of variables is defined for the F-test and deletion from the model.

4. Calculate a reduced model including all explanatory variables that were not identified for deletion.
5. If any previously significant variables become insignificant in the reduced model, calculate an F-test for all variables previously deleted from the model and the newly insignificant variables under the guidelines provided in step 3.

4.6 Call Center Findings and Discussion

This section describes the findings of the Call Center models and offers some interpretation.

To facilitate interpretation, the findings are presented in a variety of formats. The primary comparison between models is done via percentage effects, derived from the B-coefficient for each variable, as described below. For the final models, we also present information about the significance, order of entry and partial R^2 of each variable. The order of entry discussion includes possible mechanisms to explain the behavior of each physical variable.

4.6.1 Percentage Effects

The percentage effect shows how much the outcome variable would change over a certain range of that variable, if all other factors considered in the regression equation were held constant. If the variable is a simple yes/no variable, then the percentage effect is the model prediction for when that variable is "yes" and all other variables are held constant at norm. If the explanatory variable is logged, such as daylight illumination, then the percentage is based on a 10% increase in that variable. If the variable has a linear scale, we choose an understandable and likely value, such a two degrees warmer, or ten more people in the Call Center.

For a linear outcome variable, as we used for the two daily AHT models, the percentage effect is calculated by multiplying the B-coefficient by a specified range and then dividing by the mean of the outcome variable. For a logged outcome variable, such as the natural log of hourly AHT that we used for the November Hourly model, the percentage effect is essentially the B-coefficient for that variable. Full descriptive statistics and SAS output for each model are provided in the appendix.

Figure 30 summarizes the percentage effects for the three Call Center models over the specified ranges of the explanatory variables. Percentage effects are only shown for those variables that were found significant ($p<0.10$). Dashed lines indicate that a variable was not considered in a particular model. Those explanatory variables that have a consistent effect across all three models are underlined.

The positive effect shown in the white column indicates improved (faster) performance. A negative effect shown in the gray column indicated poorer (slower) performance. For example, in the daily September model a worker with the best *Primary View* is seen to perform 6% faster than those workers with no *Primary View*, but to have no significant change in the November models.

Variable Name	Range	Daily Models: September R2 =0.211		Daily Models: November R2 =0.223		Hourly Model: November R2 =0.078	
Lighting							
Daylight (nL)	if increased by 10% …				-0.2%		
Electric Light (nL)	if increased by 10% …					0.3%	
Total Light Range (nL)	if increased by 10% …		-0.2%				
Number of Task Lights	from none to 1 additional …		-7%				
Daylight Range (nL)	if increased by 10% …	----	----			----	----
View							
Break View	from none to best …	6%		7%		7%	
Primary View	from none to best …	6%					
Partition Height	from none to highest …		-11%		-11%		-18%
Distance to North Wall	if 10 ft more …			3%		5%	
Distance to South Wall	if 10 ft more …						
Temperature and Ventilation							
Indoor Air Temperaure	if increased by 2 deg F …						-2%
Floor Register Status	from closed to open …	10%		3%		4%	
Personal Fan	If yes …						
Outside Air Delivered	if increased by 1 CFM/sf …	----	----			4%	
Call Center Status							
Average Seconds to Answer (nL)	if increased by 10% …		-0.9%		-0.6%		-0.7%
Total Calls Answered	if 100 more calls per hour …			11%		9%	
Population	if 10 people more …				-14%		-12%
Personal Status							
Part Time Worker	If yes …						
Team Leader	If yes …	19%		17%		18%	
Years on Job (nL)	if 10% more …		-0.1%		-0.2%		-0.1%
First Hour of Shift	If yes …	----	----	----	----		
Last Hour of Shift	If yes …	----	----	----	----		
Group Assignment							
group a	If yes …		-8%				
group b	If yes …		-10%				
group c	If yes …		-7%			6%	
group d	If yes …		-5%				
group e	If yes …	3%		11%		17%	
group f	If yes …			9%		15%	
group g	If yes …	5%		9%		15%	
group h	If yes …	4%		10%		14%	
group i	If yes …			6%		11%	

Figure 30: Percentage effects of the three Call Center models

The Average Handling Time for our data sets was approximately 7 minutes per call. Thus, a +10% improvement indicates handing calls 10% faster on average, or within 6.3 minutes. A -10% reduction indicates handling calls 10% slower, or within 7.7 minutes on average.

4.6.2 Order of Entry and R-squared

We considered the order of entry and the partial R^2 for the variables in each Call Center model in our interpretations. Figure 31, Figure 32 and Figure 33 display the order in which each explanatory variable entered the model and the partial R^2 of that variable. Variables that have the greatest explanatory power generally enter the model first. The partial R^2 is the additional percentage of variation explained by a variable when it is added to the model. The variables describing a physical condition are highlighted in bold.

The model R^2 values range from a low of 0.08 for the November Hourly model to a high of 0.22 for the November Daily model. In general, one expects more averaged data to be more predictable. Hence models based on averaged data, such as the daily September and November models, are expected to have substantially higher R^2 values than those with finer level of detail about variations in an individual's behavior, such as predicting hourly differences in how quickly a worker handles incoming phone calls.

As might be expected, an individual's seniority (*Years on Job*) and *Team Leader* status had the highest predictive power for explaining an individual's performance on any given day or hour. These two variables typically accounted for about one half of the models' explanatory power. In predicting an individual's performance we expect those explanatory variables that are most specific to an individual to have the highest predictive power. The next most powerful group of variables are likely to be those that describe group membership, such as shift group, or collective conditions specific to the task, such as number of incoming calls or total population of the center. It is interesting, however, that a number of physical variables were found to have higher explanatory power, i.e. entered the model sooner, than group membership.

In Figure 31, Figure 32 and Figure 33 we also calculated the cumulative R^2 for all the physical variables which were found to be significant in each model, and the percentage of the model R^2 represented by the physical variables. This value is an indication of the relative importance of environmental conditions compared to other influences on worker performance. In the three models we find that the physical variables account for 13%, 18% and 20% of the explanatory power of the models. Thus, of the variation in Call Center worker performance that we can predict, environmental variables account for about 1/8th to 1/5th of explained variation, or about 2% to 4% of the total variation.

Order of Entry	Variable	Significance	Partial R-Square	Cumulative R-Square
1	Team Leader	<.0001	0.082	0.082
2	Years on Job (nL)	0.068	0.035	**0.117**
3	group g	0.001	0.014	**0.131**
4	**Floor Register Status**	<.0001	0.012	0.142
5	**Partition Height**	0.002	0.010	0.153
6	group e	0.050	0.009	0.162
7	Average Seconds to Answer (nL)	0.001	0.007	0.169
8	group c	0.000	0.006	0.174
9	group b	<.0001	0.006	0.180
10	**Number of Task Lights**	<.0001	0.005	0.185
11	group a	0.000	0.007	**0.192**
12	group d	0.019	0.006	0.198
13	**Total Light Range (nL)**	<.0001	0.006	**0.204**
14	**Break View**	0.006	0.003	0.207
15	group h	0.030	0.001	**0.208**
16	**Primary View**	0.050	0.003	**0.211**
Cumulative R-Square for all Environmental Variables			0.038	
Percentage of Model R-Square			18%	

Figure 31: Order of entry and partial R-squared, September daily

Order of Entry	Variable	Significance	Partial R-Square	Cumulative R-Square
1	Years on Job (nL)	0.024	0.065	0.065
2	Team Leader	<.0001	0.054	**0.119**
3	Average Seconds to Answer (nL)	0.069	0.024	**0.143**
4	Population	<.0001	0.009	0.152
5	Total Calls Answered	<.0001	0.013	0.165
6	**Break View**	<.0001	0.007	0.172
7	**Floor Register Status**	0.036	0.007	0.178
8	**Partition Height**	0.003	0.006	0.184
9	**Daylight (nL)**	0.003	0.007	0.191
10	group i	0.059	0.006	0.197
11	group e	<.0001	0.003	**0.200**
12	group h	<.0001	0.003	0.204
13	group f	<.0001	0.006	**0.209**
14	group g	0.000	0.010	0.220
15	Distance to North Wall	0.071	0.003	**0.223**
Cumulative R-Square for all Environmental Variables			0.030	
Percentage of Model R-Square			13%	

Figure 32: Order of entry and partial R-squared, November daily

Order of Entry	Variable	Significance	Partial R-Square	Cumulative R-Square
1	Years on Job (nL)	0.096	0.028	0.028
2	**Partition Height**	<.0001	0.005	**0.033**
3	**Outside Air Delivered**	0.003	0.004	**0.037**
4	Population	<.0001	0.006	0.043
5	Total Calls Answered	<.0001	0.008	0.051
6	Average Seconds to Answer (nL)	<.0001	0.004	0.056
7	group e	<.0001	0.003	0.059
8	group f	<.0001	0.003	0.061
9	group g	<.0001	0.003	0.064
10	group h	<.0001	0.003	0.067
11	**Break View**	<.0001	0.002	**0.069**
12	Team Leader	<.0001	0.002	0.071
13	**Floor Register Status**	0.002	0.002	**0.073**
14	group i	<.0001	0.002	0.074
15	**Distance to North Wall**	0.007	0.001	**0.075**
16	**Electric Light (nL)**	0.001	0.001	**0.076**
17	group c	0.012	0.001	0.077
18	**Indoor Air Temperaure**	0.092	0.000	**0.078**
Cumulative R-Square for all Environmental Variables			0.016	
Percentage of Model R-Square			20%	

Figure 33: Order of entry and partial R-squared, November hourly

4.6.3 Discussion of Call Center Findings

The findings of the Call Center models are generally consistent with management experience and findings of other researchers.

Personal Status. The largest changes in performance are associated with being identified as a team leader (19%, 17% and 18% faster performance for the three models). The other demographic variable that proved significant in all three models is length of service as a CSR. For each 10% increase in service time, CSRs are slowing down ever so slightly, by 0.1% to 0.2%.

Work Intensity. The intensity of incoming calls and the number of CSRs working at a given time clearly affects performance. Consistent with management experience, the more people working in the Center the slower calls are being answered overall. For every 10 more people added to the list of active CSRs, performance slowed in November by 14% daily or 12% hourly. Similarly, as the average time to answer calls (Average Seconds to Answer) increases by 10%, Average Handling Time slows down by about 1%. However, the more total calls answered by the Center (implying a high density of incoming calls matched by enough CSRs to handle them) the faster everyone is working, by 9% to 11%.

Illumination. Daylight was only significant in one model, November Daily, and was found to slow overall performance slightly, by -0.2% for every 10% increase in average daily daylight horizontal illumination level. The intensity of electric illumination, on the other hand, is found to increase performance by about the same amount, +0.3% in the November Hourly model. The relative effect of these two findings is shown in Figure 34, where the dashed line is average daily daylight illuminance and the solid line is electric illuminance.

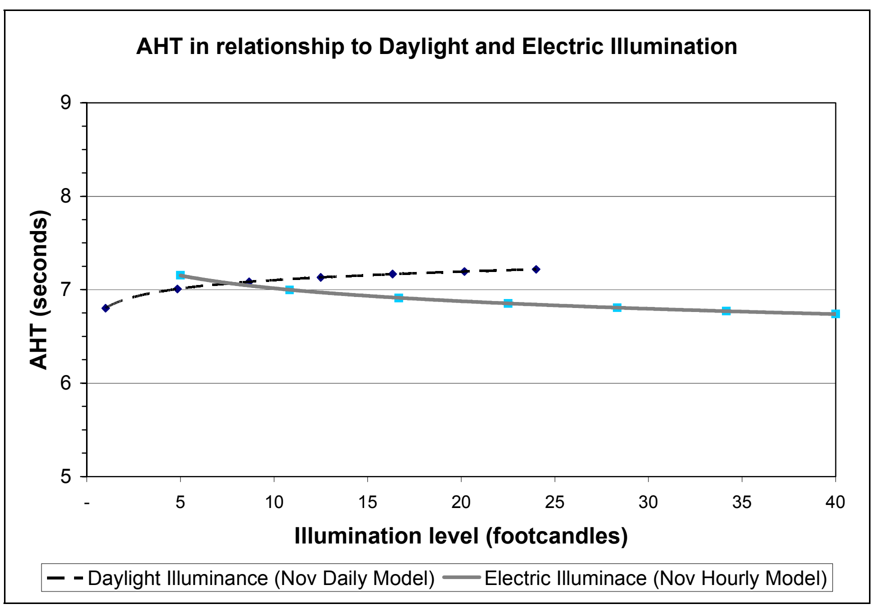

Figure 34: AHT in relationship to daylight and electric illumination

It is somewhat surprising that the *Daylight* variable was not significant in the hourly model, where it represented hourly variation, while the *Electric Light* variable, which does not vary hourly, showed up for the first time. Neither proved to be very consistent across all models tested.

Since we know from our illumination transects that electric light increases in the center of the Call Center and daylight increases at the perimeter, these two effects are basically complements of each other. It is possible that people in the core are functioning slightly better than people at the perimeter for some other reason than illumination, although we tried to control for any such confounding effects with the *Distance to Window* variables. We see that in the same November models being further from the north windows predicts a positive effect of handling calls 3% to 5% faster.

View. The findings about view are perhaps one of the most striking findings in these models. A better *Break View* consistently predicts 6% to 7% faster performance. A better *Primary View* also predicts an additional 6% faster performance in the September daily model.

As a complementary finding, those employees at a workstation with partition heights above eye level on two sides are seen to be performing 11% to 18% slower than those with all their partitions below eye level. Workers with high partitions have fewer opportunities for views, especially *Primary View*. The highest partitions are at the boundaries of the workgroup and along the central corridor. However, it is also possible that low partition height is associated with higher status, since the assistant supervisors in our analysis are given workstations that allow views out across their shift group neighborhood.

For our view variables we did not attempt to model the dynamic situation of how the position of the window blinds interacted with the view from each cubicle. The vertical blinds at the Call Center have 5% perforations making them semi-transparent. Thus, from certain angles, even when the blinds are closed, there is still a view to the outside. We know that blind conditions varied during the study period, but the static variable describing view potential remained important in all models. Therefore it may be that even subtle indications of a view, as seen through the filter of perforated blinds, are important for worker performance.

Alternatively, the view variables may reflect people's exposure to vertical illumination. When the blinds are open employees typically have views of the sky or the adjacent building wing, both of which are quite bright. When the blinds are closed the blind surface still tends to be brighter than the surrounding field of view, especially if the blinds are in the sunlight, as on the south façade. It is possible that our view metric is actually a better indicator of exposure to high luminance levels at the eye than the horizontal daylight illumination measured by the Hobos.

Thus, the positive impact of the view variables could potentially be explained by a number of causal mechanisms. These include theories that a relaxing view improves performance via stress reduction, that an interesting view improves ability to maintain focus, or that higher luminance levels viewed by the eye may help enhance performance via physiological circadian stimulus.

Temperature and Ventilation. Cooler temperatures are associated with faster performance handling calls in the November Hourly analysis. A small increase in air temperature inside of the space, from the average of 74°F to 76°F was seen to slow worker performance by 2%. There was never more than a 6°F range in indoor air temperatures in the hourly data, so the maximum size of this effect would be a 6% difference in worker performance. Air temperatures were measured at five feet above the floor for groups of two to four cubicles. Thus there is also some spatial sensitivity to this data.

It is interesting that this temperature relationship showed up in the hourly analysis but not the daily analysis, implying that it is a fairly immediate effect rather than a longer term effect responding to daily average temperature. The hourly analysis did have more statistical power since it was based on eight data points per day rather than just one, so it is more likely to find subtle effects. It should also be noted that *Air Temperature* was the last variable to enter the hourly model as significant and thus has the lowest predictive power of the significant variables in the model.

Those workers who had their floor registers set to fully open, presumably to maximize ventilation near their workstation, were consistently seen to have faster performance than those with their floor registers fully closed. The observation that *Floor Register Status* was one of the most powerful explanatory variables in the preliminary September analysis induced us to pay closer attention to ventilation conditions in the Call Center for the Phase 2 analysis. The magnitude of the positive effect associated with a more open floor register varied from 3% to 10% faster performance in the three models, but it was consistently significant. This finding could potentially be related to increased local air flow or to lower local air temperature.

Upon examination of the facility records for the study period we confirmed that the delivery air temperatures were substantially cooler than average room air temperatures for the Call Center. In September the delivery air ranged around 58°F, about 15°F cooler than the room air, while in November the delivery air was at about 64°F, or about 10°F cooler than the average room air. Thus, people with their floor registers open were receiving both more ventilation air and cooler local temperatures than those with their registers closed.

In the November Hourly model we were able to include a variable indicating the amount of outside air introduced into the space on an hourly basis (*Outside Air Delivered*). As the rate of outside air per square foot increased, performance also improved. Increasing the rate of outside air by one cubic foot per minute per square foot (CFM/sf), or double the average rate, was associated with 4% faster handling of calls. The range of outside air CFM/sf varied between 0.5 to 2.0

CFM/sf for our study. Thus the largest range in performance expected due to changes in outside air rates from lowest to highest would be about 6%.

Again it is interesting that this metric was significant in the hourly analysis but not the daily analysis. Furthermore, the outside air delivered variable entered the hourly model as the third most important explanatory variable. This suggests that more attention should be given to the relationship worker performance and changes in outside air delivery rates. Furthermore, this relationship should be studied at a fairly fine grain, considering local workstation conditions and data at the hourly or finer level of detail.

Hourly Analysis. We undertook the November Hourly model in order to study the dynamic effect of hourly variation of daylight and ventilation on worker performance. We even artificially varied these inputs in order to better study their impact (see discussion earlier on Phase 2 Interventions). Changes in daylight illumination were not found to be significant in the hourly model, but changes in outdoor air ventilation rates were highly significant, and this variable was third to enter the model. *Indoor Air Temperature* was also significant in the hourly model. There were four other dynamic variables that were also significant in the hourly model: three describing work load conditions and the indoor air temperature.

As mentioned earlier we tested lagged versions of the *Daylight* variable in all models, and found that added the lagged *Daylight* variable to the hourly model increased the explanatory power of the model slightly, even though the variable itself did not prove significant. From this exercise, and other preliminary models tested, we concluded that daylight illumination levels of the previous hour were more strongly associated with worker performance than concurrent levels. This suggests that any influence of daylight on worker performance is more likely to operate via a delayed physiological effect than an instantaneous visual effect.

We suspect that the hourly versions of *Indoor Air Temperature* and *Daylight* may be somewhat collinear with each other; however we were not able to investigate such a relationship. It would be interesting to be able to distinguish between the thermal effects and the illumination effects provided by windows and daylight.

It was very advantageous to be able to study worker performance at the fine grain of hourly data. Many environmental conditions vary over the course of an hour, and in our models we were able to detect changes in worker performance that responded that this level of time detail. Field conditions supporting this level of analysis are very rare. Indeed, call center workers present one of the few situations where office worker performance is routinely monitored at that fine level of detail. Thus, we strongly recommend that future studies consider the use of call centers as field study sites to investigate the relationships between indoor environmental conditions and office worker performance.

5. DESKTOP STUDY

The Desktop study presented us with the opportunity to study office worker performance across a greater range of daylighting and other environmental conditions than the Call Center study. We had the opportunity to investigate three buildings with a substantial range of daylight versus view conditions: one with basically no views and no daylight, one with excellent views and no daylight, and the third with a combination of high daylight levels provided by skylights where workers often had little or no view and other areas with both high daylight levels and excellent views. All three buildings also included core office areas where workers had no daylight and no views.

The greatest challenge of the Desktop study was creating a metric of performance that could be uniformly administered to the participants and would create a meaningful measure of changes in office workers capabilities. As described in the introduction to this report, most previous studies considering office worker performance have been performed in laboratory environments, using simulated office tasks and temporary workers for experimental subjects. We were also constrained by the need to minimize the time requirement to participate in the study so that the study itself did not create a negative productivity impact on SMUD's ongoing operations. In discussion with management we agreed to create a test of performance that would take no more than five or ten minutes to complete.

Since we wanted to analyze the relationship of actual workplace environmental conditions to worker performance, this assessment had to be administered at the worker's own desk and under as uniform and normal conditions as possible. We decided to create a computerized assessment test that could be administered simultaneously to our full study population. This assessment was successfully administered to a final study population of over 200 participants multiple times. Volunteers took the test from one to four times over the course of a five week study period in October and November 2002. The details of the study methodology and its findings are described below.

5.1 Selection of Study Population

For the Desktop study we wanted to recruit a sufficiently large population in order to be able to able to analyze a range of environmental conditions and achieve sufficient statistical power in order to be able to detect fairly subtle effects. Initial calculations suggested that we would require a study population of about 225, with a minimum of at least 150 needed for successful analysis.

We needed to find a population that was fairly evenly distributed across the range of environmental conditions that we wanted to study, and represented a sufficiently balanced population to avoid introducing inadvertent demographic bias. In order to recruit this population we first worked with the Human Resources Department within SMUD to identify an initial pool of potential study participants, and then used a survey to further screen the population and recruit volunteers. This selection process is described below.

5.1.1 Department Selection

We worked with SMUD personnel officers to identify the departments and locations of employees who had somewhat similar job positions and task. From this exercise we identified a potential pool of about 700 employees from twelve departments in the three buildings (CSC, headquarters and 59th street) from which we could create matched set comparisons between the CSC building and at least one of the non-daylit buildings. Of these 700 employees, about 125 were filtered out as inappropriate for the study, because they were not professional or clerical employees, were part time employees, were located in the wrong area or were inappropriate for other reasons, leaving us with an initial survey population of 575.

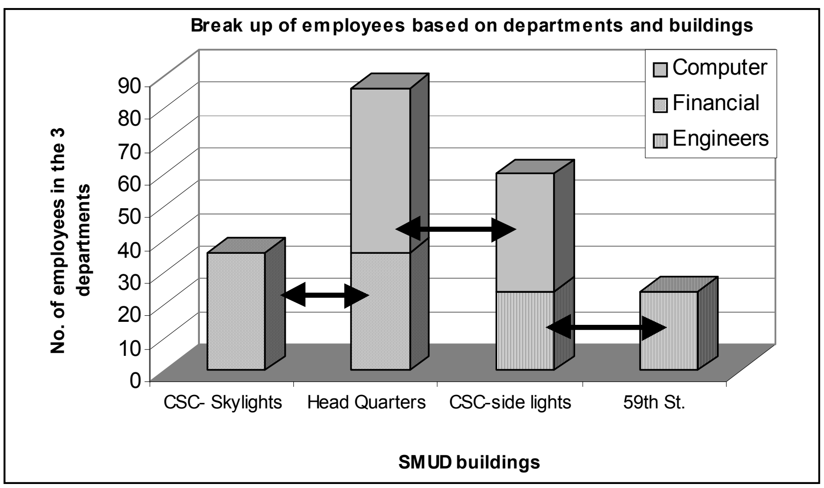

Figure 35: Employee distribution in 3 SMUD buildings by job category Arrows indicate possible comparison between similar departments located in different buildings.

Of the twelve departments considered, we grouped them broadly into three types: engineers, computer professionals and financial professionals. We wanted to then make sure that each group was represented in at least two of our three study buildings. Our data collection goal identified employee workstation location by building and its relationship to windows or skylights. The goals described in the research plan are summarized in Figure 36 below:

	Head Quarters				CSC			CSC Sky			59th		Total
	Core	S	N	E/W	Core	S	N	Core	S	N	Core	E/W	
Engineers						12	12				12	12	48
Computer	12		24	24	12	12	12						96
Financial	12	12	12		12			12	12	12			84
Total	24	12	36	24	24	24	24	12	12	12	12	12	228
Bldg Total				96						108		24	

1

Figure 36: Research plan goal for Desktop study population (S= cubicle near to south window, N= cubicle near to north window E/W = cubicle near to east or west window, Core =3 cubicles away from N, S, E or W windows)

5.1.2 Initial Survey Administration

We prepared a one page flier giving a brief description of our office study and inviting SMUD employees to participate in the initial survey, and announced a drawing for a prize among those who participated. SMUD management provided us with email addresses and mail stops of employees of the selected departments. Based on this, we invited participation via e-mails and fliers.

Participation in the survey and the subsequent study was completely voluntary. A seven page survey was created requesting demographic information such as age, level of education, years with the company, employment status, etc. We also asked information about the employees' workspace and their use of it, such as their monitor type, number of hours they spend at their desk and number of hours doing certain tasks, and simple details about their workstation. A copy of the initial survey is provided in the Appendix.

The survey was administered over the company intranet system. Participants simply clicked on the listed URL, and the survey form opened up on their computer screen. As they took the test, the results were automatically downloaded to an Access database. With this system we could track progress on the survey. Their log-in was subsequently translated into a unique numerical ID in order to preserve anonymity of the responses, but allowing us to contact them in the future via e-mail.

We mapped the approximate location of the initial 575 employees who were invited for the initial survey and discovered that we had low population of employees in skylit areas. We later send out initial surveys to 40 people in two more departments that were located on skylit floors. Out of a total of 614 initial invitations, we received 515 responses to the initial survey.

5.1.3 Selection of Final Test Invitees

Out of the 515 employees who responded to the initial survey, further screening of the population was done on the basis of their responses. People who were inappropriate, unavailable or uninterested in the study were eliminated. Criteria for elimination included:

- Located in a private office
- Working at the desk for less than 7 hours per week
- Highly unusual computer tasks or computer set up
- Managerial position
- Part time employee or not specifically invited to participate
- Did not volunteer to participate in study
- Not available during study period

The participants were also asked to list all the days in the coming two months in which they would be unavailable at their desks to take Mini-Tests, so that we could schedule the test days on which we would reach the maximum potential participants.

We checked that this list represented a demographically balanced population that was distributed around the buildings approximately according to our proposed sampling frame. We mapped each participant to their location in the buildings and made sure that they were located in clusters. A few people in isolated locations were also eliminated so that we could economize on the number of data loggers set out to record environmental conditions.

From this response we created a list of 234 employees who would be invited to participate in the study. Our ideal data collection goal was 225 participants. We judged that we could have as few as 150 to support our intended analysis. We successfully collected Mini-Test results from 214 participants who took it at least once, 184 who took it at least twice, 147 who took it at least three times and 45 who took it four times. One last screening of these 214 participants was done based on which of these participants had completed both at least one Mini-Test and the final questionnaire, resulting in a final study population of 201 shown in Figure 37.

HQ				CSC				CSC Sky				59th St.		Total
Core	S	N	E/W	Core	S	N	E/W	Core	S	N	E/W	Core	E/W	
35	6	4	9	43	31	30	1	11	5	11	2	8	5	
54				105				29				13		201

Figure 37: Final Desktop study population, by location (S= cubicle near to south window, N= cubicle near to north window E/W = east or west window, Core =3 cubicles away from any window)

The final study population shown in Figure 37 has a very good distribution balance between workers located in the core and near windows, those under a skylight and distribution within the three buildings. We are fairly confident that in the final analysis increasing levels of daylight and view were not confounded by higher professional status in the company. We recruited a good mix of high status professionals in the Headquarters building with wonderful views from their cubicles but no daylight, and we also had a fairly large population of clerical workers in the core of the top floors of the CSC building who had very high daylight levels due to the skylights overhead but comparatively little view. We also achieved a population of engineers, some located in the Distribution Services Building with no daylight and no view, and others located in both Headquarters and the CSC building with a variety of conditions.

Figure 38 gives the number of responses in each filtering step of the recruitment process and the resulting final study population.

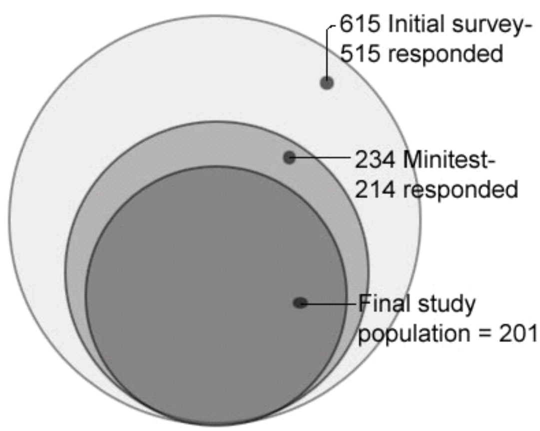

Figure 38: Venn diagram showing filtering of study population.

5.2 Environmental Data Collection

The process of onsite data collection for the Desktop study was based on the experience from the Call Center study. We used a similar methodology to collect information about the workstations, their illumination levels and other environmental conditions.

We spent two Saturdays on-site with eight to ten surveyors each day to collect all of the data. We mapped the location of the 235 potential study participants to their cubicles in the three study buildings and noted their location on a floor plan of the building. We found each cubicle and assessed its static environmental conditions such as distance from window or skylight, view factors, glare from windows and floor register status. Hobo data loggers were set in place at the same time and remained recording illumination and temperature data for the duration of the study period.

We followed the procedures described earlier in the Call Center study to rate the *Primary View* and *Break View* at each desk. We took digital photographs of conditions in each space and documented the view out of each window, standing five feet from the window. We rated the glare potential from the window sitting at the monitor, and noted any obvious sources of glare on the monitor. We collected illumination data and radiant temperatures using handheld equipment following the methodology described for the Call Center Phase 2. In the CSC building we also noted the floor register status for each cubicle.

In the Customer Services Building, occupants located next to a window had the opportunity to adjust their blinds and open or close windows. We noted that compared to the Call Center, where we had observed blind operation over the course of three weeks, in the rest of the CSC blinds were adjusted even less frequently, since they were not required to be closed at night. We observed that ¼ to ⅓ of the blinds had controls that were very difficult to reach due to furniture arrangements. Some occupants had taken remedial measures, such as devising clever control extensions to help them make changes to the blinds. Typically, blinds were 80-90% fully open on the north windows and 80-90% partially closed in the south, east and west walls in a wide variety of settings from fully closed, to drawn but set at an angle allowing clear views out from some positions.

We did not attempt to formally assess the frequency of operation the operable windows, but would estimate that during our study periods we observed that perhaps 10-25% of the windows were open at any given time. The building is pressurized, and thus an open window should result in net flow of air out of the workstation, rather than inducement of a breeze into the workstation. Interviews with occupants informed us, however, that sometimes they do feel air moving in to the building from an open window. They also reported that there was likely to be a slight increase in traffic noise from outside the building near an open window. The on-site data collection process is described in further detail below and in the Appendix.

5.2.1 Illumination and Temperature Data

We took horizontal illumination readings at each desk. Surveyors were instructed to take three to five readings across the surface of the desk at four feet above floor level. The average of these readings was then entered into the dataset. Separate readings were taken with lights on and off. For the CSC building additional readings were taken with blinds open and closed and at different times of the day to capture the variability of daylight illumination.

Hobos were placed at representative locations chosen to capture the variability in environmental conditions. Thus, along perimeter cubicles with substantial daylight we located Hobos every two or three cubicles. In the core of the buildings, where there was little variation in daylight or temperature, only two or three Hobos were located to represent all core cubicles for that area.

We placed 60 Hobos in the CSC building, 18 in Headquarters, five in 59th street and 13 were located in various air handling units to monitor HVAC conditions. On average, we had one Hobo located for every three cubicles that could potentially be included in the study. It was possible that some of the Hobo locations would become extraneous since we had to locate the Hobos in advance of the employees' participation in the study. In addition we located four Hobos and two Licor illuminance meters on the roof of the CSC to take continuous readings of outdoor temperature and illumination levels in case we needed them to calibrate the inside Hobo readings.

The data collected from Hobos was processed to create illumination and temperature readings for each of the cubicles in the study. Hand held readings taken at both the Hobo locations and cubicles were used to calibrate dynamic Hobo readings to cubicle locations. Since the Mini-Tests were taken by the participants only between 10:30 AM to 12:30 PM for any of five Thursdays, a two hour average for both daylight illumination and temperature readings was created for each of the five study days.

The radiant temperature measurement gun was used to assess radiant comfort conditions in the various spaces. Both survey days were warm sunny days with clear blue skies and outside air temperatures peaking in the upper 80s. The air conditioning system was off during the Saturdays when we were there, so air temperatures were typically around 78°F - 84°F. Radiant temperatures of surfaces, including windows tended to be in a very similar range. Interior surfaces of windows that had recently been in direct sunlight were often 10°F warmer than other surfaces.

Radiant temperature readings were also taken for the skylight glazing and wells on the top floors of the CSC building. The surfaces of the skylight wells tended to be 10 to 15°F warmer than the ambient air temperatures. The skylight glazing was up to 40°F warmer in the sun and only 10°F warmer when the glazing was currently in the shade.

Description of the procedure of measuring and calculating daylight and electric illuminance is given in the Appendix.

5.2.2 Ventilation and IAQ Data

We hoped to calculate ventilation rates from a combination of data from the automatic energy management system (EMS) data collection, weather data and information from the Hobos placed in the air handling units. However, the SMUD EMS system failed to record data for some of the locations and some of the days in our study period. As a result we were unable to calculate changes in ventilation rates or outdoor air components for the study.

We did know the supply and return air temperatures for most locations, and confirmed that all of the study areas stayed within comfort conditions at 72°F to 75°F. The Customer Services Building tended to be maintained about one or two degrees warmer than the other two buildings.

We were not able to directly measure the variation in ventilation rates by time or location for the Desktop study due to missing data from the facilities EMS system for the study period. The Headquarters and 59th street buildings did not have economizer systems and thus the outside air component was maintained at relatively constant ASHRAE recommended levels. For the CSC building the percentage of outside air supplied was a function of both economizer function and the position of the operable windows, and so was highly variable in both time and space.

We also noted the floor register status of each cubicle location in the CSC as a proxy measure of ventilation rates. Similar to the Call Center findings, we noted that about 25% of the occupants changed their floor register setting over the six week study period, with a balance between those that were more open or more closed at the end of the period. We could not, however, assess the frequency of these changes.

We know from the UC Berkeley study[1] that employees in the CSC building had more complaints about the floor registers than any other feature of their building. They most frequently complained of cold air blowing on their legs and annoyance from dust blown up from the floor vents. We confirmed this with our own informal interviews and observations. Surveyors often noted an accumulation of small debris particles in the vent baskets. Employees told us that these were remnants of the carpet cleaning process. A number of employees told us that they covered their vents to prevent a draft on their legs. In the UC Berkeley study a number of employees also mentioned that they covered their floor vents in order to prevent their chair or high heeled shoes from getting caught in the register. We found roughly 5% of the floor registers purposefully blocked.

For the Desktop study we collected hourly CO_2 levels for a day in one representative space in each building. For the CSC and HQ buildings we measured the CO_2 levels in the return air plenum, while we measured the CO_2 levels inside the space in the 59th street building. The CO_2 levels were seen to show similar hourly variation as seen for the Call Center study, and values were observed to be well below the ASHRAE recommended limits. Between the three buildings, the CSC building had the lowest average CO_2 level (475 ppm) with the HQ building having an average CO_2 level of 520 ppm and the Distribution Services Building with an average CO_2 level of 670 ppm. Thus we did not find any significant variations in the CO_2 levels that could indicate unhealthy air quality in any of the study's spaces.

5.3 Performance Metrics

In the Desktop study we were faced with a rather unique challenge—how to measure office worker performance in the field in a meaningful way that might

[1] UC Berkeley study

influence a manager's assessment of overall organizational productivity. We needed to do this in a way that would:

- Standardize testing under field conditions
- Minimize impact on employee time
- Minimize administration and analysis costs
- Provide widely accepted performance metrics, referenced to other studies
- Create a system that could potentially be replicated in other studies

We decided to create a series of "Mini-Tests" that would assess employee visual and mental performance, including short term and long term memory. Our primary criterion was that these tests could be administered in a five to ten minute time span. We decided to identify a suite of tests that could be:

- Self-administered at a worker's own computer
- With performance metrics that could be automatically measured and recorded by the computer

This created fairly rigorous selection criteria which narrowed our search for potential tests to relatively few possibilities.

After examining research literature of similar studies, which tried to assess visual and mental performance but primarily in a laboratory or clinical setting, we identified a range of candidate tests used by other researchers. We interviewed many of these researchers to understand their use of the tests, the availability of normative data, the ability of the test to discriminate a range of performance between individuals and the potential of the test to be self-administered and computerized.

Based on these interviews and reviews, we selected five types of tests that represented a range of commonly used visual and cognitive assessments, and seemed that they could be successfully administered in a 5-10 minute computer session. We coordinated our development of the Mini-Tests with the researchers who had developed four of five of the formats. For the first three visual acuity tests, Chris Hunt of City Visual Systems Ltd. was extremely generous and helpful in helping us adapt the CITY University Vision Screener to our computer format.[1] Dr. Jeb Schenck consulted on the administration of the memory test, which he developed as a research tool for comparing various educational methodologies. The fifth test, Backwards Numbers (Digit Span Backwards), is a computerized variation of a standard psychological test developed in the 1950s. Our adaptation was based on basic psychology texts and interviews with practicing researchers and psychiatrists who use the tool.

[1] The CITY University Vision Screener for VDU Users was developed under the direction of Dr.W.D. Thomson, senior lecturer, Department of Optometry and Visual Science, City University, London

A single Mini-Test session was constructed with each of the five tests. Each session of a Mini-Test included three to four trials of each test type. The five tests are as follows:

1. **Landolt C**: identify the direction of a square “c”. As administered in our format, it measures visual acuity and speed of response. It is a standard visual acuity test, widely used in vision research.

2. **Letter Search**: find a “c” in a random field of “o”s; measures visual acuity, visual scanning efficiency, manual dexterity and speed of response.

3. **Number Search**: count the number of a certain digit randomly distributed in a larger matrix of digits; measures visual acuity, visual scanning efficiency, mental alertness, speed of response and short term memory.

4. **Backwards Numbers**: repeat a series of digits backwards; a standard psychological test for mental acuity, attention span and short term memory.

5. **Memory Test**: remember a number of images presented earlier; measures short term (within ten minutes of first presentation) and long term visual and verbal memory (two to four weeks later).

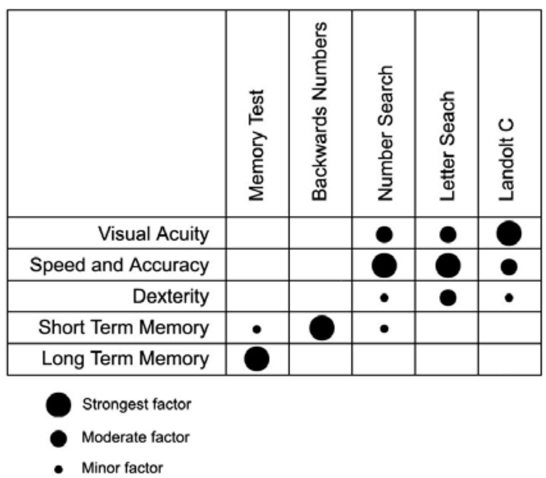

Figure 39: Cognitive functions assessed by the five Mini-Tests

Figure 39 gives a graphic representation of the cognitive functions assessed by each of the five Mini-Tests.

5.3.1 Description of Mini-Tests

The Mini-Tests were made available to the participants on an internal server within the SMUD intranet. The participants could access the tests by typing in a web address in their internet browsers from their workstations. In a single session of the Mini-Tests, the participant took a version of all five tests. New screens with randomized answers were presented each session, so that no participant saw the same exact image twice. A sample of a complete session of the Mini-Tests is provided in the Appendix.

The Mini-Tests were designed using active serve pages (asp) and SQL server technology to provide database connectivity and interactivity. This allowed us to administer the tests over the intranet to our test population and instantaneously record their response to a SQL database. We were also able to capture response time of the participant at the level of milliseconds.

Each test consisted of images that are displayed on the participant's computer monitors. To adjust for the different screen resolutions that the employees may have on their individual monitors, the application was programmed to first check the user's screen resolution and then display appropriately sized images. This ensured that the relative scale of the images and their pixel symmetry remained constant even when the images were seen at different screen resolutions. Given the field conditions, we could not control for monitor contrast settings or observer distance to the screen. However, we assume that the office workers had already set their monitors to preferred settings and locations for their visual needs and preferences, and therefore the screens' settings had generally been optimized for each individual.

We controlled for variation in time of day and daylight exposure by restricting the time of taking to tests to a two hour time slot before lunch, between 10:30 AM and 12:30 PM. This time period was chosen to let the employees be exposed to the environmental conditions in their workspace for a few hours before they took the tests, and to be tested when daylight illumination was likely to be near its highest but before they were likely to leave the workplace for a lunch break, and thus be exposed to outside environmental conditions. Participants were sent an e-mail reminder the evening before.

The participants were instructed to take at least four sessions of the Mini-Tests, on four consecutive Thursdays between mid October and November of 2002. Thursday was chosen to maximize exposure to the workplace during the week, while avoiding the reduction in population observed on Fridays. A make-up session was scheduled for the third week in November for anyone who had missed taking a Mini-Test session earlier. To ensure the participants took the tests only at the specified times, access on the intranet was granted only in this two hour window on the Thursdays.

Instructions were provided at the beginning of each session and for each type of test. A practice test was provided for each type of test with a correct response illustrated. For the timed tests participants were asked to be "as quick and accurate as possible." Instructions for the two un-timed tests explained the purpose of the test, such as: "this test assesses your ability to pay attention to sequences on information." Participants were asked to complete the test session within one sitting and minimize disturbances while taking the test. The software tolerated pauses between each test trial, but timed out if a participant waited more than ten minutes before taking another action.

Landolt C

In the Landolt C test, a square was shown on the center of the computer screen, and the subject was asked to identify in which direction an opening in that square points. The opening could be pointing either "Up", "Down", "Right" or "Left." The subject responded by clicking an appropriate button below the image.

In one session, the shape was presented four times consecutively, with an increasing level of difficulty. In the second screen the size of the C shape was reduced by 50%. Then in the third screen, the original size was again used but this time, the contrast between the C shape and the background was decreased, thus making it harder to see. For the fourth screen, both reduced size and reduced contrast were used.

A sample image of a Landolt C screen is shown in Figure 40 below.

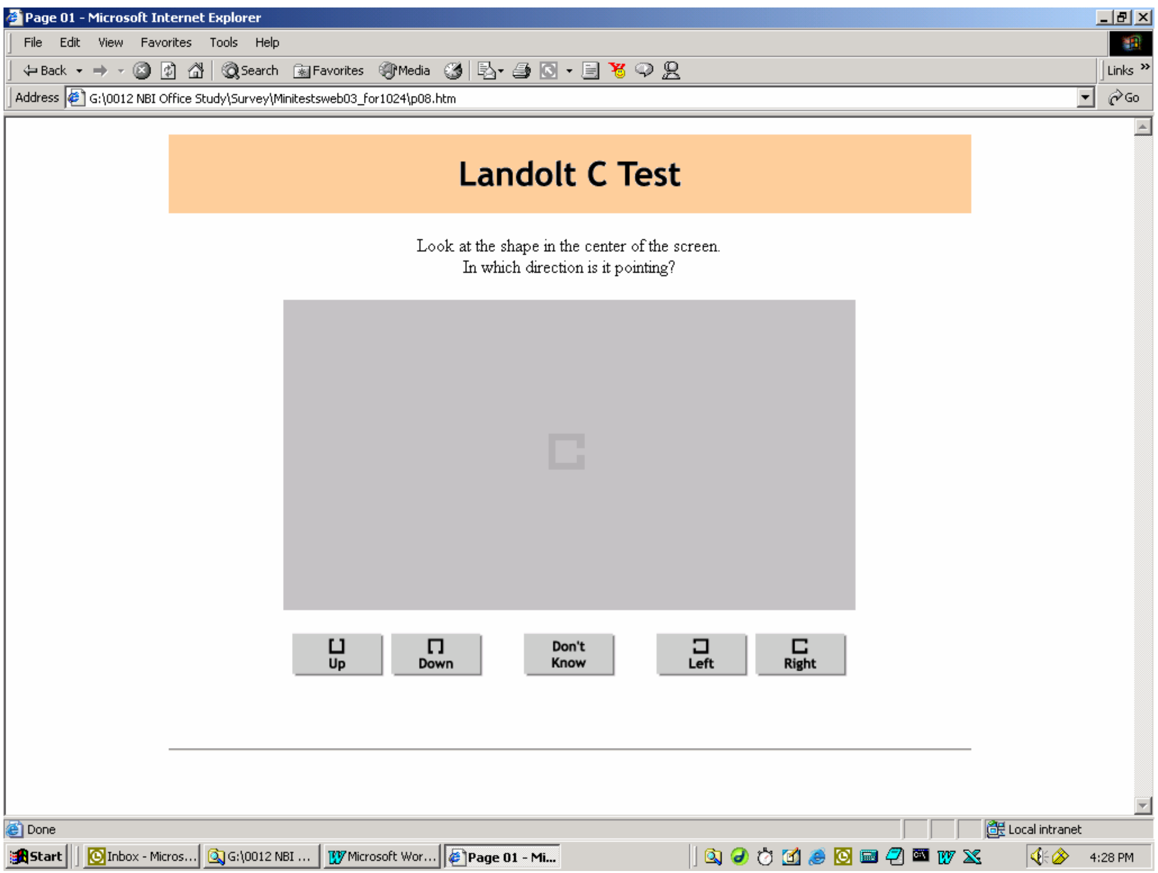

Figure 40: Screen shot of Landolt C test.

Letter Search

In the Letter Search, an image was presented in the center of the screen that had many circles and one incomplete circle. The subject was required to identify the incomplete circle and then click on it using the left button on the mouse.

In one session three screens of the Letter Search were presented consecutively, each with a different image and a randomized location of the target.

A sample image of a Letter Search screen is shown in Figure 41 below.

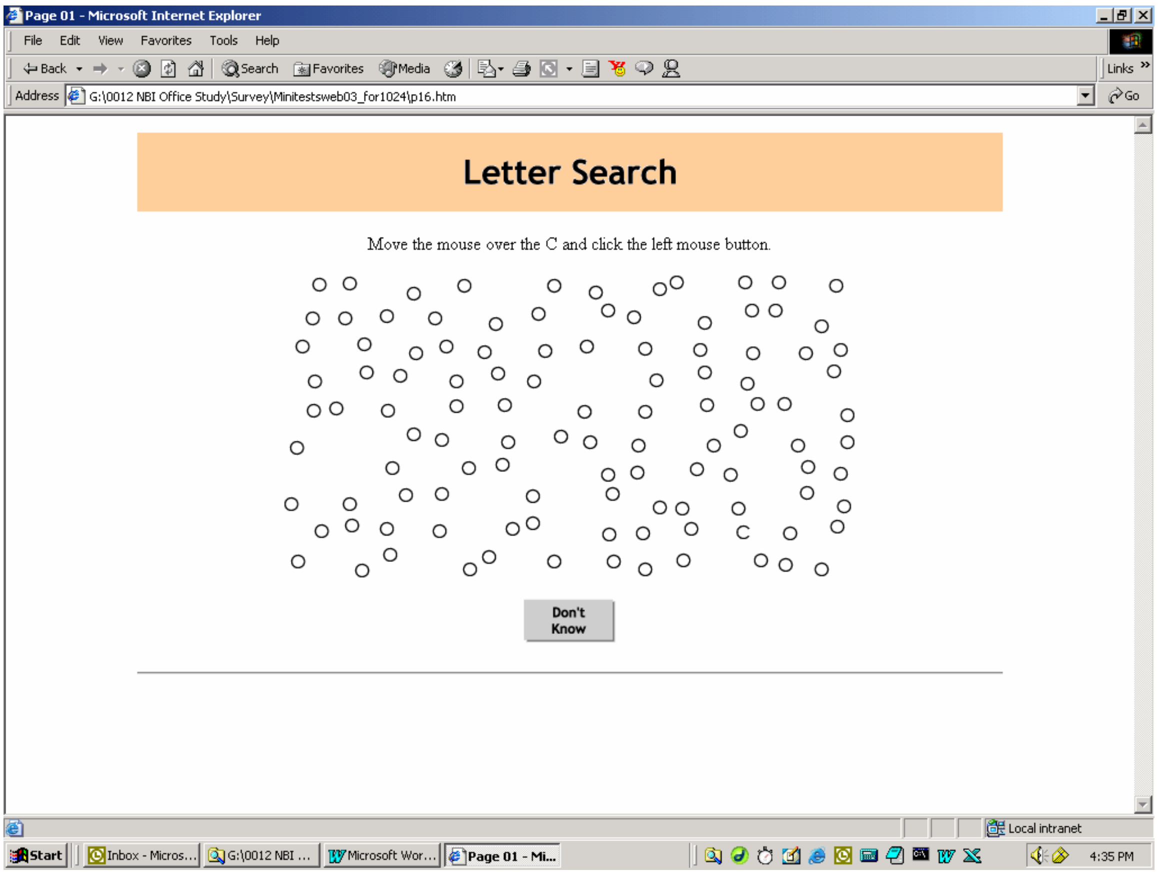

Figure 41: Screen shot of Letter Search

Number Search

In the Number Search, an image was presented in the center of the screen that had an array of single digit numbers on it. The subject was required to identify how many of a particular number there were in that array. The subject then responded by clicking on an appropriate button below.

In one session three screens of the Number Search were presented consecutively, each with a different image.

A sample image of a Number Search screen is shown in Figure 42 below.

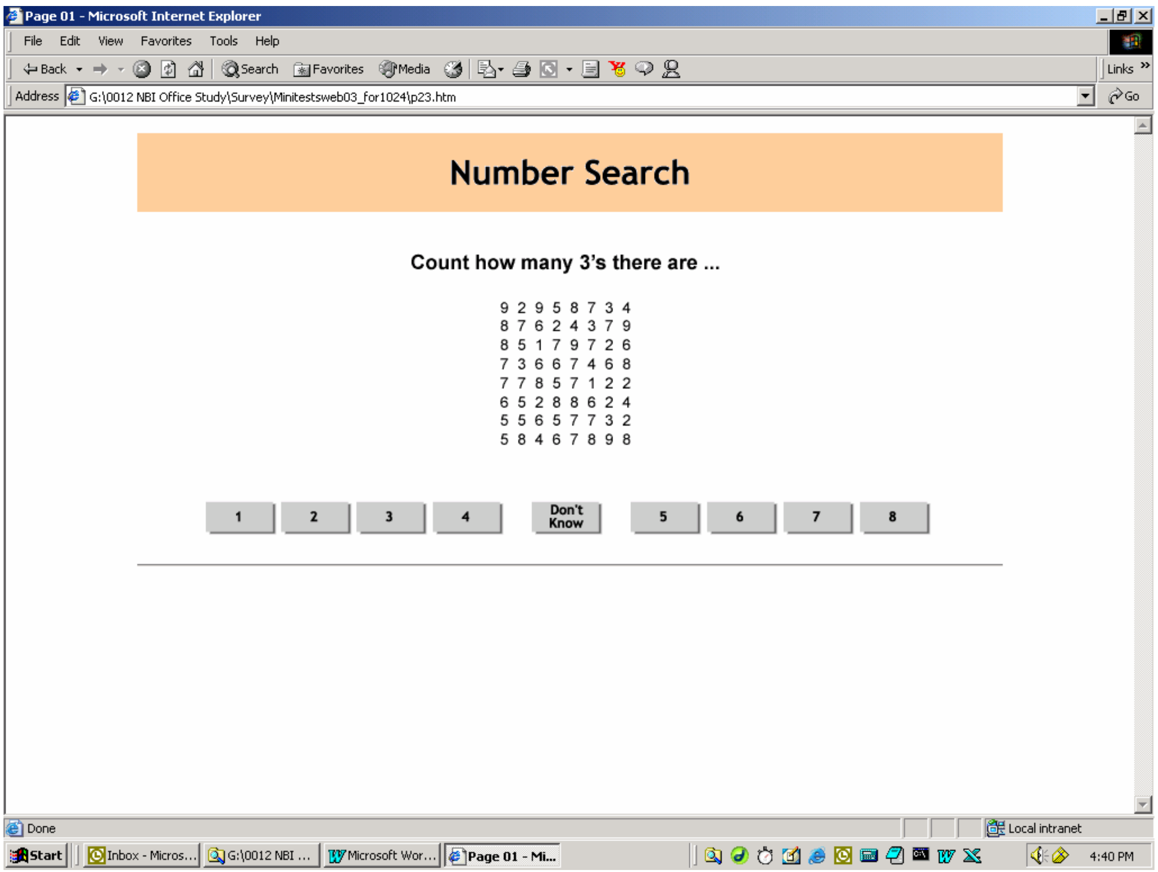

Figure 42: Screen shot of Number Search

Backwards Number

The Backwards Numbers test was an adaptation of the "Digit Span Backwards" test which is commonly administered by psychologists to test attention span, focus and short term memory capacity. It is normally administered by speaking out random numbers exactly one second apart to the subject, who is then asked to repeat the numbers but in the reverse order.

To make this a computer-based, self-administered test, we used Macromedia Flash to develop flash images that displayed numbers for precisely one second each, and then the subject was asked to type in the numbers he or she saw in the reverse order.

A sample image of a Backwards Numbers screen is given below in Figure 43.

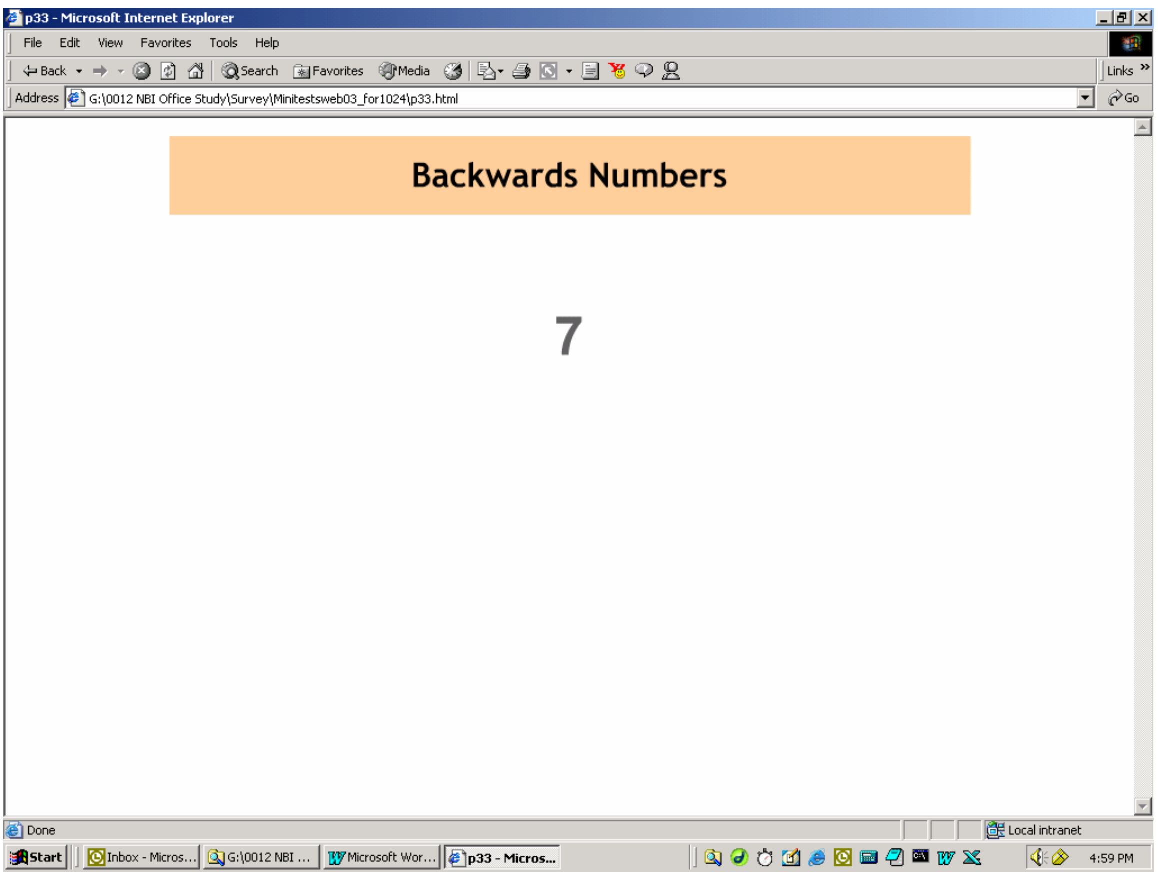

Figure 43: Screen shot of Backwards Numbers

The test began with a presentation of two sets of three digits, and then the number of digits was increased progressively up to two sets of seven. The initial images of numbers in the series were colored gray, and the final image was colored black to indicate the series was finished. For each progression of digits from three to seven, two sets of randomized numbers were presented so there was a total of ten possible sets for each session of the Mini-Tests. However, once the subject got two responses wrong the remaining screens were automatically skipped.

Memory Test

In the beginning of the first session of Mini-Tests, an image was shown to the subjects for exactly 30 seconds. This image contained 24 household objects. This test was developed as a method of assessing the efficacy of various teaching methodologies in improving long term memory.

A screen shot of the page with the initial image and the response page are shown in Figure 44 and Figure 45 below:

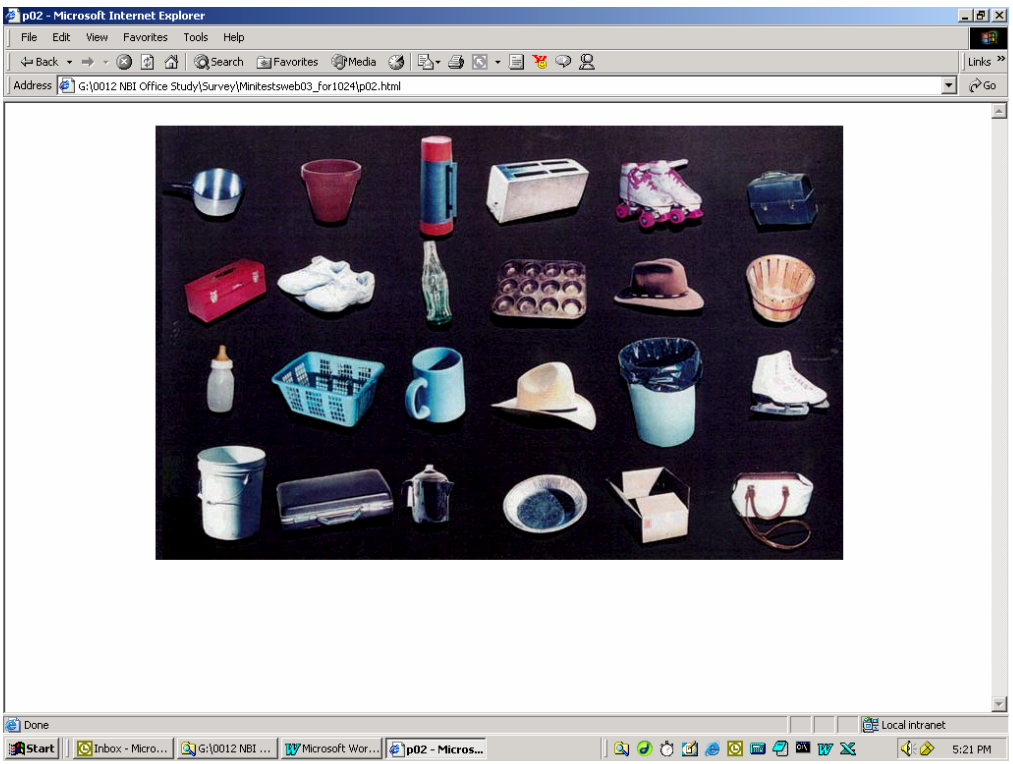

Figure 44: Screen shot of the Memory test image page

At the end of each session of Mini-Tests, we asked the participant to remember all the objects they could from the initial image. They were presented with a list of 48 similar objects from which they could select those objects that were in the initial image. The same list, but in randomized order, was presented at the end of each session. The image was only presented once, in each participant's first session of the Mini-Tests. Thus, in their first session of the Mini-Tests, this challenge came about five to ten minutes after they had seen the image. In subsequent sessions, there had been a one to four week delay since they had seen the initial image.

Interestingly, this was the most unpopular test in the Mini-Tests battery. After the second session, a number of participants sent us an e-mail to complain, either that they thought their version of the Mini-Tests must be dysfunctional since they hadn't seen the image again, or to complain that asking for such a long term memory test was not fair. We doubled our efforts to encourage participation in this test and got higher participation on the third and fourth sessions.

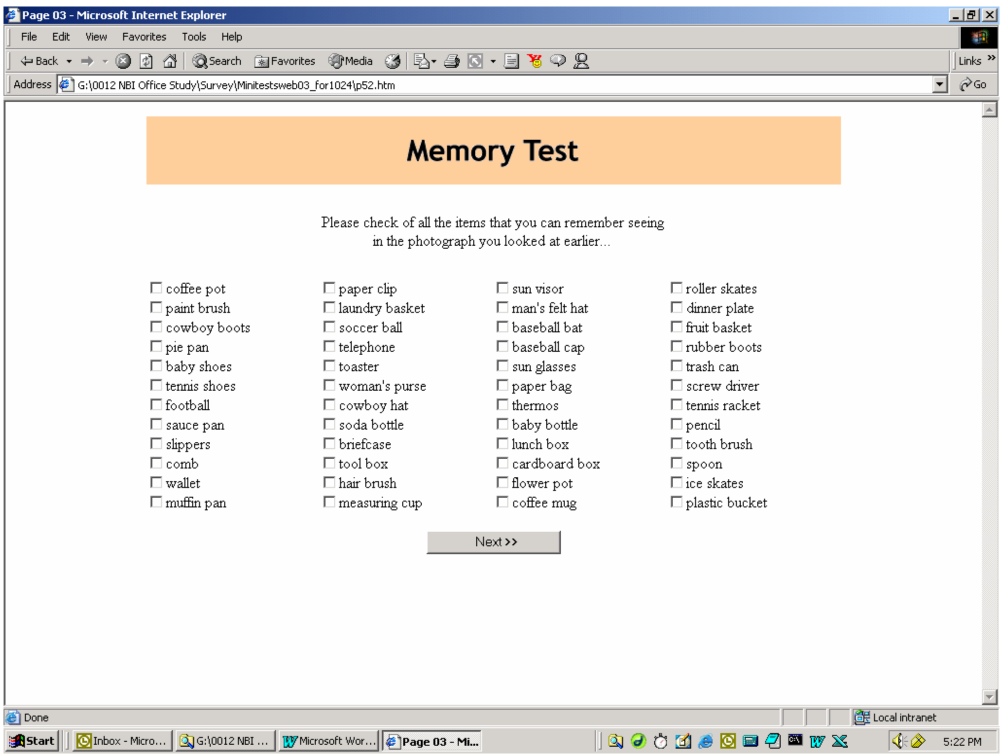

Figure 45: Screen shot of Memory Test response page

5.3.2 Mini-Tests Response

After selecting the population for the Mini-Tests, the participants were sent an email inviting them to take the Mini-Tests, with information about the format and procedures. They were asked to take the Mini-Tests three or four times on sequential Thursdays mornings. They were told that the Mini-Tests are a part of a study looking at the influence of different environmental conditions on office workers. They were not told that it specifically focused on lighting conditions or mental performance. We were able to receive e-mail questions from participants if they wanted further instructions or clarification.

The Mini-Tests were installed on a server within the SMUD intranet and were accessed via an internal URL hyperlink. The computers on the employees' desks had restricted access to the internet and firewalls which prevented us from installing the Mini-Tests on an outside internet server. The SMUD Business

Administration Services (BAS) department graciously provided the access to the server space for hosting of the Mini-Tests and greatly helped in tailoring the application to their server environment. The hyperlink was sent to the participants in an email reminder every Thursday morning, but was only activated during the specified test period.

At the end of each week a lottery was held to award a small prize for those who participated. The winner was announced in the e-mail reminder the following week.

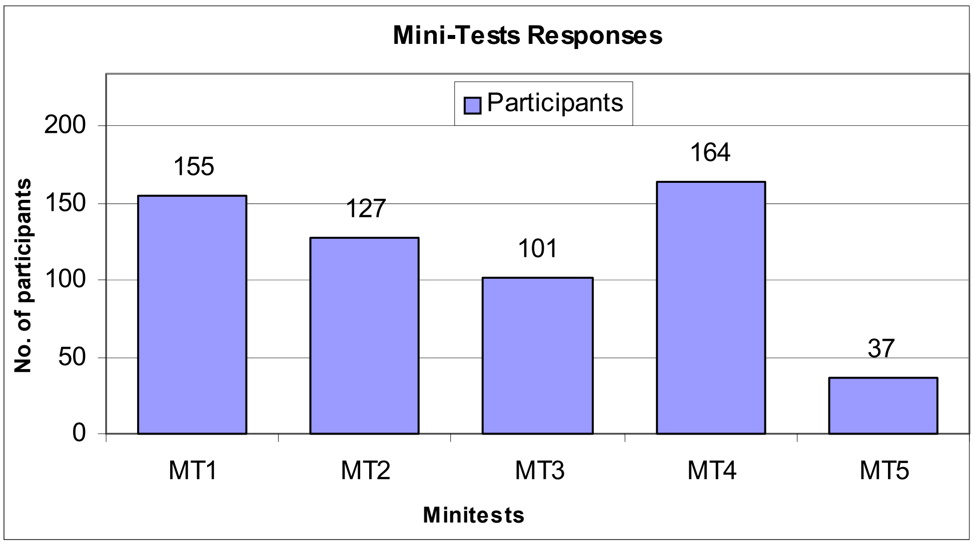

Figure 46: Number of participants by week for Mini-Tests

We received 155 responses for the first week from the 234 participants whom we invited. Participation fell to 127 in the second week and 101 in the third, as shown in Figure 46. To ensure higher participation, we sent out another flier after the third week to encourage participation in the final weeks. As a result the number of participants increased to 164 in the fourth week of the tests. Those who had missed a week and wished to complete a full round of the tests were invited to take another session on the fifth, make-up week, with the promise of a final lottery for those who completed at least three sessions.

Results from the Mini-Tests were collected on the SMUD server in a SQL database, then converted to an MS Access database for processing. The database recorded each participant's response, along with the time in milliseconds for each response. The records were identified by the cubicle number and participant ID. About five people relocated to a new cubicle during the course of the study. They were included in the study if we had comparable information about their new cubicle location.

5.3.3 Questionnaire

In addition to the Mini-Tests, the participants were asked to fill out a 15 page questionnaire at the end of the study period. Topics included thermal comfort, air quality, lighting quality, view, acoustics, stair usage and general health. General comfort questions were asked on a 7-point scale. An example of the questionnaire format and the 7-point scale is shown in Figure 47.

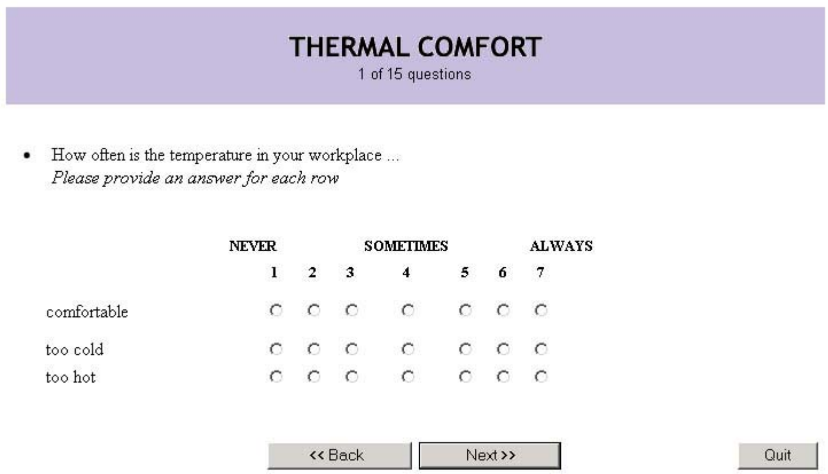

Figure 47: Screen shot of questionnaire showing 7-point scale

Other questions detailed specific problems with the use of checkboxes if that problem applied. These pages also included a choice of "other" with a space for respondents to make comments. The entire questionnaire is provided in the appendix for reference.

This questionnaire was based on an earlier survey administered to SMUD employees by the University of California at Berkeley's Center for the Built Environment in 1995.[1] The format of the original questionnaire was modified to provide greater discrimination in response. We also simplified and shortened the original questionnaire to suit our study interests.

The answers to the questionnaire allowed us to compare employees' own assessment of their workstation environment with our physical measurements and subjective surveyor ratings. We used Pearson's correlations to look at these relationships. For example, there was a strong correlation between survey rating of a better view and employee assessment of the size of their view.

We also used the questionnaire to answer questions raised during the regression analysis and provide insight to the findings. For example, we found a strong correlation between proximity to skylights and complaints about glare on

[1] E Ring and G Brager, Summary Report of Indoor Environmental Quality Assessment, by UCB Center for the Built Environment for SMUD, December 1999 . 179 employees in the newly opened CSC completed this survey.

computer screens, but no correlation between proximity to skylights and complaints about thermal comfort.

We also tested preliminary regression models explaining results on the Mini-Tests using a selected group of responses to the questionnaire as explanatory variables. These regression models were not conclusive and are not included in this report.

5.4 Variable Definition and Statistical Methodology

The data from the initial survey, cubicle observations and Hobo data collection were transformed into explanatory variables for use in the regression analysis. The data sources and definitions of the various demographic and environmental explanatory variables are described below.

The results from the Mini-Tests were transformed into “scores” for use as outcome variables. Scores for the timed tests were based on speed and accuracy. Scores for Backwards Numbers and the Memory Test were based on number of correct responses. The rationale and formula for creating these scores is also explained below.

Demographic Variables

The data for the demographic variables was mostly self-reported by the employees through the initial survey. Department and worker status was obtained from SMUD as part of our initial population assessment. Monitor resolution was recorded automatically by the server at the time of the test, as was the session indicator. The following variables were created from the available data.

- ***Years at SMUD*** (*YearsAtSmud*) the number of years the employee has been employed at SMUD
- ***Highest Degree*** (*degree1*) the highest degree obtained by the employee from high school diploma to PhD
- ***Age*** (*age1*) the age of the employee in five bins of 10 years, where 0= 20-29 yrs and 4= 60+ years
- ***Gender*** (*male/female*) a yes/no variable that indicates the gender of the employee
- ***Worker Status*** (*OSE/PAS*) a yes/no variable that indicates the work status of the employee. OSE indicates the employee is a member of Organization of SMUD Employees, and PAS indicates the employee is a non-union employee with professional, administrative or supervisory status.
- ***Net Hours Spent at Desk*** (*NetHours*) a self-reported number of estimated hours the employee spent working at his/her desk in the

past week. Hours spent on task away from desk such as meetings, site visits, lunch, etc., were not included.

- ***Departments*** (*Dept A – Dept K*) the department to which an employee belongs. The names of the departments have been masked for confidentiality.
- ***High Resolution Monitor*** (*mon1024*) monitors with resolution from 1024x768 to 1152x864.
- ***Higher Resolution Monitor*** (*monOther*) monitors with resolution at 1280x1024 or higher. The default condition is 800x600.

We consider monitor resolution to be a demographic control variable, since we believe it is more indicative of the “type” of person and the type of work they perform than an indicator visual acuity or other physical conditions. We went to great lengths to control for the impact of monitor resolution on visual acuity by automatically identifying the resolution of each screen and then administering images calibrated to that resolution. It turned out in practice that there were more than three resolutions in use, so we binned the various types into low, medium and high resolution monitors. By far the greatest number of participants had their monitor resolution at the lowest level, (800x600),which became the default for comparison. The next largest group was in the mid level. The smallest and most diverse group were those with the highest resolution monitors. Upon checking departments and task occupation we determined that most of those with high resolution monitors were CADD or specialized computer operators. This re-affirmed our hypothesis that this variable was best considered a demographic control variable.

- ***Session 2-4*** (sessionx), indicates the session of the Mini-Tests, with the first session is the default
- ***Missing Questionnaire*** (*missQuest*) an indicator that the participant had not attempted the questionnaire, or had left it incomplete

Environmental Variables

Environmental variables were created from data collected by the surveyors or recorded by the Hobos. The Hobo readings were averaged for the time between 10:30 AM and 12:00 PM to create a single reading for each of the five days the Mini-Tests were administered.

- ***Total Illuminance*** (*TI*) the illumination level recorded by the nearest Hobo, and calibrated to the cubicle location
- ***Electric Light*** (*Elmin_revised*) the electric illumination level from handheld readings at the cubicle during Saturday surveys based on the difference between two conditions: blinds closed-lights on and blinds closed-lights off. For measurements under skylights, where the

daylight contribution could not be excluded during the survey, we took nighttime readings from the Hobo, calibrated to cubicle location.

- ***Daylight illumination*** (*DI*), created by subtracting the estimated electric illuminance from the total illuminance recorded by the nearest Hobos, calibrated to the cubicle location
  - ***Daylight (nL)*** (*DI_log*) the natural log of daylight illuminance
- ***Skylight Zone*** (*SkylightsDistance_revised*), proximity to a skylight, where 0=none nearby and 3=underneath a skylight

To create the skylight zone category, we plotted the skylights and their splays on a floor plan. 3 = Cubicles directly under a skylight or splay of the skylight well. 2 = Cubicles that were between two skylights. 1 = Cubicles adjacent to one skylight splay. 0 = Cubicles with no skylight influence or in a non-skylight location. (See Figure 48 for a sectional diagram)

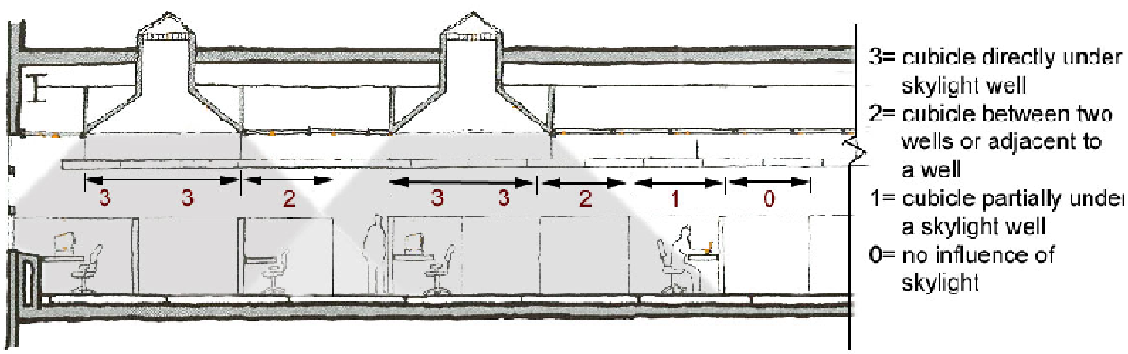

Figure 48: Location of Skylight Zone, shown in section 3= under skylight, 2= one desk away from skylight, 1= two desks away from skylight, 0= no skylight

- ***Primary View*** (*ViewFactor*) rating of workstation view of window while looking at monitor within a 90 degree field of view from 0=none to 5=best. See discussion in Call Center study for rating procedure.
- ***Break View*** (*ViewBreak*) rating of workstation view of window while looking away from monitor in any direction from 0=none to 5=best. See discussion in Call Center study for rating procedure.
- ***Distance to External Wall*** (*DeskDistance*) the distance in feet between a cubicle's chair location and the nearest outside wall
- ***Glare from Windows*** (*Glare*) rating of the potential for occasional glare from window in primary field of view, including moving cars or sunlit surfaces from 0=none to 3=worst. See discussion in Call Center study for rating procedure.

- ***Floor Register Status*** (Flreg) position of the vent on the floor register at an employees' workstation, with 0 = missing or blocked, 1= completely closed, 2 = 10-40% open, 3 = 50-80% open, 4 = fully open
- ***Air Temperature*** (*Temp)* the indoor air temperature in degrees F recorded by the Hobo nearest to the cubicle
- ***CSC Building*** (*CSC/HQ or bldg59th*) a yes/no variable indicating if the employee is located in the CSC building

5.4.2 Outcome Variables

The outcome, or dependent, variables were defined for each of the five Mini-Tests. The three timed tests were translated into an average score for each session based on speed and accuracy. The time taken to respond to a screen was captured by the computer in milliseconds. It recorded the time elapsed from when the screen was first displayed to when the respondent selected an answer or button to continue to the next screen. The two un-timed tests, Backwards Number and the Memory Test, were scored based on the number of correct answers.

We examined the average, standard deviation, minimum and maximum of the results on each test to make sure that we had achieved an appropriate and sufficient range of response for analysis. We also preformed sensitivity analysis to make sure that there were no significant differences in the data that we were combining.

We examined the data and removed any individual that had exceptional success or failure. In the Backwards Number test, a series of very low scores followed by a series of perfect scores was considered a sign of cheating and removed from the population.

Ultimately we decided to include a "session variable" as an indicator variable for which session was being considered. This variable captured any systematic change in performance between sessions, as might be expected with either a learning curve if participants did progressively better with each session or a fatigue or boredom factor, if they did worse with each session.

The formula to create an individual score which was used as the outcome variable for each test is described below. The descriptive statistics for the study population's performance on these tests is included in the Appendix.

Landolt C

The first three screens of the Landolt C tests had an extremely high success rate, with 98% to 100% of respondents always getting the image correct. The fourth screen, with the smallest image and lowest contrast, had a lower response rate that ranged from 88% to 95% correct for various sessions. Thus, we decided to use only results from the fourth screen for our analysis.

If a respondent got a correct answer, their score was the amount of time to respond to the fourth screen. If a respondent got an incorrect answer, their score was their time plus the average of all correct times for that screen for that session.

We analyzed this approach to scoring to make sure that it provided an appropriate distribution of responses. The average of all wrong times was almost always slightly greater or very close to the average of all correct times, and was always greater than the standard deviation of correct times. Thus, with this weighting method, the average weighted wrong score was always greater than the average of correct scores plus one standard deviation. Weighted wrong responses tended to be above the 85th percentile of scores. The average weighted score on this test was 3.6 seconds.

Letter Search

For the Letter Search test, the three screens were determined to be equally difficult, with a correct response rate of 93-100%. The times also had a normal distribution for all screens, thus we decided to use an average of the response for all three screens per session.

We used the same scoring method as Landolt C, but this time applied to all three tests per session. If a respondent got a correct answer, their score was the amount of time to respond to that screen. If a respondent got an incorrect answer, their score was their time plus the average of all correct times for that screen for that session. Their score for all three screens was then averaged for a session score. The average weighted score on this test was 5.1 seconds.

Number Search

For the Number Search test, the three screens varied in difficulty somewhat according to which digit respondents were requested to find, and how many of those digits they needed to find. We conducted paired sample t-tests to determine if there were any significant differences in time between trials in a single week, between digits, and between weeks. After sensitivity analysis, we concluded that there was sufficient uniformity in difficulty between the sessions that they could be compared. The times also had a normal distribution for all screens. This test was clearly more challenging than the previous two. Correct response rates varied from 70% to 96%. We decided we could use an average of the response for all three screens per session.

We used the same scoring method as Letter Search, described above. The average weighted score on this test was 15.6 seconds.

Backwards Number

The outcome variable for Backwards Numbers was the highest score each individual achieved per week, based on the standard scoring method used for this test by clinical psychologists. Time taken for completing the screens was not considered. The score was determined by the count of how many digits the participant could correctly remember. Participants were given two chances for each count of digits. If they got both randomized strings of numbers correct for a given count of digits, then that number of digits was their score. If they only got one of a pair correct, then their score was one half point less. Thus, if their highest correct answer was two strings of fours, their score = 4. If their highest correct answer was only one string of fours, their score = 3.5. Failure to get the either of the first strings of three digits was a zero.

Norm for the adult population for the test as administered aurally by a clinical psychologist is 4.5. The norm for our study population as administered visually on the computer was 5.23.

Memory Test

The Memory Test results can be used to predict long and short term memory. For short term memory, the score from the first session, in which the participant is shown the image at the start of the test, was considered the outcome variable, while for long term memory, the score of the participant's second, third and fourth sessions would be considered.

Our preliminary analysis of the results from the Memory Test show a clear and marked decline in the number of correct items checked from the first to the second session. This decline in memory was not significantly different between the second test and any subsequent test. Thus, we felt confident lumping the second, third and fourth tests together for analysis.

The score for the Memory Test was the number of correctly remembered objects. In addition we added explanatory variables that accounted for the number of correct answers on the first test and the number of imagined objects for each session. Thus, if a person tried to "hedge their bets" by selecting more responses, they were penalized by this second explanatory variable. The average score for the second through fourth sessions of the Memory Test was 11.6 objects correctly remembered out of 24 potentially correct.

5.4.3 Preliminary Statistical Investigations

The outcome variables for the Landolt C, Letter Search and Number Search tests in the Desktop study were based upon the amount of time taken by each person to complete each trial. Since there were multiple trials for each test in one session, and a person could take each test multiple times over the course of the testing period, it was necessary to devise a defensible method for combining the results from all the trials into a single outcome variable for each test.

In consultation with our advisors, we concluded that it was necessary to conduct paired sample t-tests to determine if there were any significant differences in time between trials in a single week, since each trial in the sessions were different and may have posed differing levels of difficulty. We also tested for differences between weeks to determine if there were significant differences in the scores between the weeks. The testing between weeks also allowed us to test the hypothesis that there was a learning effect associated with the tests and that people who took the tests multiple times had shorter times in subsequent tests. We also tested to see if there was a significant difference in time between people with differing monitor resolutions. We found that there were few significant differences between trials, sessions and monitor resolutions among people who had attempted a single session and those who had attempted multiple sessions. Therefore we concluded that it was appropriate to use straight averages to combine the trial results into a single outcome variable for each test.

Preliminary analysis of the data was performed to test for heteroscedasticity and collinear variables. Pearson's correlations were used to look for collinearity among explanatory variables. In addition, since daylight illumination was our greatest interest, we also created a preliminary regression model using daylight illumination as the dependent, or outcome, variable with all other data included as explanatory variables. This model revealed that indoor air temperature was the strongly correlated with measured horizontal daylight illumination levels, with a one degree increase in air temperature predicting a six footcandle increase in daylight illumination. All other variables that could predict daylight illumination levels were entirely expected, such as being closer to a window or a skylight predicting higher levels, with the exception of two. Younger people were found to have better chance of higher daylight levels and those with the mid resolution monitors also had slightly higher daylight levels. The Daylight-as-outcome model is included in the Appendix.

5.4.4 Final Models

All of the analysis was pursued using multivariate regression models run in SAS (Statistical Analysis Software). The analysis used $p \leq 0.10$ as the threshold criteria for inclusion of explanatory variables in the models, meaning that for a variable to be considered significant, there must be no greater than a 10% chance of error in making this decision, or 90% certainty. All statistical terms are explained in the Appendix.

Alternate forms of both outcome and explanatory variables were considered, such a linear versus logged versions, as discussed above. Models were judged based on their R^2 (the percentage of variation in the data explained by the model), the parsimony (minimum explanatory variables for maximum explanatory power) and consistency between the models.

The variable selection methodology was the same used in the Call Center study, as described in Section 4.5.6.

5.5 Desktop Findings and Discussion

In this section we discuss the findings from the regression analysis, for each of the five Mini-Tests. The Mini-Tests were administered to the participants in order of increasing difficulty and increasing mental function. However, here we report on them in reverse order, starting with the most challenging, involving the highest order mental processing—long term memory—and progressing to the least challenging, Landolt C, measuring only visual acuity. After discussing the findings of each test in turn, we then compare the results across the tests to consider possible reasons for consistency or lack of consistency in the findings.

5.5.1 Reporting Format

The results are presented here in a variety of formats to aid interpretation. For each test we first present the findings as a percentage effect, as determined by a specified range of the explanatory variable. We also present the findings of each model in terms of order of entry and partial R^2 of the explanatory variables.

In the percentage effect tables, all those variables that had a significance of more than 90% (p-value ≤ 0.1) are reported. Explanatory variables that were tested in the model but did not achieve this significance threshold are left blank. The percentage effect shows how much the outcome variable would change over a range of the explanatory variable, if all other factors considered in the regression model were held constant. The percentage effect was calculated using the B-coefficient for each variable multiplied by a specified range for that variable, and then divided by the mean of the outcome variable. For a simple yes/no variable the percentage effect is the change in performance observed when that variable is "yes." For variables with a scalar range, we choose a consistent and meaningful range for comparison. For example, for, *Daylight (nL)* we report the effect seen with an increase of daylight illumination of 10%, or for *Air Temperature* we report the effect seen when indoor air temperature increases by 2°F.

In the second, order of entry tables, we present information about the order of entry, p-value (significance) and partial R^2 of each variable. The order of entry and partial R^2 give an indication of each variable's explanatory power in the model. Those variables with highest explanatory power will tend to enter the model first and have the largest partial R^2. The p-value, or the significance level of variables, is perhaps the best way to assess their strength in the model and their likelihood of consistently appearing in other models. The highest significance level, p≤0.0001, expresses that there is a 99.99% certainty that the effect does indeed exist, or is not zero. A significance level of p≤0.10 expresses that there is a 90% certainty of a valid effect. The lowest criterion for entry into the models was p≤0.10.

Figure 49 , shown earlier, presents a summary of the cognitive functions assessed by each of the five Mini-Tests. Descriptive statistics and statistical details of results for each model are provided in the Appendix.

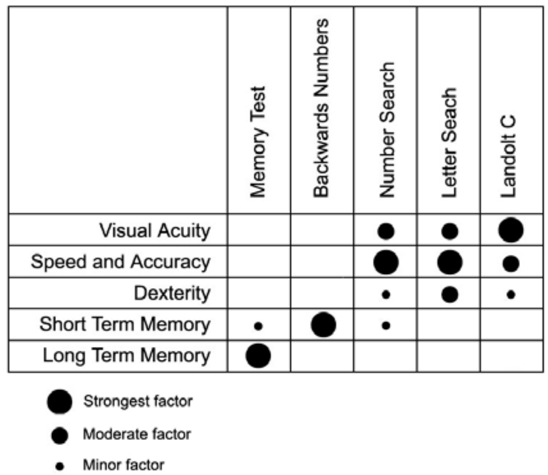

Figure 49: Cognitive functions assessed by the five Mini-Tests.

5.5.2 Memory Test

The Memory Test was a visual memory test which asked participants to remember a set of images shown to them at the very beginning of their first session. They were allowed to look at the image only once for 60 seconds. Scores for the test were based on the number of objects that participants could correctly remember later, either at the end of the first session, or in later session one to four weeks after seeing the image. Thus, we consider this to be an indication of the short term (first session) and long term (second through fourth session) visual memory capabilities of the employees.

We tested a number of model formats and found that, in general, this metric of performance was not very well predicted by any of our explanatory variables, including department, demographics or physical conditions. Models where we looked only at the outcome of the first session to indicate short term memory—the ability to remember objects correctly at the end of the first session, about 10 minutes after first seeing the images—found that none of our explanatory variables were significant. There are at least two possible conclusions from this exercise: either that this capability is randomly distributed in the population and is not influenced by any physical comfort conditions, or alternatively that the test is not a highly sensitive indicator of mental performance and thus would require a much larger sample size to reveal significant relationships.

Variable	Range	Memory Test	
		R2 = 0.511	
		better	worse
Lighting			
Daylight (nL)	if increased by 10% …		
Electric Light	if increased by 10% …		
Skylight Zone	from no skylight to below a skylight …		
View			
Primary View	**from none to most …**	**16%**	
Break View	**from none to most …**	**9%**	
Glare from Windows	**from none to most …**		**-17%**
Distance To External Wall	from 6 ft to 60 ft …		
Temperature			
Floor Register Status	from closed to completely open …		
Air Temperature	**if increased by 2 deg F …**	**8%**	
Location			
CSC Building	if located in CSC …		
Demographic			
Age	**if 10 years older …**	**5%**	
Years with Company	if 10 years more …		
Education	from High School degree to PhD …		
Gender	**if selected gender …**		**-13%**
High Monitor Resolution	**if yes …**		**-13%**
Higher Monitor Resolution	if yes …		
Session			
Session 2	if yes …		
Session 3	**if yes …**		**-6%**
Session 4	if yes …		
Correct on 1st Memory Test	if 5 more …	26%	
Imagined per Memory Test	if 5 more …	19%	
Department			
Dept A	if yes …		
Dept B	if yes …		
Dept C	if yes …		
Dept D	if yes …		
Dept E	if yes …		
Dept F	if yes …		
Dept G	if yes …		
Dept H	**if yes …**		**-10%**
Dept I	if yes …		
Dept J	if yes …		
Dept K	**if yes …**		**-21%**

Figure 50: Memory Test, percentage effects

We then separately analyzed scores from the later sessions indicating long term memory. In these models we included explanatory variables that controlled for performance on the first test and number of objects incorrectly "imagined" on the tests. Both these variables clearly show that the more objects a person got correct in the first session, the more they were likely to get correct in following session. Furthermore, the more objects incorrectly imagined in the following tests, the more correct objects a person was also likely to identify. Once we controlled for these “test” effects, influences of other variables also showed up as significant. Looking at the order of entry table in Figure 51, it is clear that these two explanatory variables were the most powerful predictors of a person’s performance, explaining 43% of the variation in scores.

In the final model of long term visual memory presented here in Figure 50, four environmental influences on performance were found significant. Three of these relate to the window view, and one relates to the air temperature.

When a participant had the best possible *Primary View*, they could remember 16% more objects correctly than those participants with no *Primary View,* or about two more objects out of a potential list of 24. Likewise those employees with the best *Break View* also increased their performance by 9% over those with no *Break View*. These two results are additive, so any employees with both the highest *Primary View* and *Break View* would be performing *25%* better than those with none. However, in this model we also see *Glare from Window* as a negative influence, reducing performance by 17%. Thus this negative effect of *Glare from Window* could be a self-canceling effect of the benefits from the *Primary View. (Glare from Window* was only a function of the primary view.) Adding an interaction variable between *Glare* and *Primary View* did not change the model.

Higher *Air Temperature* was also seen to be associated with improved long term memory performance. A 2°F increase in *Air Temperature* was seen to improve long term memory by 8%. Since a higher air temperature was strongly correlated to more daylight at the workstation it is possible that this could also be an indirect indication of a daylight effect. (See Daylight-as-Outcome model in Appendix)

Among the other control variables, it is interesting that *Age* was found to be significant and a positive indicator of better long term memory performance. Two dimensional analysis showed that there was a downward trend in the absolute number of objects remembered as the study population increased in age, but that the relative decline between the first and later session (the metric measured in the analysis) was slightly less. In our study population the average age was about 42 years old, with a standard deviation of eight years. The model predicts that, once number of objects remembered on the first test is controlled for, people who are forty-two years old will correctly remember about one more object than a twenty-two year old. Other demographic control variables, such as *Gender*, *High Monitor Resolution, Session2, Dept H and Dept K* also indicated negative performance.

Figure 51 gives the order of entry for all the significant variables in the Memory Test model. The environmental variables, indicated in bold, can be seen lower in the order, while demographic and visual variables are higher up the order. At the bottom of the table, the total R^2 for the four environmental variables is calculated and its percentage with respect to the full model is determined. Thus, all together the four environmental variables are responsible for 4% of the explanatory power of this model. This low contribution of environmental variables might be attributed to the number of intervening environments each participant was exposed to over the one to four week period between seeing the image and reporting on remembered objects.

Order of Entry	Variable	Significance	Partial R-Square	Cumulative R-Square
1	*Correct on 1st Memory Test*	*<.0001*	*0.340*	*0.340*
2	*Imagined per Memory Test*	*<.0001*	*0.085*	*0.426*
3	Gender	<.0001	0.023	0.449
4	High Monitor Resolution	0.001	0.014	0.462
5	Age	0.012	0.012	0.474
6	**Air Temperature**	0.004	**0.007**	0.481
7	Session 3	0.066	0.006	0.487
8	Dept H	0.032	0.004	0.491
9	Dept K	0.048	0.005	0.496
10	**Break View**	0.060	**0.004**	0.500
11	**Primary View**	0.009	**0.004**	0.504
12	**Glare from Windows**	0.032	**0.008**	0.511
Total R-Square for all Environmental Variables			0.022	
Percentage of Model R-square			4%	

Figure 51: Memory Test, order of entry and partial R^2.

The R^2 for this model is substantially higher, at 0.51, than the other Mini-Tests models, which range from 0.11 to 0.19. This is entirely due to the contributions of the two top variables, which provide information on individual performance on the tests rather than demographic or environmental conditions. When those two variables are subtracted form the model, the remainder is the lowest of all, at 0.085, meaning that all these other variables only explain 8.5% of the variation in performance on this test. Of this remaining percentage, the environmental variables are responsible for 26%.

5.5.3 Backwards Numbers

Backwards Numbers was the short term memory test in which the participants were asked to remember a sequence of numbers flashed on screen and then type them into the computer in reverse order. The scoring is based on the maximum number of digits that the participant could remember correctly. This test is widely accepted by psychologists worldwide as an assessment of attention span and shot term memory. This test indicates the ability to focus one's attention and remember details. Of the five Mini-Tests, we consider it to be the closest to an overall assessment of mental performance. Poor scores on this test could indicate mental fatigue or inability to shut out distractions to concentrate.

Variable	Range	Backwards Numbers R2 = 0.126 better	worse
Lighting			
Daylight (nL)	**if increased by 10% …**	**0.4%**	
Electric Light	if increased by 10% …		
Skylight Zone	from no skylight to below a skylight …		
View			
Primary View	**from none to most …**	**10%**	
Break View	from none to most …		
Glare from Windows	**from none to most …**		**-15%**
Distance To External Wall	from 6 ft to 60 ft …		
Temperature			
Floor Register Status	from closed to completely open …		
Air Temperature	if increased by 2 deg F …		
Location			
CSC Building	if located in CSC …		
Demographic			
Age	if 10 years older …		
Years with Company	**if 10 years more …**		**-4%**
Education	**from High School degree to PhD …**	**11%**	
Gender	**if selected gender …**		**-7%**
High Monitor Resolution	if yes …		
Higher Monitor Resolution	if yes …		
Session			
Session 2	if yes …		
Session 3	if yes …		
Session 4	if yes …		
Department			
Dept A	if yes …		
Dept B	if yes …		
Dept C	if yes …		
Dept D	**if yes …**		**-10%**
Dept E	**if yes …**		**-16%**
Dept F	if yes …		
Dept G	if yes …		
Dept H	if yes …		
Dept I	if yes …		
Dept J	**if yes …**	**15%**	
Dept K	if yes …		

Figure 52: Backwards numbers, percentage effects.

Figure 52 shows the percent effects calculated for all significant variables in the Backwards Numbers model. Among the environmental variables, the results show *Daylight (nL)* to be a highly significant and a positive indicator of performance. For every 10% increase in daylight illumination, a 0.4% increase in performance can be expected. Although this may sound like a very modest effect, this variable was on a logged, not a linear scale. Thus, it predicts increasing larger effects at lower levels of illumination.

The predicted effect of daylight on Backwards Number performance is plotted on a linear scale of increasing daylight footcandles (fc) in Figure 53. It shows that an increase in daylight from 1 to 20 footcandles results in a 0.7 point improvement in performance over the 3-7 point scale in our test, or a 13% improvement in performance. A full one point improvement in performance is seen from 1 to 67 footcandles of daylight illumination, translating in to an overall increase of 19% compared to norm. However, due to the logged scale of the variable, an increase in 20 footcandles at the upper end of the range, from 70 fc to 90 fc, results in very little improvement in performance. This is consistent with expectations that the greatest effect of daylight would be at the low end of indoor illumination levels, with a decreasing relative effect at higher illumination levels.

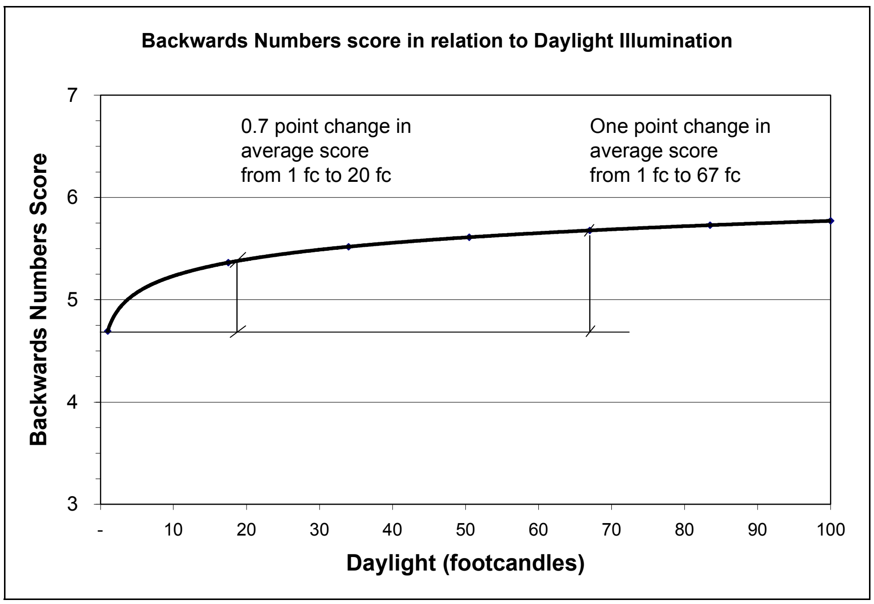

Figure 53: Backwards Numbers score in relation to Daylight Illumination

Along with daylight, a higher quality *Primary View* was also found to be a positive indicator of performance, increasing performance by 10%. *Glare from Windows* was also found significant, and is predicted to have a negative influence on performance. A high glare workstation can be expected to reduce performance of the office worker by 15% as compared to a workstation with no glare from the windows. We tested an interaction variable between *Glare* and *Primary View,* which was significant for this one model. Analysis of the net effect showed that in this case a participant with a high Primary View only performed better when there was also no glare potential from that window.

The demographic control variables that show up as significant and positive were *Education* and *Dept J,* while negative performance was indicated by *Years at Company, Gender, Dept D* and *Dept E.* The results suggest that higher education will result in better focused attention, while more years at the company is an indication of poorer performance.

Order of Entry	Variable	Significance	Partial R-Square	Cumulative R-Square
1	**Daylight (nL)**	<.0001	**0.031**	0.031
2	Years with Company	0.009	0.021	0.052
3	Dept J	0.003	0.019	0.071
4	Dept E	0.001	0.018	0.089
5	Dept D	0.012	0.010	0.099
6	Gender	0.009	0.007	0.106
7	Education	0.018	0.007	0.112
8	**Glare from Windows**	0.005	**0.006**	0.118
9	**Primary View**	0.031	**0.008**	0.126
Total R-Square for all Environmental Variables			0.045	
Percentage of Model R-square			36%	

Figure 54: Backwards Numbers, order of entry and partial R^2

For the Backwards Numbers model, we see in Figure 54 that the daylight variable entered the model first and has the largest partial R^2. It also has the highest significance, denoted by the lowest p-value in the significance column. The remaining environmental variables of glare and view enter the model last, with much smaller partial R^2. In this model, the environmental variables are responsible for 36% or about one third of the explanatory power of the model.

We are fairly confident that increasing levels of daylight and view are not confounded by higher professional status in the company for two reasons. First, if proximity to the perimeter of the building, and a thus a better view or more daylight, were the most relevant indicator of performance, than the variable *Distance to Wall* would be more significant than *Primary View* or *Daylight (nL).* Secondly, as mentioned earlier, we had a good mix of high status professionals in the Headquarters building with wonderful views from their cubicles but no daylight, and we had a fairly large population of clerical workers in the core of the top floors of the CSC building who had very high daylight levels due to the skylights overhead.

With these results, daylight was shown to be a significant indicator of better performance in tasks related to mental alertness and short term memory. The results for *Primary View* and *Glare from Windows* show consistency with results from the Memory Test.

5.5.4 Number Search

The Number Search Test involved a mix of mental function and visual acuity. The participant was required to visually scan through a matrix of numbers and count the number of times a specified digit appeared. The test requires visual acuity to find the digits with a coordinated scanning motion of the eye across the matrix, while also remembering the number of times the digit appears, which requires mental alertness and short term memory. The scoring is based on time taken to respond, weighted for a correct response, as described in Section 5.4.2.

Variable	Range	Number Search R2 = 0.111	
		faster	**slower**
Lighting			
Daylight (nL)	if increased by 10% …		
Electric Light	if increased by 10% …		
Skylight Zone	from no skylight to below a skylight …		
View			
Primary View	**from none to most …**	**8%**	
Break View	**from none to most …**	**8%**	
Glare from Windows	**from none to most …**		**-21%**
Distance To External Wall	from 6 ft to 60 ft …		
Temperature			
Floor Register Status	**from closed to completely open …**	**17%**	
Air Temperature	if increased by 2 deg F …		
Location			
CSC Building	if located in CSC …		
Demographic			
Age	**if 10 years older …**		**-4%**
Years with Company	**if 10 years more …**		**-4%**
Education	from High School degree to PhD …		
Gender	**if selected gender …**		**-6%**
High Monitor Resolution	if yes …		
Higher Monitor Resolution	**if yes …**		**-10%**
Session			
Session 2	if yes …		
Session 3	if yes …		
Session 4	if yes …		
Department			
Dept A	**if yes …**	**13%**	
Dept B	**if yes …**	**16%**	
Dept C	if yes …		
Dept D	if yes …		
Dept E	if yes …		
Dept F	if yes …		
Dept G	**if yes …**	**11%**	
Dept H	**if yes …**	**9%**	
Dept I	if yes …		
Dept J	if yes …		
Dept K	if yes …		

Figure 55: Number Search, percentage effects

From the results shown in Figure 55, *Primary View* and *Break View* were found to be statistically significant in having a positive influence on performance of this test. The highest level of both *Break View* and *Primary View* were found to be associated with enhanced performance of 8% each when compared a workstation with no view. Once again, *Glare from Windows* also came in significant and was found to have negative impact of 21% on performance. Adding an interaction variable between *Glare* and *Primary View* had no effect on the model.

In the Number Search model *Floor Register Status* was found to be significant and have a positive association with performance. Hence those workers who kept their floor register completely open performed 17% better than those with their floor register completely closed.

Age, Years with Company, Gender and *Higher Resolution Monitor* were the demographic control variables that had statistical significance and all had a negative effect on performance. Four of the departments also came in as significant with a positive relationship to performance in this test. Although we pledged general anonymity for the departments in reporting, we think it is reassuring to mention that the Accounting Department was one of the groups that did well on this test—potentially confirming the skills of that department and the validity of the test as a performance indicator for those who must deal with lots of numbers throughout the day.

Order of Entry	Variable	Significance	Partial R-Square	Cumulative R-Square
1	Years with Company	0.051	0.023	0.023
2	**Floor Register Status**	<.0001	**0.013**	0.036
3	**Glare from Windows**	0.000	**0.014**	0.049
4	Higher Monitor Resolution	0.001	0.011	0.060
5	Dept H	0.018	0.009	0.069
6	Dept B	0.007	0.008	0.077
7	Age	0.014	0.006	0.083
8	Dept A	0.008	0.007	0.091
9	**Break View**	0.034	**0.004**	0.095
10	Gender	0.026	0.004	0.099
11	Dept G	0.021	0.007	0.106
12	**Primary View**	0.088	**0.005**	0.111
Total R-Square for all Environmental Variables			0.035	
Percentage of Model R-square			32%	

Figure 56: Number Search, order of entry and partial R^2

The order of entry table for Number Search is shown in Figure 56. The environmental variables can be seen higher in the order, compared to the earlier two purely memory related tests. The physical variables were found to be responsible for 32%, or again about one third, of the explanatory power of the model.

The results about *Glare*, and *Primary View* and *Break View* are again consistent with findings from the two memory and mental alertness related tests discussed earlier—Backwards Numbers and Memory Test. The other consistent variables in the three tests have been *Years with Company* which had a negative effect on performance, and *Gender* which also had a consistently negative effect.

5.5.5 Letter Search

Variable	Range	Letter Search R2 = 0.132 faster	slower
Lighting			
Daylight (nL)	if increased by 10% …		
Electric Light	if increased by 10% …		
Skylight Zone	**from no skylight to below a skylight …**		**-15%**
View			
Primary View	from none to most …		
Break View	from none to most …		
Glare from Windows	from none to most …		
Distance To External Wall	from 6 ft to 60 ft …		
Temperature			
Floor Register Status	**from closed to completely open …**		**-15%**
Air Temperature	if increased by 2 deg F …		
Location			
CSC Building	if located in CSC …		
Demographic			
Age	**if 10 years older …**		**-6%**
Years with Company	**if 10 years more …**		**-6%**
Education	from High School degree to PhD …		
Gender	**if selected gender …**	**12%**	
High Monitor Resolution	**if yes …**	**12%**	
Higher Monitor Resolution	**if yes …**	**16%**	
Session			
Session 2	**if yes …**	**18%**	
Session 3	**if yes …**	**27%**	
Session 4	**if yes …**	**22%**	
Department			
Dept A	if yes …		
Dept B	if yes …		
Dept C	if yes …		
Dept D	if yes …		
Dept E	if yes …		
Dept F	if yes …		
Dept G	if yes …		
Dept H	if yes …		
Dept I	if yes …		
Dept J	**if yes …**		**-18%**
Dept K	if yes …		

Figure 57: Letter Search, percentage effects.

The Letter Search test was one of the two out of five tests whose focus was mainly on visual acuity. The participants were asked to locate a “c” among a random image full of “o”s. It required visual acuity, good visual scanning ability, as well as speed, accuracy and dexterity to quickly get the mouse in the right location to select the “c”. This was a fairly easy visual task, as indicated by the high percentage of participants who always got it right (93%-100%). The weighted score was determined by how long it took to respond correctly.

Figure 57 presents the percentage effect findings for the Letter Search model. The only environmental variables that were significant were *Skylight Zone* and *Floor Register Status*. Both show a negative influence on performance. Those employees who were directly under a skylight did 15% worse than those who were not near a skylight. Those employees who kept their floor register completely open also performed 15% worse than those with their registers completely closed (or those without a floor register, as in Headquarters and the 59th street building).

The other control variables that were significant were *Age, Years at Company* and *Dept K*, all of which had a negative effect on performance, and *Gender, High Monitor Resolution, Higher Monitor Resolution, Session 2, Session 3* and *Session 4*, all of which had a positive influence.

Order of Entry	Variable	Significance	Partial R-Square	Cumulative R-Square
1	Age	0.018	0.025	0.025
2	Session 3	<.0001	0.023	0.048
3	Gender	0.003	0.018	0.066
4	Session 2	0.000	0.015	0.081
5	Session 4	0.004	0.014	0.095
6	**Floor Register Status**	0.004	**0.012**	0.107
7	Years with Company	0.023	0.004	0.110
8	**Skylight Zone**	0.007	**0.004**	0.114
9	Higher Monitor Resolution	0.002	0.005	0.120
10	High Monitor Resolution	0.028	0.005	0.125
11	Dept J	0.033	0.007	0.132
Total R-Square for all Environmental Variables			0.016	
Percentage of Model R-square			12%	

Figure 58: Letter Search, order of entry and partial R^2

The order of entry table in Figure 58 shows that *Age* had the most explanatory power, followed by the learning curve implied by the session variables. The environmental variables come in at the middle of the model order, followed by monitor resolution status. The two environmental variables are responsible for 12%, or 1/8th, of the explanatory power of the model.

The negative effect attributable to skylights might best be interpreted as a glare problem. From the questionnaire responses we saw that being under a skylight was highly correlated with reporting problems of skylight reflections in the computer monitor (see discussion in Section 5.5.9).

In this visual acuity test, it is interesting that those employees with a high monitor resolution clearly have an advantage. Although the Mini-Tests controlled the image size in the tests depending on the three most common monitor resolutions to produce the same size image on screen, we did not control for all possible settings of resolution.

The three session variables that came in significant show the effect of a learning curve from the second session to the fourth, in which individuals got progressively better at this test with each trial. Higher *Age* and *Years at the Company* were both indicators of slower performance, which is consistent with the observation that both visual acuity and dexterity tend to decrease with age.

5.5.6 Landolt C

Variable	Range	Landolt C R2 = 0.195	
		faster	slower
Lighting			
Daylight (nL)	if increased by 10% …		
Electric Light	if increased by 10% …		
Skylight Zone	from no skylight to below a skylight …		
View			
Primary View	**from none to most …**		**-16%**
Break View	from none to most …		
Glare from Windows	from none to most …		
Distance To External Wall	from 6 ft to 60 ft …		
Temperature			
Floor Register Status	**from closed to completely open …**		**-20%**
Air Temperature	**if increased by 2 deg F …**		**-8%**
Location			
CSC Building	**if located in CSC …**	**29%**	
Demographic			
Age	**if 10 years older …**		**-13%**
Years with Company	if 10 years more …		
Education	**from High School degree to PhD …**		**-29%**
Gender	if selected gender …		
High Monitor Resolution	**if yes …**	**33%**	
Higher Monitor Resolution	**if yes …**	**29%**	
Session			
Session 2	if yes …		
Session 3	**if yes …**	**16%**	
Session 4	**if yes …**	**22%**	
Department			
Dept A	if yes …		
Dept B	if yes …		
Dept C	if yes …		
Dept D	if yes …		
Dept E	if yes …		
Dept F	**if yes …**	**19%**	
Dept G	if yes …		
Dept H	if yes …		
Dept I	if yes …		
Dept J	if yes …		
Dept K	if yes …		

Figure 59: Landolt C, percentage effects

The Landolt C test is a visual acuity test commonly used in human factors vision and lighting research. The participants were asked to identify which direction a square “C” was pointing. The weighted scoring was based on time for a correct response. We presented four versions of this test, with progressively more difficulty as the size and contrast was reduced. Only the fourth, most difficult, test showed any discrimination among the capabilities of the participants. We interpret this test to be primarily an assessment of the visual acuity of the employee under their standard workstation conditions.

Figure 59 presents the percentage effects for the Landolt C model. Here three environmental variables were significant and associated with negative performance. They were *Primary View, Floor Register Status* and *Air Temperature*.

Those employees with a large *Primary View*, directly within the field of view while looking at the monitor, were seen to perform 16% worse than those with no *Primary View*. Interestingly, those with their floor registers completely open performed 20% worse on this test than those with their registers closed (or in Headquarters or the 59th street building). This needs to be tempered by the other finding that those employees in the CSC building were performing 29% better (faster) than those in the other two buildings. Likewise, higher *Air Temperature* was also found to have a detrimental effect on the test score by 8% for every 2 degrees increase. We know that those in the CSC building tended to have slightly higher air temperatures by about 2°F and as did those employees directly located under a skylight.

Order of Entry	Variable	Significance	Partial R-Square	Cumulative R-Square
1	Age	<.0001	0.053	0.053
2	Education	0.001	0.025	0.078
3	Higher Monitor Resolution	<.0001	0.026	0.103
4	High Monitor Resolution	<.0001	0.038	0.141
5	Session 3	0.002	0.010	0.151
6	Session 4	0.010	0.010	0.162
7	Dept F	0.037	0.008	0.170
8	**Primary View**	0.015	**0.004**	0.174
9	CSC Building	0.000	0.004	0.178
10	**Floor Register Status**	0.016	**0.010**	0.188
11	**Air Temperature**	0.035	**0.007**	0.195
Total R-Square for all Environmental Variables			0.021	
Percentage of Model R-square			11%	

Figure 60: Landolt C, order of entry and partial R^2

The order of entry table in Figure 60 shows that the environmental variables come into the model at the bottom of the order. *Age* again has the most explanatory power. The three environmental variables are responsible for 11%, or again about 1/8th, of the explanatory power of the model.

We would interpret these findings to suggest that having a large view in the visual field while looking at a computer monitor may interfere with speed and accuracy of visual performance. This may be either due to sources of glare or to distraction. This result is opposite to the findings from the three memory related tests, where view was found to be associated with enhanced performance.

The floor register status result is consistent with the result from Letter Search where having floor registers open is associated with poorer performance on visual acuity related tasks. However, it is opposite to the finding for the Memory Test, where more open floor registers were associated with better performance. We will discuss the implications of the floor register findings further in the general discussion in Section 5.5.8 at the end of this report.

5.5.7 Desktop Results Summary

As seen earlier in Figure 49, in a session of Mini-Tests, the first two tests, Landolt C and Letter Search, focus heavily on visual acuity, speed and accuracy, and dexterity, while the last two tests, Backwards Numbers and Memory Test, are mainly related to short and long term memory. Number Search in the middle requires functions of both visual acuity and speed, combined with short term memory.

Figure 61 presents a table with the analysis results for all five tests, allowing comparisons for consistency across models. As in the previous tables, only the percentage effects of the significant variables are shown.

The results from the analysis clearly fall into the two categories of visual acuity and memory. We always found consistency in the signs of significant variables, i.e. positive or negative, within the two pure visual acuity tests or the two memory related tests. The explanatory variables for the Number Search test, representing both visual acuity and memory functions, either followed the pattern of the earlier visual acuity pair or the memory pair.

		<< Visual Acuity						Memory >>			
Variable	Range	Landolt C		Letter Search		Number Search		Backwards Numbers		Memory Test	
		R2 = 0.195		R2 = 0.132		R2 = 0.111		R2 = 0.126		R2 = 0.511	
Lighting											
Daylight (nL)	if increased by 10% …							0.4%			
Electric Light	if increased by 10% …										
Skylight Zone	from no skylight to below a skylight …				-15%						
Glare											
Glare from Windows	from none to most …						-21%		-15%		-17%
View											
Primary View	from none to most …		-16%			8%		10%		16%	
Break View	from none to most …					8%				9%	
Distance To External Wall	from 6 ft to 60 ft …										
Temperature											
Floor Register Status	from closed to completely open …		-20%		-15%	17%					
Air Temperature	if increased by 2 deg F …		-8%							8%	
Location											
CSC Building	if located in CSC …	29%									
Demographic											
Age	if 10 years older …		-13%		-6%		-4%			5%	
Years with Company	if 10 years more …				-6%		-4%		-4%		
Education	from High School degree to PhD …		-29%					11%			
Gender	if selected gender …			12%			-6%		-7%		-13%
High Monitor Resolution	if yes …	33%		12%							-13%
Higher Monitor Resolution	if yes …	29%		16%			-10%				
Session											
Session 2	if yes …			18%							
Session 3	if yes …	16%		27%							-6%
Session 4	if yes …	22%		22%							
Missing Questionnaire	if yes …										
Correct on 1st Memory Test	if 5 more …	---	---	---	---	---	---	---	---	26%	
Imagined per Memory Test	if 5 more …	---	---	---	---	---	---	---	---	19%	
Department											
Dept A	if yes …					13%					
Dept B	if yes …					16%					
Dept C	if yes …										
Dept D	if yes …								-10%		
Dept E	if yes …								-16%		
Dept F	if yes …	19%									
Dept G	if yes …					11%					
Dept H	if yes …					9%					-10%
Dept I	if yes …										
Dept J	if yes …				-18%			15%			
Dept K	if yes …										-21%

Figure 61: Comparison of percentage effects for all five Mini-Tests.

5.5.8 Desktop Results Discussion

The discussion below first assesses the success of the Mini-Tests as a tool to measure office worker performance under field conditions. We then discuss the findings across all five Mini-Tests and potential implications.

Success of Mini-Tests

The Mini-Tests administered in the Desktop study were successful in differentiating between performance among individuals and produced results that were reasonably consistent with normative values for each type of test. The findings of the statistical models explaining performance on the tests were also fairly consistent with expectations for the various explanatory variables, such as the predicted effect of age or monitor resolution. Thus, overall the approach of using Mini-Tests administered at the workstation can be judged fairly successful as a tool to assess individual office worker performance under field conditions.

Some of the Mini-Tests were more successful than others. The validity of each test and its ability to discriminate among the performance of participants should be taken into consideration in evaluating the implications of the findings for each mini-test.

The Landolt C test proved rather insensitive, with little diversity in response among participants. As a result, we used only the most difficult of the four Landolt C screens in our analysis. A more discriminating assessment of visual acuity using computer based images should be considered for similar future research.

The Letter Search and Number Search tests were more discriminating than the Landolt C tests. While most participants could easily find the “C” in the field of “O’s” for Letter Search, the timed response did show reasonable variation. The Number Search test was the most difficult to get correct of the three tests involving visual acuity, and also provided us with the greatest discrimination in response time. Thus, we would judge the Letter Search test to be the most successful of the three. However, we would recommend two improvements to the use of Letter Search in the future. First, a researcher should give attention to carefully balancing the difficulty of screen images for each session. Secondly, recording the value of the participant’s numbered response, rather than just ‘yes/no’ for a correct response could provide more discrimination in the analysis.

The Backwards Numbers (a.k.a. Digit Span Backwards) test provided the greatest range of responses among workers of all tests considered. While it has been widely used in psychological research for decades, this is the first time that we are aware of that it has been administered visually and automatically over a computer. The one drawback to our unsupervised approach seems to be the possibility to subvert the test by writing the numbers down while viewing. We found evidence of such behavior in only about three of 214 participants, where very low scoring participants suddenly achieved perfect scores. Any sets of all perfect scores were also eliminated from the analysis.

The Memory Test proved the least satisfactory of the five Mini-Tests, in that the explanatory variables that we considered had very little relationship to initial performance (short term memory assessment) of the test. Once we considered the relative difference in long term memory performance for the second through fourth trials, and controlling for initial performance and number of “imaged’ images, then this test was able to provide some discrimination in performance among individuals. We would recommend that future research consider using a different assessment of long term memory that can be easily adapted to field conditions.

Overall, for any future research, we would recommend a slightly reconfigured battery of assessments that focus less on visual acuity and more on cognitive performance, especially attention span and short term memory.

Lighting and View

Daylight came up significant and positive for the highly accurate short term memory assessment test of Backwards Numbers. The analysis indicates that for every 10% increase in daylight illuminance on the log scale, there was a 0.45% increase in performance in the Backwards Numbers test. Daylight can be inferred to be consistent with a higher level of concentration and better short term memory recall. The magnitude of this effect is plotted in Figure 53 shown earlier, which implies that there is a larger gain in performance at small increases of daylight illumination at the low ranges of illumination, and a diminishing effect at higher illumination levels.

Daylight was not found significant for any of the tests measuring speed and visual acuity or for the long term Memory Test where one to four weeks intervened between seeing the image and taking the assessment test.

Electric Light illumination levels did not show up as significant in any of the models.

Primary View was significant in four out of the five tests, positive for the three tests requiring mental function, and negative in the test based purely on visual acuity function. For the Letter Search, Backwards Numbers and Memory Tests, it was found that being at a workstation with the highest quality primary view results in an increase in performance by 8%, 10% and 16% respectively. It is interesting to note that as the requirement for mental function increases, from Letter Search to Backwards Numbers to Memory Test, there is an increase in the magnitude of the percentage effect also. The negative effect of 16% in Landolt C test might best explained as a distraction issue, reducing response time ever so slightly.

Break View also was significant and positive for Letter Search and Memory Test. Both tests again require mental function rather than visual acuity, dexterity or speed. It was found that being at a desk with the highest quality *Break View* was associated with an increase in performance by 8% and 9% for Letter Search and Memory Test respectively, as compared to having no *Break View* at all.

The consistency of these results suggests a remarkable importance of view in office worker performance. It is possible that the mental stimulation or relaxation achieved from a view improves mental function. It is also possible that the higher vertical illumination levels to which an employee is exposed when looking at a view help stimulate a physiological circadian response. It may be that view, as a measure of vertical luminance, is a better measure of daylight exposure than the horizontal illumination readings which we collected with our Hobos.

Interaction between Glare and Primary View

Glare from Windows was assessed by the researchers on a subjective four point scale based on the probability that the workstation occupant might experience glare from the windows at some point over the course of the day or the year. It is not known what glare conditions the participants were actually working under when they took the tests.

In the results we find that glare was significant in three of the tests and had a consistently negative impact for each of them. It is interesting that whenever *Primary View* is positive, *Glare from Windows* is negative, implying that the positive effect of a large field of view while looking at the monitor needs to be modified by the negative potential for *Glare from Windows*.

Employees were more likely to have a high glare rating if they looked out onto sunlit building surfaces or parking lots, and likely to have a lower rating if they looked out to only vegetation or had no view at all. Employees near windows on the south side of the CSC building were twice as likely to have a high glare rating as those on the north. Those on the north were most likely to have a high glare rating if they looked out onto a brightly sunlit portion of another wing of the building.

We also observed informally that employees on the south side of the building were much more likely to keep their blinds closed. Thus, “glare potential from windows” could also potentially be a proxy for “window blinds closed more often”. Unfortunately, we did not collect data on blind position for the Desktop study to investigate such a relationship further.

The glare rating was also likely to have a collinear relationship with the *Primary View* rating, since employees with no *Primary View* would also have no *Glare from Windows*. *Primary View*, however, was not synonymous with glare. Rather those employees with a high glare rating were only a small subset of those with a high view rating. For example, while there were 24 employees in the study population with the highest *Primary View* rating of 5, there were only 6 employees with the highest *Glare* rating of 3.

To clarify the relationship between *Glare* and *Primary View*, we tested an interaction variable between *Primary View* and *Glare* for the three models in which both variables were found significant. Two of the models were not changed with the additional consideration of an interaction variable. The interaction variable was however significant when tested in the Backwards Numbers model. Calculation of a net effect between the three variables—*Primary View*, *Glare* and *Primary View*Glare*—showed that *Primary View* was only associated with a positive effect for Backwards Numbers when there was no glare potential from the windows.

This study was not designed to tease out the relationships between glare potential from windows, occupants response with use of window blinds, and the resulting changes in daylight illumination and view quality. Certainly there is likely to be some behavioral accommodation to glare that could affect all of these parameters. However, it is clear from these models that higher window glare potential is associated with negative performance impacts which modulate the positive impacts of view.

Skylight Zone

The *Skylight Zone* variable came up significant and as having a negative effect for the Letter Search test. When the participant's desk was located directly below a skylight as in Zone 3, it was found that they performed 15% worse in Letter Search than a participant who was not located near a skylight.

We believe this is best interpreted as a glare issue. In a correlation study between the self-reported problems by participants reported in the questionnaire and physical measurement variables collected by the surveyors, we found a statistically significant and inverse relationship between people who reported glare from skylights on their computer screen and distance of their desk from the skylight. We did not, however, find a significant link between complaints about temperature and distance of desk from skylight, which could have been an alternate explanation for the negative results associated with skylights. See Section 5.5.9 for a further discussion of the questionnaire findings.

Ventilation

We were not able to consider variations in outside air ventilation in the Desktop study as we were in the Call Center study due to missing data. The *Floor Register Status* variable perhaps provides a proxy for local ventilation rates, but may be confounded by many conditions. First of all floor register vents only existed in the CSC building. Thus all participants in the Headquarters and Distribution Services Building were grouped together with those in the CSC who had a blocked or non-existent floor register. Secondly, per the discussion of the Call Center findings, *Floor Register Status* is potentially confounded with *Air Temperature*. This potential relationship, however, is less extreme for the Desktop study than the Call Center study, since air supply delivery temperatures were much closer to room air averages in the Desktop study. Finally, from evidence from the questionnaire (discussed in Section 5.5.9 below) we learned that workers were more likely to fully open their floor registers because they were dissatisfied with air flow rates and temperatures. Thus, *Floor Register Status* may be more indicative of need for corrective action than actual ventilation rates. Further understanding of this issue would require much finer grain monitoring of air flow rates and temperatures within each cubicle.

Temperature

Higher *Air Temperature* was significant and a negative indicator of performance for the Landolt C and a positive indicator for the Memory Test. The percentage effect for a two degrees increase in temperature was 8% for both cases. This is the inverse of what might be expected with the usual expectation that warmer temperatures slow mental functions but improve manual dexterity. Since all of the air temperatures within this study are considered within a normal comfort range, we may be dealing with an indicator of one's location in the three buildings. We do know that air temperatures in the CSC building averaged about two degrees warmer than the other two buildings.

Alternatively, it is possible that the *Air Temperature* findings in the Desktop study are also a secondary indicator of the amount of daylight illumination level exposure for workers. Indeed, when we ran a model with daylight as the outcome variable for the Desktop study, *Air Temperature* was highly correlated with more daylight ($p>.0001$). That model predicted that for each one degree increase in air temperature around a cubicle that daylight illuminance would increase by six footcandles. Since the range of air temperature in the study was only eight degrees from minimum to maximum, this potentially represents a range of 8*6, or 48 footcandles. Assuming the *Air Temperature* is also an indicator of daylight illumination would make the findings above more consistent with expectations that higher daylight illumination might slow performance on the Landolt C test while improving performance on the long term Memory Test.

Unfortunately, we were not able to further explore the relationship between air temperature and other explanatory variables in the study. More detailed analysis of the data may be able to reveal more about the interrelationship between air temperature and other variables of interest.

Location

A yes/no variable was included in the analysis to indicate those employees in the CSC building. The variable was included to capture the effect due to any other differences between the CSC building and the Headquarters and 59th Street buildings, besides those that were been accounted for by other explanatory variables. The CSC building as a whole only entered one model as significant, with a positive association for performance on the Landolt-C test. In general, in the preliminary models we saw that being in the CSC building was always associated with positive effects on the Mini-Tests performance, but not at a significance level sufficient to enter the final models.

Monitor Resolution

Monitor resolution at 800x600 pixels was found to be the most common resolution and was considered as norm. The variable *High Monitor Resolution*, represented any resolution between 800x600 and 1024x768 pixels, while all resolutions more than 1024x768 were represented by *Higher Monitor Resolution*. It was found that in general, higher resolutions monitors were indicative of better performance in visual acuity related tests (as would be expected), and worse performance in mental function related tests. *High Monitor Resolution* was a significant and positive indicator of performance in Landolt C and Letter Search by 33% and 12% respectively, and *Higher Monitor Resolution* was a significant and positive indicator of performance by 29% and 16% respectively in the same two tests. Participants with *Higher Monitor Resolution* also did worse by 10% in Number Search, while those with *High Monitor Resolution* monitors did worse by 13% in Memory Test. We considered the monitor resolution variable to be primarily a control for whatever demographic characteristics were associated with people who used these monitor settings.

Session Effects

Session variables demonstrate a learning curve for the tests, as is clearly shown for Letter Search and Landolt C tests. As the participants took more tests, they got progressively better at them. Including the variable in the analysis allowed us to control for this learning effect. A decay of long term memory is also seen with the 8% decrease in score of the Memory Test in Session 3. Why then would session 3 show worse performance than Session 4? We believe that people who took four sessions were highly motivated and found satisfaction in taking the tests, since they found them challenging rather than frustrating. Thus, those participants who took the fourth session were most likely to be high performers.

5.5.9 Questionnaire Findings

The results from the questionnaire provided us with a very rich data set which helped inform interpretations of the regression model findings. There is far more to be learned from this exercise than we can present here in this report. The discussion below summarizes some of the more interesting observations. In general, we highly recommend including such a self-assessment of comfort and health in future research on the relationship between human performance and the indoor environment.

The questionnaire was a fifteen page online survey which asked the participants to assess aspects of their physical environment and comfort. The final page of the questionnaire asked the participants to report the number of days they experienced symptoms for thirteen health related symptoms such as headache, fatigue, eye strain, common cold, migraine, etc.

We looked at the results of the questionnaire by using Pearson's correlation between the various responses to the questionnaire and the physical data collected from the onsite surveys. The value of a Pearson's correlation shows the strength of association between two variables, varying between 1.0 for a perfect one-to-one relationship between two types of information, to -1.0 for a perfect negative correlation. A zero value means that there is no relationship between the two types of information.

The first set of analysis compared participants' responses to the comfort related questions and the physical data collected from onsite surveys. A second set of analysis compared the responses from the health related question and both the responses on other comfort related questions and the physical data.

Section 1.2 of the Appendix provides the tables for these two Pearson's correlation studies. In the tables, the variables that were included in the analysis are shown to the left. The correlation coefficient is shown for only those variables that had high significance levels, p<0.1. Positive and negative correlations are shown separately in two sets of tables.

Pearson's Correlations Findings for Comfort Condition

Figure 13 and Figure 14 of the Appendix are the tables comparing the comfort assessments to the surveyed physical variables. The following discussion highlights some of the results from these two tables for each category of variables. The value of the Pearson's correlation coefficient is given in parenthesis for each variable mentioned.

View

Having a high *View Factor* (*View Primary* and *View Break* combined) as rated by the surveyors, was found to be strongly and positively correlated to having a 'large size window view' (0.77), an 'interesting' view (0.55) and/or a 'relaxing' view (0.43) as rated by the participants. The relationship between *View Factor* and 'large size window view' (0.77) was one of the strongest correlations found in this comparison. This seemingly obvious result is of interest as it somewhat validates the view calibration and assessment done by the researchers with the assessment from the participants. More *Daylight (nL)* was found to be positively, but more weakly, correlated to a 'large size window view' (0.32), an 'interesting' view (0.29) and/or a 'relaxing' view (0.17).

As would be expected, we also found that being *Distance to Exterior Wall* was negatively correlated with having an 'interesting' view (-0.39) and having a 'relaxing' view (-0.32).

It would be useful for future research on view to develop a self-report of view assessment that has high consistency with measured data. This would greatly reduce the cost of additional research on the interaction between workers and view.

Lighting

Many indications of discomfort due to lighting were positively correlated to *Distance to Exterior Wall*. These include 'not enough daylight' (0.23), 'no task lights' (0.22), being bothered by 'reflections of electric lights' (0.22), 'light is too dim' (0.14) and 'not enough sunlight' (0.13), While the correlations to 'not enough daylight' and 'not enough sunlight' would seem fairly obvious as workers are located further away from exterior walls with windows, the other complaints about reflections and dim lighting may be more related to lack of exposure to daylight or views than a decline in electric lighting quality, since all workers basically had the same electric lighting conditions within a given building, regardless of their distance from an exterior wall.

A high *Primary View* was positively correlated to being bothered by ‘reflections of windows’ (0.30), ‘too much daylight’ (0.16)and ‘too much sunlight’ (0.14) .This pattern shows that glare from windows, specifically on computer screens, is likely to be a greater discomfort than the intensity of the daylight. Facing computer monitors away from windows, using low-glare monitor surfaces, providing user-controlled blinds and avoiding creation of exterior sources of glare are all design measures that can help address this issue.

Being closer to a skylight, as indicated by *Skylight Zone,* was positively correlated to reports that the ‘light is too bright’ (0.17), but not complaints about too much daylight or too much sunlight.

More *Daylight (nL)* was positively correlated to lighting being ‘just right’ (0.13) and negatively correlated to lighting being ‘too dim’ (-0.20) and ‘too dull’ (-0.22). But more *Daylight (nL)* is also positively correlated to the discomforts of ‘too much daylight’ (0.19), ‘too much sunlight’ (0.30), being bothered by ‘reflection of windows’ (0.26) and ‘reflections of skylights’ (0.13).

Thermal Comfort

We found that *Floor Register Status,* indicating that the vent was more open was positively correlated to more reports of discomfort due to temperature being ‘too hot’ (0.20) and negatively correlated to temperature being ‘too cold’ (-0.22). This suggests that those occupants who are opening up their floor register to increase the flow of cool air from the air conditioning system are doing so because they are too warm, and closing them if they are too cold. Interestingly, those with the most open floor registers were more likely to complain that the air was ‘too dry’ (0.29) and that air movement was ‘too low’ (0.25). Again, this relationship suggests that floor register status was set in order to offset perceived discomfort.

Being closer to skylights as indicated by *Skylight Zone,* was negatively correlated to having ‘no temperature problems’ (-0.18). In other words, the occupants in buildings with no skylights, lower floors of the CSC or positioned further away from skylights were more likely to report that they were comfortable with the temperature. However, being close to skylights was not correlated to any reports of thermal discomfort.

Pearson’s Correlations Findings for Heath Symptoms

Figure 15 and Figure 16 of the Appendix are the tables for the health symptoms correlations. In this analysis, the responses from the question related to health symptoms were correlated to the surveyed physical variables and the other questionnaire responses to comfort conditions. The value of the Pearson’s correlation coefficient is given in parentheses.

In general we found strong evidence that the those who reported no comfort related problems were the most likely to also report no or fewer health symptoms. Hence those who responded positively to questions such as ‘lighting is just right’, ‘I have no temperature problems’, and ‘air quality is just right’ etc. were also found to report fewer symptoms of health aliments. The causal relationship could potentially go either way here, where those with more health symptoms are more sensitive to discomfort, or where those who are most content with their environment are experiencing the least health stresses. The consistency of this relationship, however, is striking. It is consistent across all comfort conditions considered—lighting, view, thermal comfort, acoustics and air quality. The fewer complaints employees had about their physical environment, the fewer negative health symptoms they also reported.

View

From the positive correlations table, we found that a ‘boring’ view was significantly correlated with increasing reports of ‘fatigue’ (0.25), ‘headache’ (0.19), ‘difficulty concentrating’ (0.16), and ‘flu’ (0.13). Similarly from the negative correlations table, we found that those with an ‘interesting’ view had negative correlation to symptoms of ‘fatigue’ (-0.27), ‘difficulty concentrating’ (-0.20), ‘headache’ (-0.20), ‘flu’ (-0.15) and ‘eye strain’ (-0.12). A ‘relaxing’ view also had a negative correlation to most of the same symptoms of ‘fatigue’ (-0.31), ‘difficulty concentrating’ (-0.22), ‘eye strain’ (-0.21) and ‘headache’ (-0.20).

‘Large size window view’ was also found to have a negative correlation with increased reports of ‘fatigue’ (-0.22), and ‘headache’ (-0.18) and ‘eye strain’ (-0.13). Thus, the larger a view a participant reported, the fewer of those symptoms they reported.

The questionnaire also asked what can be seen from the window. People who reported that they can see more ‘sky’, were less likely to report ‘fatigue’ (-0.22), ‘headache’ (-0.20) and ‘eye strain’ (-0.13) problems. Those with more ‘trees’ in their view were less likely to report ‘fatigue’ (-0.22), ‘headache’ (-0.20) while the ones with more view of ‘people outside’ were less likely to report ‘fatigue’ (-0.24), ‘headache’ (-0.19) and ‘eye strain’ (-0.14) problems.

Thus the content of view (more sky, trees or human activity) had about the same negative relationship to health symptoms (i.e. fatigue, difficulty concentrating, headache, eye strain) as size of view, while qualitative assessments of view (more interesting, more relaxing) had a slightly stronger correlation to lack of these health symptoms.

Lighting

Having ‘too dim’ lighting was positively correlated to reporting more ‘headache’ (0.29), ‘eye strain’ (0.25), ‘fatigue’ (0.16) and ‘flu’ (0.16). The four symptoms were also likely to be reported for lighting that was ‘too dull’. Similar symptoms were also most likely to be reported by those with ‘not enough electric light’ viz.

’fatigue’ (0.16), ‘eye strain’ (0.25) and ‘headache’ (0.29), and by those with ‘not enough daylight’ viz. ‘fatigue’ (0.24), ‘headache’ (0.16) and ‘eye strain’ (0.13). In addition, those with ‘not enough daylight’ also reported more ‘difficulty concentrating’ (0.14).

Those who said there was ‘too much electric light’ were also likely to report ‘difficulty concentrating’ (0.15) and ‘eye strain’ (0.13). Similarly, those who complained about ‘not enough control of electric light’ were also likely to report the same two symptoms of ‘eye strain’ (0.17) and ‘difficulty concentrating’ (0.15) along with ‘headache’ (0.20) and ‘fatigue’ (0.18).

Those bothered by ‘reflections of electric lights’ were more likely to have reports of ‘headache’ (0.19), ‘difficulty concentrating’ (0.16), ‘eye strain’ (0.17), ‘fatigue’ (0.13).

From the negative correlations table, we see that those who had ‘no lighting problems’ had also indicated fewer symptoms of ‘eye strain’ (-0.22), ‘difficulty concentrating’ (-0.19), ‘fatigue’ (-0.18), ‘headache’ (-0.14) and ‘flu’ (-0.14). Those who said their ‘lighting was just right’ were also less likely to report the same five symptoms of ‘eye strain’ (-0.31), ‘headache’ (-0.28), ‘difficulty concentrating’ (-0.27), ‘fatigue’ (-0.25) and ‘flu’ (-0.19).

Fatigue

We found ‘fatigue’ to be one of the most interesting and sensitive indicators of problems related to the person’s physical environment. Figure 62 and Figure 63 below show the negative and positive correlations results isolated for only reports of ‘fatigue’. Both the tables have been sorted by the Pearson’s correlation coefficient, with the strongest (negative or positive) correlation on top. Only those variables that had high significance level, where $p<0.1$, are shown.

Category	Variable	Pearson Correlation Coefficient	Significance level
View	My view is realxing	-0.31	<.0001
View	My view is interesting	-0.27	0.0003
View	I have a view of other plants	-0.26	0.0005
Lighting	Lighting is just right	-0.25	0.0006
Air Quality	Air quality is just right	-0.25	0.0008
View	I have a view of people outside	-0.24	0.0015
View	I have a view of cars outside	-0.23	0.0017
Thermal Comfort	I have no temperature problems	-0.23	0.0017
View	I have a view of trees	-0.22	0.0026
Thermal Comfort	Temperature is comfortable	-0.22	0.0027
View	I have a large size window view	-0.22	0.0035
View	I have a view of the sky	-0.22	0.0039
View	I have a view of other buildings	-0.19	0.0108
Lighting	I have no lighting problems	-0.18	0.0195
View	I have a view of 1 window	-0.16	0.0280
Acoustics	I have no noise distractions	-0.16	0.0353
Air Quality	Humidity is comfortable	-0.16	0.0373
Physical Measurements	Higher primary view factor	-0.15	0.0422
Physical Measurements	Higher break view factor	-0.15	0.0515

Figure 62: Comfort conditions negatively correlated with more 'fatigue'

Category	Variable	Pearson Correlation Coefficient	Significance level
Health	DifficultyConcentrating	0.50	<.0001
Health	EyeStrain	0.50	<.0001
Health	Headache	0.48	<.0001
Health	HighStressLevel	0.46	<.0001
Health	StomachUpset	0.44	<.0001
Health	BackOrJointsAche	0.41	<.0001
Health	NeckOrShoulderAche	0.35	<.0001
Health	Flu	0.26	0.0006
View	My view is boring	0.25	0.0009
Lighting	There is not enough daylight	0.24	0.0011
Air Quality	Air is too dry	0.21	0.0047
Health	CommonCold	0.20	0.0065
Lighting	There is not enough control of electric light	0.18	0.0144
Acoustics	Office equipment is noisy	0.18	0.0152
Acoustics	Noise level is distracting	0.18	0.0157
Acoustics	Construction noise is distracting	0.17	0.0274
Lighting	Lighting is too dim	0.16	0.0291
Thermal Comfort	Air movement is too low	0.15	0.0396
Acoustics	I wear headphones while working	0.15	0.0470
Lighting	There is not enough electric light	0.15	0.0482
Acoustics	Noise level is noticable	0.14	0.0610
Lighting	Lighting is too dull	0.14	0.0674
Lighting	There is not enough sunlight	0.13	0.0781
Health	I use the elevator more	0.13	0.0797
Lighting	Reflections of electric lights bother me	0.13	0.0802
Health	Allergy	0.13	0.0809
Thermal Comfort	The window is drafty	0.13	0.0894

Figure 63: Comfort conditions positively correlated with more 'fatigue'

In the negative correlation table shown in Figure 62 it can be seen the comfort conditions with the largest correlations are related to view: 'relaxing' (-0.31), 'interesting' (-0.27) and those having a 'view of plants' (-0.26). These are followed by lighting and air quality being ‘just right’. In other words, those who reported their views were ‘relaxing’ or ‘interesting’ were also the least likely to report incidents of ‘fatigue’ in the previous week.

In the positive correlation table we see that the top eight variables that are most significant and most strongly related to having ‘fatigue’ are all other health related problems. This means that having ‘fatigue’ is strongly associated with also having other health related problems. These are followed by a view being ‘boring’ (0.25) and having ‘not enough daylight’ (0.24).

The results show a surprisingly strong relationship between view and ‘fatigue’. Assessments of view were the most consistent predictor of ‘fatigue’ of all the comfort conditions considered.

6. OVERALL STUDY DISCUSSION AND CONCLUSIONS

Buildings are built to house human occupations. Any building that can enhance the purposes of its occupants is inherently more valuable. To the extent that we can provide reliable information to architects and building owners about how design decisions will influence the performance of workers in those buildings, we can promote the construction of a physical environment that is more supportive of our health, our comfort and our overall productivity as a society.

Energy is also used to support the purposes of the building's occupants. It is a social good to use energy as efficiently as possible, but never at the expense of the basic purposes of the building. Thus, while energy efficiency is important, it will always be less important to owners and operators of buildings than the primary purposes of the building. To the extent that we can understand how the design of buildings and their energy systems impact the performance of the occupants, we can proceed to optimize for both concerns.

This study is one of many in this relatively new field of building science which is trying to understand the impact of building design choices on human performance. In the discussion below, first we consider the potential energy impacts of building design based on the daylight conditions of the CSC building. We then discuss some of the broader findings of this study—how much influence decisions about the physical environment may have on worker performance—and useful lessons from this study for other researchers. Finally, we summarize the key findings of both the Call Center and the Desktop study together, along with providing recommendations for future research directions that will support the continued development of this field.

6.1 Energy Savings Potential

The main focus of this project was to understand the comfort and productivity related issues with daylighting in office spaces. However there are energy efficiency aspects with daylit offices that are also significant. While the energy efficiency potential of daylighting was not dealt with specifically in the onsite observations and employee surveys, we have prepared an estimate of California statewide energy savings potential which could result from adding daylighting controls to daylit office buildings like the SMUD customer services building.

6.1.1 Estimates from SMUD's Energy Simulation Analysis

Building energy simulation analysis for SMUD's Customer Services building was conducted by Energy Simulation Specialists, Inc.[1] in 1994 as the building was being designed. The objective was to estimate the amount of energy and capacity savings associated with the various energy efficiency measures incorporated in the design. The software program DOE 2.1E was used for simulation, with appropriate routines included to account for the sophisticated systems and controls in the design.

The building energy saving estimate used the modeling rules of California's Energy Efficiency Standards (Title 24) for nonresidential buildings current at the time as a reference for comparison of the enhanced design's potential for energy savings. The final analysis, however, used the proposed (actual) operation schedules for the design, rather than the standard schedules used for code compliance purposes. The assumed base case design had the same amount of daylit area (side and toplighting) as the actual Customer Services building and the same lighting power density (0.9 Wsf), but without the automatic daylighting controls.

Figure 64 shows the incremental energy savings due to the addition of daylighting controls to the base case, which resulted in a total of 69,000 kWh/per year of lighting energy savings (0.37 kWh/sf) and a total of 112,000 kWh of electric energy savings (0.6 kWh/sf) when the additional cooling energy savings are included. These savings were calculated for the total area of the customer services building (183,630 sf).

The design also produced an electricity peak demand reduction for lighting, due to electric lights turned down during the day, of 49 kW for the building (an average reduction of 0.26 W/sf over the gross sf of the building).

Annual Energy Savings	Lighting		Cooling		Total electric
Units	*kWh/yr*	*kW*	*kWh/yr*	*kW*	*kWh/yr*
Savings for SMUD	69,000	49	43,000	0	112,000
Savings per sf	0.376	0	0.234	0	0.610

Figure 64: Incremental energy savings for SMUD CSC building by adding daylighting controls to base case

Figure 65 shows the incremental cost savings for SMUD per year from adding daylighting controls to the base case, calculated using 1994 SMUD rates and dollar values. The results indicated a total utility savings of $10,090 per year ($0.05/sf) from the daylighting controls.

[1] SMUD Report: Energy and capacity savings estimates for SMUD's customer service building, 1994

Annual Cost Savings	Cooling + Lighting		Heating	Total Utility
Units	*$ Usage*	*$ Demand*	*$ Usage*	*$ Savings*
Savings for SMUD	$5,190	$4,750	$150	$10,090
Savings per sf	$0.028	$0.026	$0.001	$0.055

Figure 65: Incremental cost savings (1994)for SMUD CSC building by adding daylighting controls to base case

6.1.2 Demand Savings

Note that the value of the demand savings in Figure 65 (based on SMUD's 1994 office rate utility schedule) is almost equal to the value of the electric energy savings. An estimate of demand savings from daylighting controls is highly complex, since it must account for interactive effects between lighting and cooling loads, peak demand periods and dynamic climatic conditions. In order to do so, such an estimate requires the type of hourly annual simulation specific to a building design and climate used in this calculation. As a result of this complexity, statewide estimates of demand savings from daylighting have rarely been attempted. This estimate, based on a real office building design, is a very good indication that the potential value of daylighting controls also includes significant demand savings that may double the value of the energy savings.

6.1.3 New Construction/Retrofit Statewide Savings Potential

The energy savings calculated by the SMUD simulation process were then expanded to approximate California statewide savings for office buildings. According to the California new construction database,[1] out of a total area of new construction/retrofit buildings in California, 30.9 million sf of area are large offices and 9.9 million sf of area are small offices. This database estimates total square feet by new construction building type.

We calculated the energy savings that would result from daylighting controls if all offices in California were constructed to have daylighting potential similar to that of the SMUD Customer Services building (roughly 30% of the space sidelit and an additional 20% toplit, with dimming controls set to a minimum of 10% light output, lighting power density of 0.9 W/sf) and were operated in a similar climate (California's Central Valley). Based on these assumptions, the addition of daylighting controls to all new office buildings would result in annual electric energy savings of 24,800 MWh/yr. This calculation is summarized in Figure 66 below:

[1] 10 years of new construction (2003-2012)- Brook, M. 2002. "California Electricity Outlook: Commercial Building Systems". Presentation at PIER Buildings Program HVAC Diagnostics Meeting, Oakland, CA. April 16.

Description	Area	Lighting		Cooling		Total Electric	
Units	*sf/yr*	*MWh/yr*	*MW*	*MWh/yr*	*MW*	*MWh/yr*	*MW*
Savings for SMUD		69	0.049	43	0.00	112	0.05
Statewide Lg Office	30.9 Million/yr	11,600	8.25	7,200	0.00	18,800	8.25
Statewide Sm Office	9.9 Million/yr	3,700	2.64	2,300	0.00	6,000	2.64
Statewide Savings Potential	40.7 Million/yr	15,300	10.88	9,500	0.00	24,800	10.88
Statewide 10 Year Savings	*407 Million*	*153,000*	*108.84*	*95,000*	*0.00*	*248,000*	*108.84*

Figure 66: Energy savings potential for daylit offices in California from lighting controls only for new construction

Obviously these calculations are very rough, and would vary considerably if applied to the existing configuration of the office building stock and actual local climate conditions. Furthermore, the application of new electric lighting and control technologies would change the calculation significantly. Based on average electric costs of $0.1487 kWh[1] in California in 2003, the economic value of the energy savings calculated in Figure 66 is $3.7 million dollars per year for the first year of new construction. This would increase by tenfold to $37 million dollars per year after 10 years of accumulated construction. This value does not account for the value of any associated demand savings.

6.2 Influence of the Physical Environment on Human Performance

The statistical models discussed in this study do a modest job of describing the influences on worker performance measured by our outcome metrics. For the Call Center, our models are explaining a little over 20% of the variance in workers' daily performance, and 8% of their hourly performance. Similarly, the Desktop study models explain about the 11% to 20% of the variation in performance on the Mini-Tests.

What is interesting is the relative explanatory power of the different types of variables. As expected we find that information that is specific to the individual (such as job status or test score on a previous test) tends to have the greatest explanatory power. Information about what kind of group the individual belongs to (demographic information such as age or sex) is the next most powerful in explaining performance. And finally, information about the physical environment tends to have the least overall explanatory power.

The significant physical variables are each found to explain from about 0.5% to 1% of the variation in performance. All together, information about variation in the physical environment is found to explain about 2% to 5% of the variation in worker performance.

[1] California Energy Commission, statewide electricity average, commercial sector, 2003, www.energy.ca.gov/electricity

On the one hand, this might seem to be a very small, even trivial amount of explanatory power. However, when the power of the physical environment is held up in comparison to our ability to predict performance based on other information about people—such as their age, sex or job classification—then we see that information about workspace conditions provides about 1/8th to 1/3rd of our ability to predict variation in individual worker performance in the field. This range of explanatory power is in the same range as was found in the companion study of an elementary school district[1] .

Furthermore, it is important to note that while the variation in performance that we observed in both the workers in the Call Center and the Desktop study may seem to be small, however, this variation was observed in the field under nearly ideal office conditions. The Customer Services Building at SMUD is an exemplary office environment by current standards. It is carefully maintained at comfort conditions and provides numerous opportunities for occupants to customize their comfort conditions to their particular needs. Thus the effects we observed were not likely to be threshold effects, or at the margin of performance, but rather under close to optimum conditions.

This suggests that human resource and management decisions can make meaningful contributions to perhaps 2/3rd to 7/8th of the worker performance equation. The remaining 1/8th to 1/3rd which can be contributed by decisions about subtle changes to the physical conditions is not trivial. This is important news for managers, architects and anyone who makes investment decisions about the physical environment.

And while the potential influences of physical conditions may be subtle, even small improvements in worker productivity are of great practical importance. Furthermore, decisions about the physical design of a space that may influence worker performance are likely to have great persistence, continuing for the life of the building, and influencing tens or hundreds of employees for many years to come. Thus, both in terms of duration and number of individuals influenced, there is a fairly large multiplier which should be considered in judging the relative importance of the explanatory power of the physical characteristics considered in these models.

Both studies successfully measured variation in office worker environmental conditions and related these to measured office worker performance under actual employment conditions. The Desktop study pioneered the use of computerized cognitive assessment tools to gauge office worker performance in field conditions. The studies have shown that indoor environmental conditions can have a measurable relationship to changes in office worker performance and

[1] Heschong Mahone Group, Windows and Classrooms: A study of student performance and the indoor environment, Public Interest Energy Research, California Energy Commission, 2003.

have established a range of likely effect sizes that other researchers can use to refine the needs of future studies. Other studies will be required to test if these findings can be replicated in other settings and to explore potential causal mechanisms between the environmental conditions and worker performance.

6.3 Key Findings

- **Daylight illumination levels were significant and positive in predicting better performance on one test of mental function and attention.**

The Backwards Numbers (Digit Span Backwards) test is widely accepted in psychological research as a valid test of mental function and attention span. An increase in daylight illumination levels from 1 to 20 footcandles resulted in a 13% improvement in performance in the ability to instantly recall and mentally reverse strings of numbers. A logged function was found to have the best fit, implying the greatest increase in performance at the lowest levels of daylight illumination and a diminishing positive effect at increasingly higher daylight illumination levels. Thus, a 20 footcandle increase in daylight at the high end of illumination levels, from 80 to 100 footcandles, was reflected in only a 1% improvement in performance. Daylight illumination was found to have the greatest predictive power of any variable considered for the Backwards Numbers test.

The daylight illumination explanatory variable was defined as the natural log of the average of horizontal daylight illumination at the participant's chair position for the two hour time period during which the test could be taken. It was derived from data measured at the horizontal plane at the top of a five foot high partition near the participant's cubicle.

- **Daylight illumination levels were <u>not</u> found significant for the visual acuity tests or long term memory test. Daylight illumination levels were found to have an association with a slight decrease in Call Center performance for one of three models.**

Daylight illumination was not found significant in any of the other models considered, with the exception of the November Daily model for the Call Center, where an increase in average horizontal daylight illumination from 1 to 20 footcandles was found to be associated with a 6% decrease in performance, or a 23 second increase in daily average call handling time. An hourly analysis of the same time period did not find a significant change in Call Center performance related to hourly fluctuations in daylight illumination levels.

- **The natural log of illumination and the daylight illumination level of the previous hour were found to have the best fit in predicting performance.**

In various models tested, the natural log of both daylight and electric light illumination levels was found to have the best fit in the models for both the Call Center and the Desktop study. In addition, for the Call Center November Hourly model, a one-hour time lag of daylight illumination levels was found to provide the best model fit, even though this explanatory variable did not reach the threshold of acceptable significance in the final model. This implies that illumination levels can be expected to have diminishing effects as they increase in intensity, and that any effects on human performance are likely to have a physiological component (delayed effect) in addition to a visual component (instantaneous effect).

- **An ample and pleasant view was consistently found to be associated with better office worker performance.**

A better view was the most consistent explanatory variable associated with improved office worker performance, in six out of eight outcomes considered. Views from a workstation were rated for both primary view (angular size of window view while looking at the desktop computer monitor) and break view (angular size of view from other seated vantage points in the cubicle). Both types of view were rated on a scale of 0-5 first based on size, and secondarily by vegetation content. Workers in the Call Center were found to process calls 7% to 12% faster when they had the best possible view versus those with no view. Office workers were found to perform 10% to 25% better on tests of mental function and memory recall when they had the best possible view versus those with no view.

Results from the questionnaire administered to participants in the Desktop study supported the performance findings. There was a high correlation between workers' and surveyors' ratings of view. Those workers in the Desktop study with the best views were the least likely to report negative health symptoms. Reports of increased fatigue were most strongly associated with a lack of view.

A large window view could also potentially be an indicator of the exposure of the worker to vertical illumination levels. The visual details of window views were often partially screened by perforated vertical blinds which still provided a large bright vertical plane within the field of view.

- **Glare from windows was found to be associated with reduced office worker performance.**

In the Desktop study, each cubicle was rated for its potential of glare from the primary view windows, defined on a simple 0-3 scale of none to frequent. The greater the glare potential, the worse office worker performance was on three mental function tests, decreasing performance by 15% to 21%. For the Backwards Numbers test it was found that *Primary View* had a positive relationship to performance only if there was no glare potential from that view. It is hypothesized that participants with a high glare potential were more likely to close their window blinds, thus diminishing their view. Participants close to windows generally had control of their windows blinds, but blind position was not monitored during the test period, thus this hypothesis could not be tested.

Two other variables potentially related to glare were also found to be negative. *Primary View* was found to be associated with slower performance on the most challenging visual acuity test (Landolt C). Being closer to a skylight was found to be associated with negative performance on another visual acuity test (Letter Search). Questionnaire responses from office workers indicated that glare from skylights on computer monitors was the only negative comfort condition reported by workers close to skylights.

- **Increased ventilation was found to be associated with improved worker performance in the Call Center and improved office worker performance on one mental function test.**

In the hourly analysis of the November study period for the Call Center, it was found that a one CFM/sf (50%) increase in outside air was associated with a 4% improvement in hourly worker performance. It is possible that this finding could be confounded by other hourly changes in working conditions.

Workers in both the Call Center and the Customer Services Center had the ability to set their floor register to provide more or less ventilation from the building's air handling system. In the Call Center, those workers who set their floor registers fully open handled calls faster in all three models considered, 3% to 10% faster than those that had theirs fully closed.

In the Desktop study findings were mixed: workers who left their floor registers full opened performed 17% better on one test of mental function (Number Search), while their performance was worse for two tests of visual acuity and dexterity (-15% to -20%).

These ventilation findings may also be related to local air temperature in the cubicle. Researchers observed that the ventilation air supply temperature was 10°F to 15°F lower for employees in the Call Center than for participants in the Desktop study. Indoor air temperature in the models was measured at 5five feet above floor level, which may not have captured the personal thermal comfort effects of an individualized floor air delivery system. Thus, in the Call Center, workers with a fully open floor register were likely to be surrounded by lower air temperatures than those recorded by the data loggers, while participants in the

Desktop study were more likely to be in a local thermal environment close to the recorded air temperature.

- **Increased indoor air temperature was found to reduce worker performance in two out of eight outcomes and improve it for one outcome.**

Indoor air temperature, measured five feet above the floor near the participant's cubicle, was found to reduce worker performance in the November Hourly model. Over the course of the study periods indoor air temperature varied over only a 6°F-8°F range. For each 2°F increase in temperature, average hourly call handling speed increased by 2%. In the Desktop study, an increase in 2°F was associated with an 8% decline in performance on a visual acuity test (Landolt C) while it was also associated with an 8% increase in performance on the long term memory test.

It is likely that the air temperature findings were confounded by both ventilation supply rates, as discussed above, and by daylight illumination levels. Room air temperature was found to be collinear with daylight illumination levels: each 1°F raise in air temperature was likely associated with 6 more footcandles of daylight illumination. Further investigation looking at the interaction of these variables may be able to sort out their relative effects.

- **Physical comfort conditions were found to be an important component of models predicting office worker performance.**

Overall these potential influences on worker performance were found to have high statistical significance and represent changes in performance ranging from about 1% to 20% better or worse than norm. All together information about the physical conditions of the workers was able to explain about 2% to 5% of the variation observed in a measure of worker productivity (Call Center study) or in performance on short cognitive assessment tests that were thought to be related to worker productivity (Desktop study). Other information available about the workers such as demographic characteristics or employment status was able to explain about 6% to 19% of the variation in their performance.

The combination of physical comfort conditions considered—illumination, view, ventilation and temperature—typically provided 1/8th to 1/3rd of the explanatory power of the models, while demographic information—such as which group manager or department the employee was assigned to, their age, years of experience and education—provided the remaining 2/3^{rds} to 7/8^{ths} of the models' explanatory power. These studies were done comparing worker performance in a very uniform, modern and high quality office environment where variations in comfort conditions were maintained well within current standards of practice. This implies that facility managers can expect that subtle variations in physical comfort in their buildings could potentially alter worker performance by about 1/8th up to 1/3rd of the variation observed due to organizational or hiring practices.

- **The studies provide useful tools and guidance for other researchers who may pursue these issues.**

Both studies successfully measured variation in office worker environmental conditions and related these to measured office worker performance under actual employment conditions. The Desktop study pioneered the use of computerized cognitive assessment tools to gauge office worker performance in field conditions. The studies have shown that indoor environmental conditions can have a measurable relationship to changes in office worker performance and have established a range of likely effect sizes that other researchers can use to refine the data sensitivity needs of future studies. Other studies will be required to test if these findings can be replicated in other settings and to explore potential causal mechanisms between the environmental conditions and worker performance.

6.4 Recommendations

- **Encourage the design of office buildings with views provided for all workers.**

Both the school[1] and the office studies found strong and consistent correlations between better views and better performance. There is a clear suggestion from this work that window views are important for sustained human performance. Building codes in Europe have long required that all office workers have access to window views, typically stipulating that no workstation will be more than about 20' from a window. Initially the importance and value of views for worker performance should be communicated to office building owners, managers and designers. Eventually both government and voluntary programs and standards should encourage the design of office buildings with narrower floor plates that allow more perimeter area for views. Additional research may be able to refine the parameters involved in this interaction between view and performance, to provide more guidance on view content, quality and proximity.

- **Encourage additional research on the interrelationship between view and illumination levels.**

The findings about the importance of view in this study and the related school study[2] suggest that there is some important function of view in sustained human

[1] Heschong Mahone Group, Windows and Classrooms: A study of student performance and the indoor environment, Public Interest Energy Research, California Energy Commission, 2003.

[2] Ibid.

performance. There are many possible mechanisms to be considered. Most relevant research to date has considered either only the potential impact of view content or only illumination exposure. The issue is further complicated in our modern working environments with the transition from a primarily reflective visual task (paper) to a self-illuminated task (computer monitors). This change not only impacts the visual needs of the worker, but may also change the exposure to illumination at the eye for circadian stimulation.

- **Encourage additional research on the relationship between ventilation rates and worker performance.**

The Call Center study is strongly suggestive that increased ventilation rates are likely to improve worker performance. These findings may be confounded with other simultaneous changes in the environment. As discussed above, ventilation rates are often entangled with other environmental parameters, such as room air temperature, indoor and outdoor air quality, acoustic conditions and occupant control. In order to optimize worker performance while maintaining maximum energy efficiency, building designers need more guidance on how to balance these factors.

- **Support the development of better indoor environmental monitoring and assessment tools.**

This study was challenged by the limitations of inexpensive data collection tools for monitoring indoor environmental conditions. The miniature data loggers used for long-term data collection were well adapted to record air temperature, or static electric illumination conditions, but were far from ideal for measuring daylight illumination. Inexpensive tools to monitor air flow rates, air quality metrics or acoustic conditions over time were not available. Appropriate methods to assess exposure to vertical daylight illumination or to assess the quality of a window view have yet to be defined. The ability to study variations in indoor environmental conditions is largely dependent upon being able to accurately measure those variations. Thus, an improved tool kit for indoor environmental assessment will greatly help to advance the field and support the development of knowledge that can provide specific guidance to building designers.

- **Support continued research using call centers as a field study site.**

Many of the environmental metrics of interest (ventilation, daylight illumination) vary over a fine time scale, making the use of hourly data appropriate for trying to understand potential effects on human performance. Call centers offer one of the few office type environments with extensive monitoring of worker performance at this time scale. Comparable studies across different call centers may be able to create a cumulative knowledge base, similar to the specialized pursuit of twin studies in the fields of behavior and genetics.

- **Support the development of better tools for field assessment of office worker performance**

This study has shown that it is possible to adapt common laboratory assessment tools to administration under field conditions and obtain reasonably good discrimination in participant performance. The use of web-based assessment tools has blossomed in the past few years and offers enormous potential for creating timed tests that automatically collect performance data. The development of a standard "tool kit" for field assessment of office workers will enable comparative studies of office worker performance.

In addition, the use of self-reports of comfort or health symptoms seems a promising and potentially economical way to assess worker performance if clear linkages between self-assessments and actual measured performance can be made. Thus, it would be worthwhile to study the reliability of a relationship between self-reports and measured performance as an intermediate step to support further research in this area.

- **Support multi-dimensional research on the indoor environment**

It was clear from this study that environmental characteristics should not be studied in isolation. This proposition is fairly obvious when considered in relationship to thermal comfort, as a function of air temperature, ventilation rates, radiant temperature, humidity, clothing levels and activity levels. Mechanical engineers have had the psychometric chart to guide them on the plausible interrelationship of these factors in a field environment. Other inter-relationships of environmental variables are perhaps less obvious, but need to be considered in any study looking at human comfort and performance, since all environmental influences are ultimately integrated by the body and mind of the subjects under study. Operable windows providing natural ventilation change the acoustic conditions in a space. Daylight is likely to be associated with higher local air temperatures. People working under bright light may have higher metabolic rates than those under dim lights, changing their thermal comfort requirements. Variation in many different types of environmental variables may provide either mental stimulation or circadian stimulation or both. All physiological inputs to human comfort and function should be considered in workplace studies, both to control for their potential influences and to understand their interrelationship with other influences.