REPORT

Occupant Behavior in Response to Energy-Saving Retrofits and Operations

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EXECUTIVE SUMMARY

This study addresses occupant response to energy saving technologies and load shedding in the workplace. Particular focus is placed on satisfaction with environmental factors, usability of the new systems, work quality and productivity, and health. Two case studies of office buildings are presented in which occupant response to environmental conditions is tracked, including changes in response during periods of load shedding. The load shedding involved planned reduction of electrical consumption within each building, through reductions to both HVAC and lighting systems. The research questions asked whether these changes produced noticeable responses from the occupants in how they felt about ambient conditions in the workplace.

The study's findings are suggestive about the characteristics of buildings that are more conducive to load shedding that is acceptable or even viewed positively by building occupants, and the extent to which typical office buildings may be overcooled during the summer and shoulder months.

Also, the degree to which the load shedding causes a significant change in the perceived quality of environmental conditions appears to be a function of 1) how big the change in conditions (percentage change in lighting levels and temperature/airflow) - small changes may be beneath the threshold of detection and have minimal impacts; and 2) how satisfactory existing conditions were prior to load shedding. Therefore, larger changes in conditions, in terms of percentage of decrease in power to HVAC and lighting, are likely to be detected and may affect comfort, satisfaction, productivity, and stress. The strength of the effect and the direction of change depends on qualitative factors of building systems and nature of the load shedding, as well as prior levels of satisfaction.

These grounded hypotheses, resulting from this work, will be tested on additional buildings in BP3 en route to producing a roadmap with our industry partners regarding how to scale up successful energy efficiency interventions in commercial buildings. The data collection associated with the current effort should be viewed as a pilot, as conditions for and timing of the load shedding were evolving even as instruments were being developed and tested on site. This resulted in in data collection from a relatively small number of testing days and research subjects.

INTRODUCTION

This research sets out to examine how occupants react to environmental factors in the workplace in response to the installment of a variety of energy saving technologies, including load-shedding capabilities. The study focuses on four domains in examining the impacts: satisfaction with environmental factors, usability of the new systems, work quality and productivity, and health. Furthermore, the study examines the range of adaptive behaviors in which individuals engage in response to situations that do not provide satisfactory environmental conditions for work. We address how the installation of energy saving equipment and energy load-shedding operations impacts participants' responses and behaviors, which in turn provides information about realistic performance expectations for these buildings.

Occupants' Behaviors and Psychological Reactions to Retrofits

While great technological strides have been made in developing energy efficient systems in heating, cooling, ventilation, and lighting, the implementation of these technologies can at times pose challenges to the user. These challenges can stem from design limitations, such as insufficient and improper labeling of interfaces or inaccessibility of important control functions. Challenges may also arise due to variability in environmental conditions, which may meet optimal requirements in some parts of the building but be inadequate in others. Such variability can be difficult to eliminate given differences in exposure to sunlight and other external environmental factors. However, other challenges may be more psychological in nature. The loss of personal control that accompanies the implementation of a centralized environmental control system can be an important source of dissatisfaction. Our studies examine both sources of employees' reactions to energy saving technologies in their work environments, uncover factors which are particularly strong predictors of subjective reactions to the work environment, and point to potential areas for improvement.

Environmental Conditions and Subjective Experience

The connection between environmental conditions, such as temperature and lighting, and human responses, such as stress, comfort, and productivity are necessarily complex and intertwined, as well as multiply determined. The physical setting, even though important, is just one of several relevant sets of factors; others include job design, motivation, family situations, etc., all of which potentially mediate occupant response to the workplace. Even so, it is useful to consider how the physical setting affects behaviors, as demonstrated in prior research literature and conceptual models, and then to reflect on how changes set in motion by load shedding further impact subjective experience.

Indeed, prior findings support our presumption that environmental conditions can and do affect these occupant behaviors. Research over many decades has indicated that changes in air quality, ergonomics, privacy, and other design factors affect comfort, satisfaction, productivity, and stress levels (Fang, Wyon, Clausen, & Fanger, 2004; Heerwagen & Zagreus, 2005; Wargocki, Wyon, & Fanger, 2000; Wargocki, Wyon, Sundell, Clausen, & Fanger, 2000), even if not always in a simple or linear fashion. Being too hot or too cold can affect key outcomes in several ways. One path may be via level of comfort and satisfaction – workers who have high levels of satisfaction with their job and setting may be better motivated to work well and hard in completing tasks. Workers who are comfortable in their setting may have an easier time putting in longer hours at the job, again supporting successful work. Another pathway may involve health. Poor environmental conditions (too warm, too cold, poor quality air, or too little or too much air flow) may make it more likely that workers feel uncomfortable or ill, reducing ability to concentrate or time spent at the workplace (Heerwagen, 2000; Singh, Syal, Grady, & Korkmaz, 2010). Still another factor may involve stress. Exposure to stressful conditions, particularly when the causes are out of the control of the occupant (whether in reality or in perception), has been shown to negatively affect mood, motivation, and health, all of which can reduce satisfaction and productivity (Evans & Johnson, 2000).

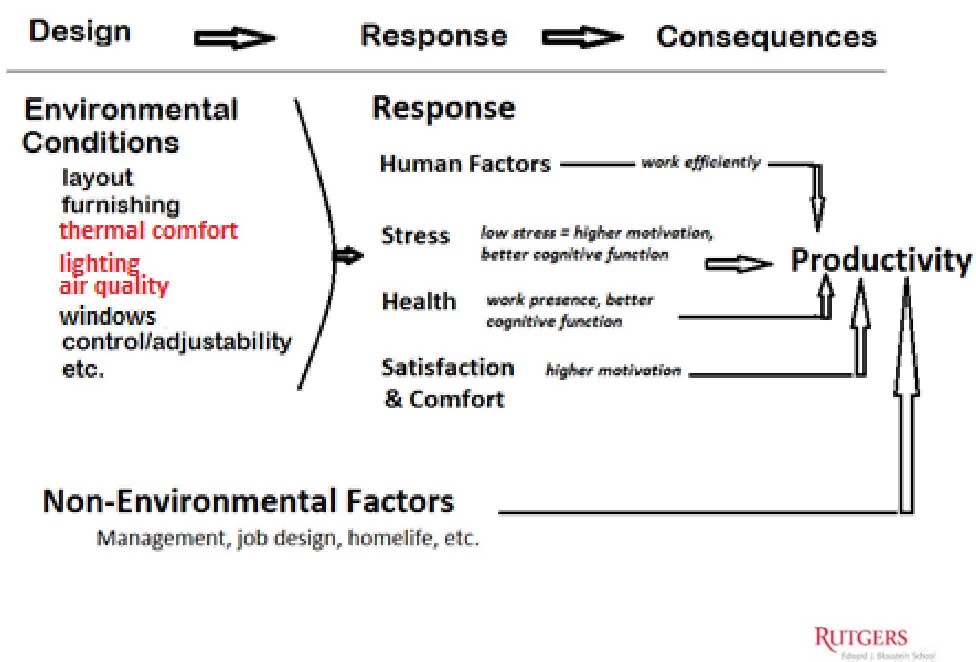

Figure 1. Occupant Response to Environmental Conditions

Load Shedding

Load shedding as a practice refers to reduction of electrical consumption supplied to several key building systems – lighting and HVAC. The purpose is to reduce electrical usage and hence the burden on electrical production and distribution systems during times of peak usage. The energy and energy-cost savings potential of retrofit buildings depends not only on the technology already in place, but also on the choice of how to create a comfortable yet minimally energy intensive environment. Since a great deal of operational energy goes into the HVAC system, this domain of building function carries significant potential for energy use reduction. Prior research suggests that buildings are often overcooled in an attempt to control the humidity, and that reduction in cooling may not have adverse effects on occupants. However, this question has not been examined in prior studies. Another domain of potential energy reduction is lighting use. The goal is to determine the range within which energy-saving decreases in temperature control and lighting brightness still offers a comfortable environment conducive to productivity and satisfaction.

What is the likely potential impact on building occupants from changes in the amount of illumination available to work areas and surfaces, and in changes to ambient temperatures in the work environment? From a psychological perspective the key questions are whether these changes are noticeable and whether they are likely to have an impact on key indices of comfort, satisfaction, productivity, and stress. While awareness of changes in environmental conditions can impact attitudes and satisfaction, it is possible that even changes in the environment that the occupant does not notice can affect behavior and other subjective responses.

For this pilot study we presume that, at baseline conditions, building management establishes parameters for temperature, lighting, and airflow that provide appropriate working conditions while maximizing efficiency and minimizing energy costs. In effect, in a facility which has been in operation for a period of time, allowing for seasonal variations, a steady state may exist in which occupants come to expect a certain level of service with respect to environmental conditions. This is not to say that these conditions are always ideal – that is the nature of tradeoffs to meet the competing needs of comfort and cost – but presumably conditions evolve to a state at which the setting is serviceable. Variation across seasons and within areas of buildings with different orientations can, of course, be considerable.

Load shedding represents a change in these conditions – a perturbation in the ongoing homeostasis. The degree to which the load shedding causes a significant change in the perceived quality of environmental conditions will be a function of 1) how big the change in conditions (percentage change in lighting levels and temperature/airflow) - small changes may be beneath the threshold of detection and have minimal impacts; and 2) how satisfactory existing conditions were. That is, where conditions were less than optimal a change that alters thermal conditions may be as likely to improve as to worsen conditions, at least for some people in some building locations.

We would predict, then, that where changes are very small, especially given the modest sensitivity of research instruments, little or no effects will be detected. Larger changes in conditions, in terms of percentage of decrease in power to HVAC and lighting, are likely to be detected and may affect comfort, satisfaction, productivity, and stress. The strength of the effect and the direction of change will depend on qualitative factors of building systems and nature of the load shedding, as well as prior levels of satisfaction.

Building and Site Descriptions

This research examines and compares two commercial office buildings, which are similar in that each building has various lighting and HVAC energy saving technologies installed and each has load-shedding capabilities. Also, both buildings are located in the greater Philadelphia region and are therefore subject to similar climatic influences. Differences between the buildings include the nature of the tenant, building structure and design, time and scope of retrofit, and degree of technological sophistication of the resulting systems. These differences offer an opportunity to examine the impact of such variability on occupant satisfaction.

Building 1

The first case study building is a three-story office building near Philadelphia that was constructed in 2004, and has 76,692 gross square feet of floor area and 227 occupants. It is owned by a real estate investment trust and, although built as a multi-tenant site, currently functions as a single-tenanted building. Recent energy efficiency retrofits to this building include the addition of dimmable, IP-addressable lighting ballasts and low-wattage bulbs; variable frequency drives for selected fans in the packaged HVAC systems; retro-commissioning of the HVAC system; updated controls that include more sensor and control points; and links to an enterprise-wide system supporting remote monitoring and control of building systems. This retrofit provides the building operator with load shedding capabilities, among other features.

Building 2

The second case study building is a multi-building complex of 755,540 square feet of office space, laboratories, experimental research areas and technical shops, housing over 450 employees. Although it is operated as a single facility, it was built over several decades starting in 1960 and is comprised of 35 buildings varying in age and building envelope. It contains several independently operated HVAC and electrical systems. This building’s systems are much less tightly integrated than those in Building 1.

RESEARCH METHODS AND DESIGN

This study employed a quasi-experimental research design using data collected through a series of participant surveys to assess building occupants' reactions to energy saving technologies in their work environment.

Quasi-Experimental Research Design

In order to test the effect of load shedding on occupant evaluations, we utilized a design in which each of the buildings under study underwent a series of load-shed events in which cooling and lighting were decreased by a preset amount. In Building 1 the decreases ranged from five to fifteen percent. In Building 2 the decreases entailed switching to weekend lighting in the hallways, and turning the HVAC system off (Table 1). Participants were surveyed on days when the building was operating under the normal energy load (control days) and during load shed days, and these measurements were compared to detect changes in responses. This data collection should be viewed as a pilot study as conditions for and timing of the load shedding were evolving even as instruments were being developed and tested on site, resulting in data collection from a relatively small number of testing days and research subjects.

Participants also completed a comprehensive survey which assessed their satisfaction with and concerns about environmental factors in the workspace, including air flow, temperature, and light, ability to alter and control the environment, choice of adaptive behaviors resorted to when environmental features do not meet needs, as well as perceived productivity and overall job satisfaction. The survey was completed during the shoulder season, in the early Fall, and again during the Winter in a shorter follow-up format. It was administered online, with each participant receiving a link to the survey in an email and completing it in the privacy of his or her workspace.

Load Shed Protocol

Load Shed Protocol

Site 1

Done incrementally, reducing lighting and/or heating/cooling by set amounts at predetermined times.

Shed Level	Lighting Reduction	Cooling Setpoint	Heating Setpoint
0	0%	74.5°F	71.5°F
1	5%	76.5°F	69.5°F
2	10%	78°F	67.5°F
3	15%	N/A	N/A

Site 2

Done categorically, taking place at predetermined times.

Shed Level	Lighting Reduction	Cooling Setpoint	Heating Setpoint
None	0%	N/A	N/A
'Weekend' mode	100% (Hallways)	Off	N/A
HVAC Off	0%	Off	N/A
Midpoint	25% (Hallways)	76°F	N/A

Table 1. Load Shed Protocol

Figure 2 shows a screenshot of Building 1 during a level 2 load shed. This more sophisticated system allows for different degrees of load shed, both for lighting and HVAC systems. In this instance (Figure 2), the load shed was set for a ten percent decrease in lighting and increased (decreased) cooling (heating) setpoints, as outlined in Table 1, Site 1, Shed Level 2.

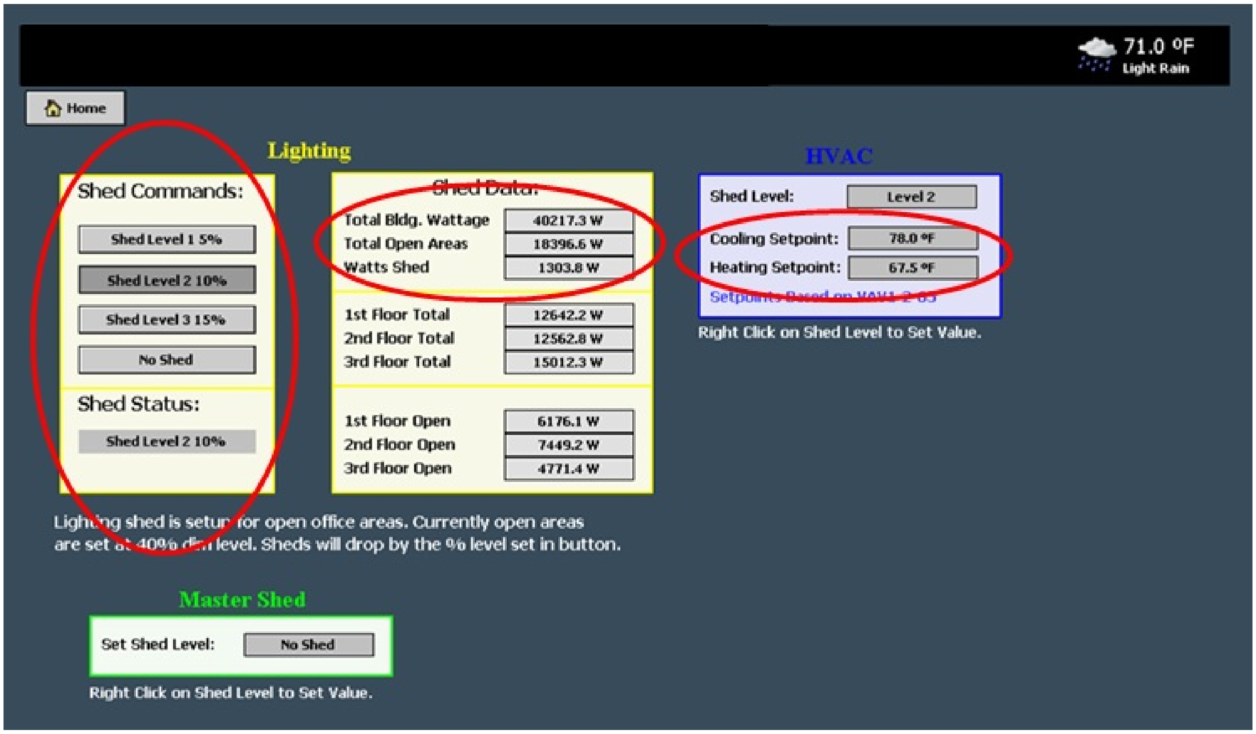

Figure 2. Building 1 Load Shed Example

Building 2 utilized a non-programmed method of load shedding. Figure 3 shows a snapshot in time for Building 2 with data measurements taken on control, load shedding, weekend, and normal workdays as an example of the load shedding procedures (in this case, for the HVAC system). The graph shows the energy usage (grey), and first (blue) and second (green) floor temperature sensor readings, as well as recorded outdoor temperature (purple) during the period from 9/21/12 through 10/1/12. Indoor temperature data obtained from sensors installed for this study corresponds with the left Y-axis Temperature readings, while the grey 'energy usage' line corresponds to the MMBtus shown on the right Y-axis.

The beige areas represent days of normally low BTU usage (weekends), the green area is a control day in which surveys were administered with no load shedding, and the blue section depicts a day where surveys were administered with load shedding.

Looking at the graph, we can see high energy spikes during mornings of days with higher outdoor temperatures, and also a mid-day spike on the load shed day. Energy usage appears to be flat (or very close to it) on weekends and nights, demonstrating the 'Weekend Mode' shed level for Building 2. We can also see a flat-line in energy usage during the load-shed day.

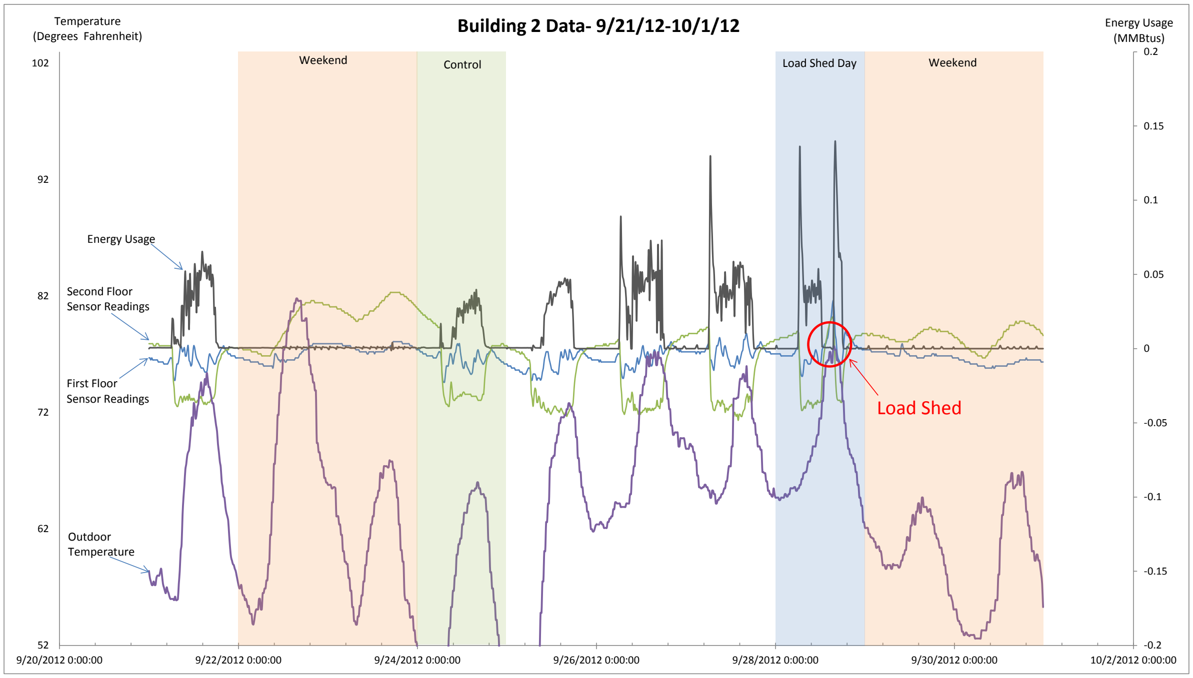

Figure 3. Building 2 Load Shed Example

Figure 4 below represents an expanded view of the blue area of Figure 3 - the load shed day. The lines and Y-axes represent the same information as in Figure 2. The beige areas represent times of low BTU usage (nights/off office hours) and the blue section depicts the time in which load shedding takes place (note the flat-line BTU reading).

The first energy spike in the figure represents the start of the work day, where the HVAC system was first powered up to drive down the indoor temperature (as can be seen with the sharp drops in the blue and green lines). We can see that the HVAC system was shut down from 12:30 to 3:30 PM (blue area), a time of peak usage (as can be seen from the climbing outdoor temperature at that time). During this time, temperatures (both indoor and outdoor) climbed significantly. After this, in order to compensate for the increased temperatures, we once again see a spike in energy usage, combined with a steep drop in indoor temperatures.

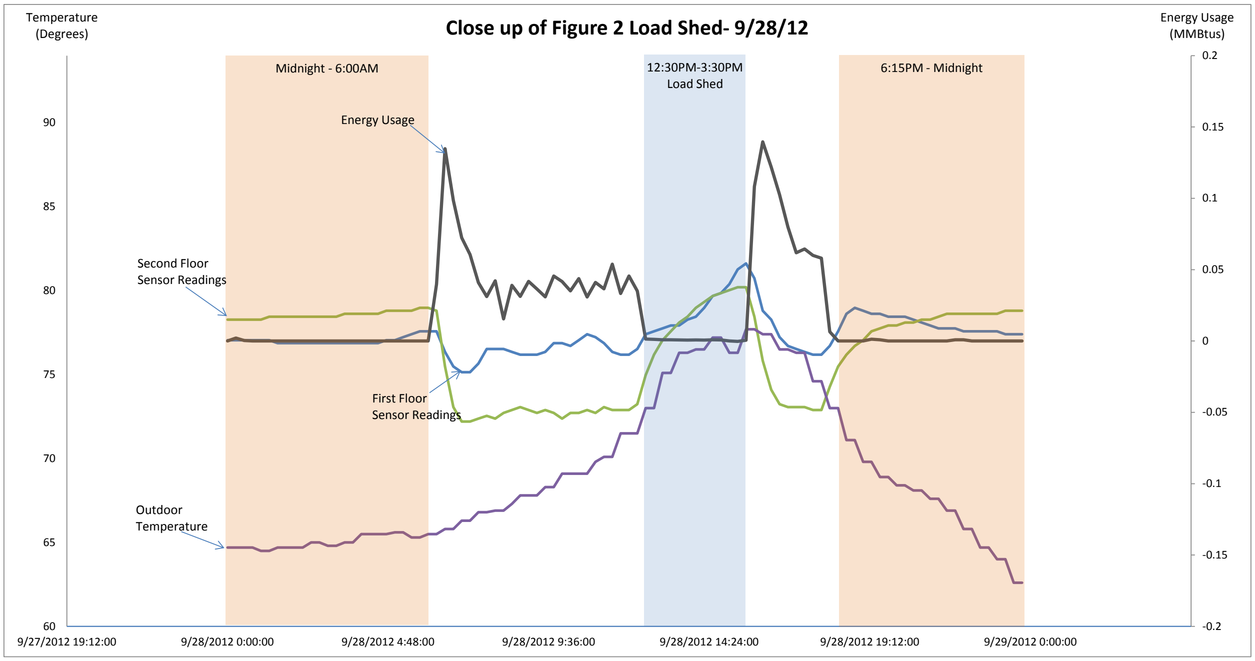

Figure 4. Close-Up of Load Shed Day

RESULTS

Building 1: Characteristics and Satisfaction with Environment

Forty seven (47) employees of the commercial company leasing Building 1 participated in the online survey. Most respondents were long-time employees of the organization, with most reporting at least three years, and about a quarter reporting more than 10 years of tenure. The vast majority held professional and technical full-time positions. Most reported working in Building 1, and occupying the same workspace, for at least three years. Current distribution of location in the building was fairly evenly split between northeastern, northwestern, and southeastern exposures, with fewer in southwestern parts of the building. Participants were equally split between occupying private offices and cubicles.

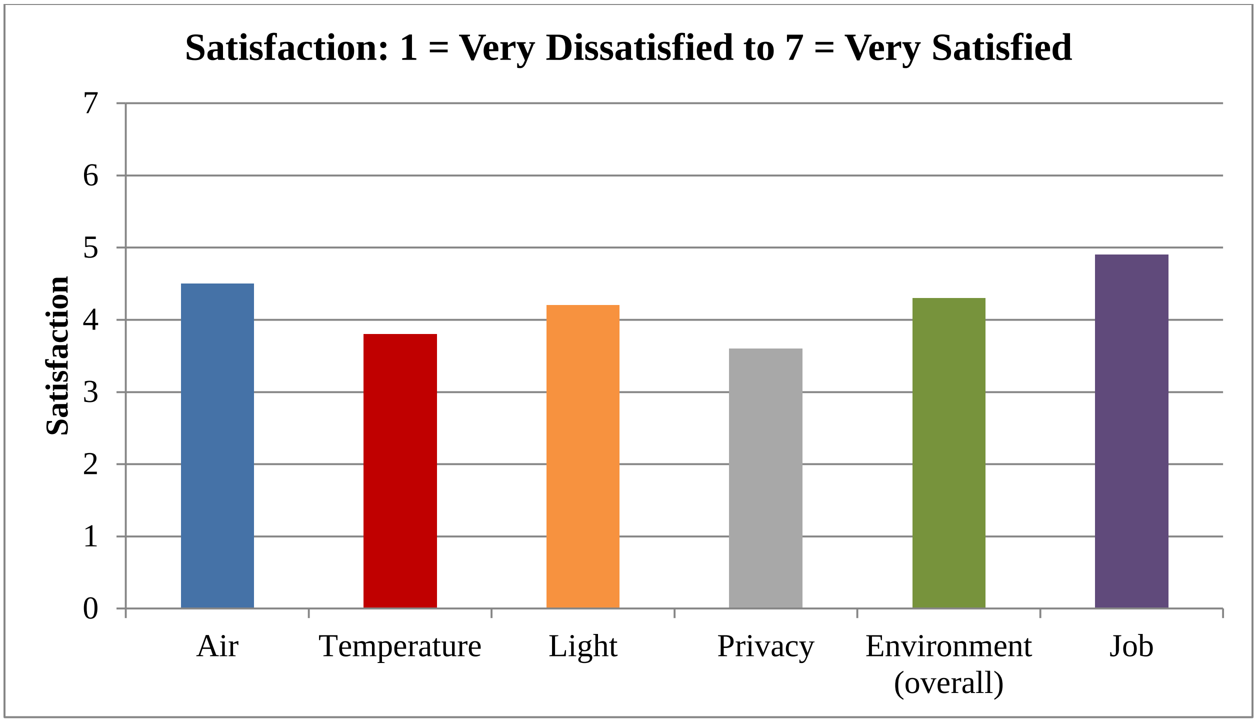

Figure 5. Satisfaction with Environmental Conditions (Building 1)

By and large, participants were satisfied with the environmental conditions in their workspace, though satisfaction with temperature and privacy of workspace was slightly lower (Figure 5). However, many reported an inability to control and adjust environmental factors, including the HVAC and lighting systems (which incorporates occupancy sensors), and were somewhat dissatisfied with their inability to adjust electric lighting (Figure 6). With respect to airflow, about a third of respondents felt that conditions were just right. Those who felt a need to adjust airflow engaged in a variety of activities, including using fans and opening and closing doors. About a quarter of participants felt that the lighting was just right, others made use of desk task lighting and adjusting of window blinds to control light, while over half felt there was nothing they could do to affect lighting. The greatest variability in responses to and satisfaction with environmental conditions was in the domain of ambient temperature. Participants were equally split between perceiving actual temperature as lower than, equal to, or higher than their desired temperature. A common approach to dealing with resulting discomfort was to dress in layers – two thirds of respondents reported taking this approach, and about a third used this as a solution on a daily basis. Many reported that their primary approach to changing environmental conditions was to notify the management, and most reported satisfaction with the response they received.

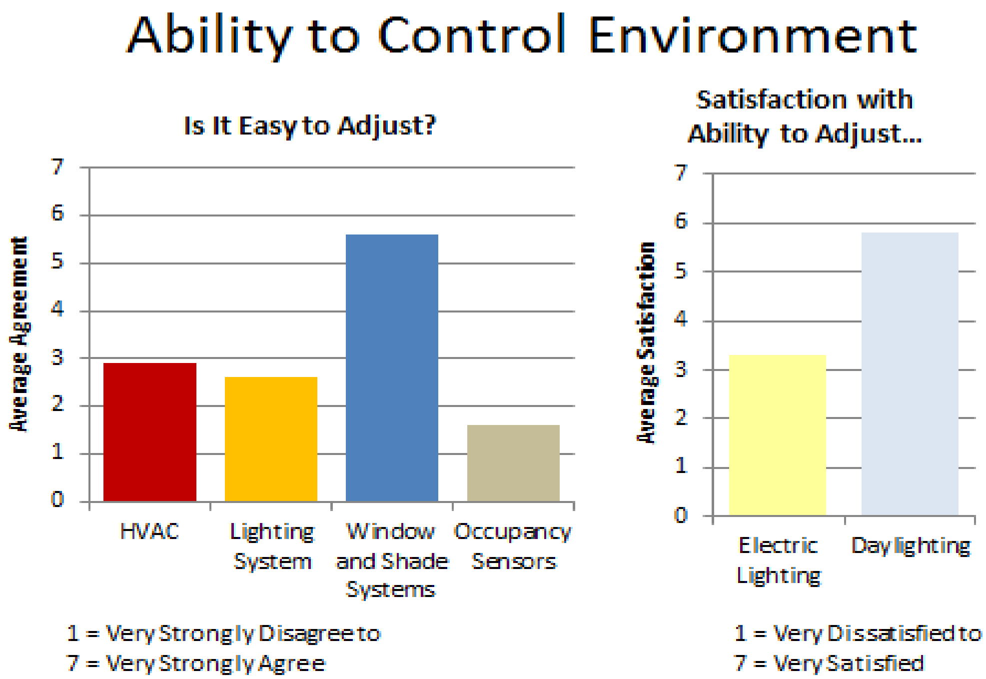

Figure 6. Ease and Satisfaction with Adjusting Environmental Factors (Building 1)

There was variability in satisfaction across physical location and type of workspace. Participants in offices were significantly more satisfied with many aspects of their work environment, including heating, having the desired temperature, ability to adjust daylighting, visual and acoustic privacy, and overall satisfaction with the work environment and with their job. With respect to exposure, participants located in the northeastern part of the building were less satisfied compared to others with air movement and freshness, humidity, heating and cooling, lighting, and overall environmental conditions.

Importantly, it appears that occupants believe that environmental conditions are important for work performance. In particular, satisfaction with lighting made a significant positive contribution toward performance for respondents from Building 1.

Building 2: Characteristics and Satisfaction with Environment

Seventy-one employees located in Building 2 participated in the online survey. About half of the respondents had worked at the organization between one and ten years, while a third had more than 20 years of tenure. Almost all participants were full time employees in professional and technical positions. About a third of respondents had worked in Building 2 under three years, another third between three and ten years, and another third for over ten years. Current distribution of location in the building was fairly evenly split between north, south, and west exposures, with fewer in east parts of the building. Most participants were located in offices, and about two thirds of these had private offices, while a third shared the office space.

Participants were generally satisfied with the environmental conditions in their workspace, and in particular with lighting conditions (Figure 7). Yet, most felt a need to adjust air quality in their space. Unlike in Building 1, participants reported much higher ability to adjust their environmental situation by opening windows and using thermostats that control temperature in their space only (Figure 8). In order to adjust air quality, participants opened and closed windows and doors, used fans and air fresheners, and decorated with plants.

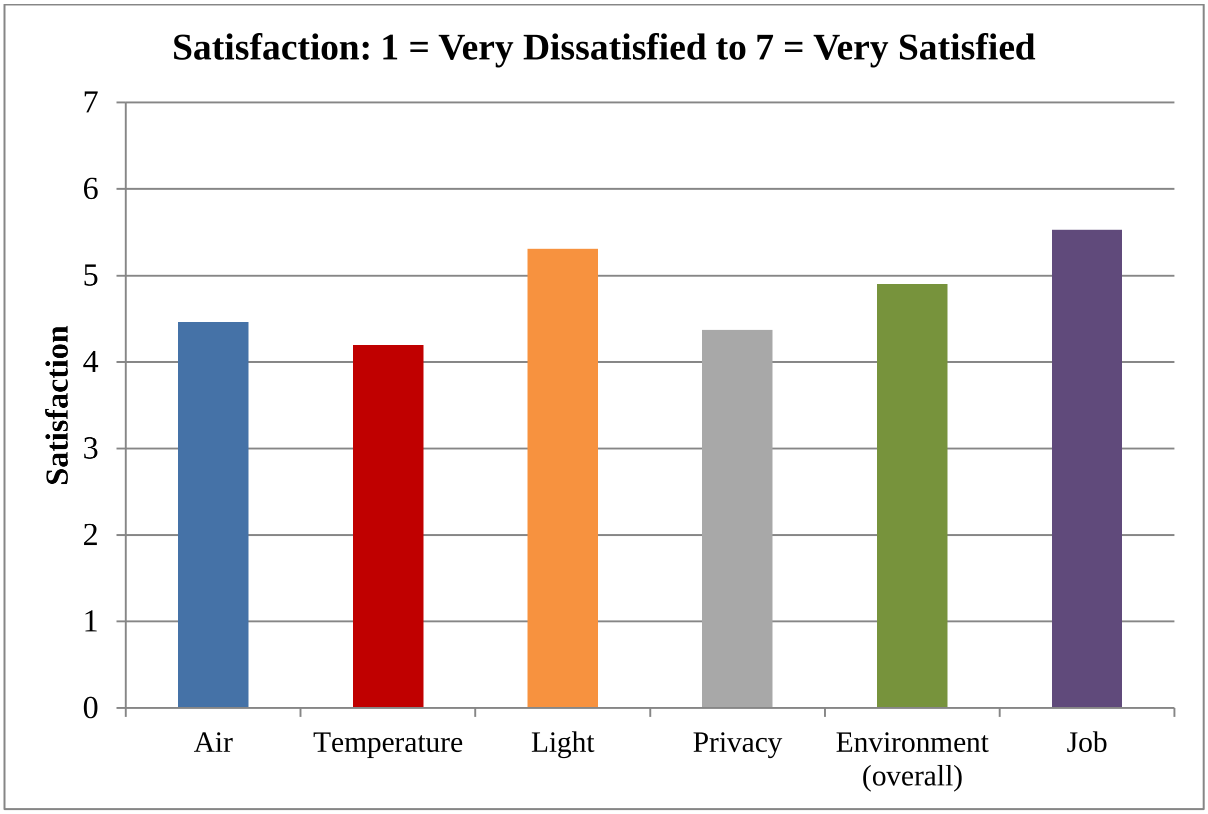

Figure 7. Satisfaction with Environmental Conditions (Building 2)

About half of the participants felt that temperatures can be too cold in the heating season, and half of this group experienced this on a daily basis. Comments suggest that participants' ability to work was compromised by the cold temperature. During the cooling season about half of participants did not report problems with the temperature, while those whose needs were not met were equally split between being too hot and too cold. Measures taken to improve the situation included running space heaters, adjusting the thermostat or the room air conditioning unit, using a portable fan, opening and closing doors, and adjusting window blinds and shades. In line with Building 1, over half of participants made use of wearing layers to adapt to ambient temperatures in the workspace. Less than one seventh of participants in Building 2 contacted the building management for assistance with light and temperature adjustment, in contrast to Building 1, where this was the most common measure.

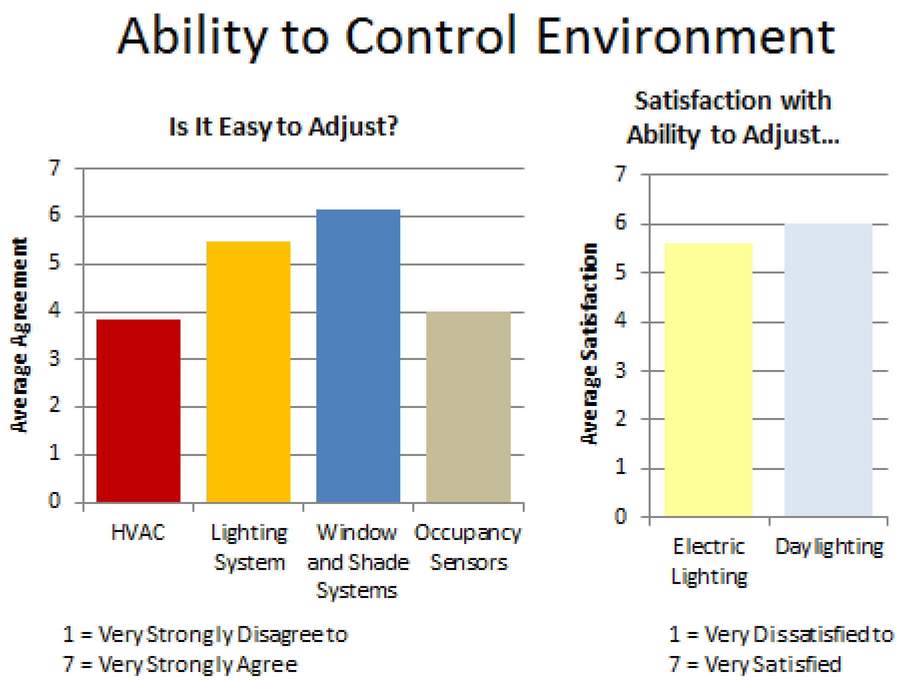

Figure 8. Ease and Satisfaction with Adjusting Environmental Factors (Building 2)

As with Building 1, satisfaction with environmental conditions in Building 2 varied depending on location within the building. Participants in the east and north oriented parts of the building were less satisfied with air quality, humidity (as was the case for western exposure), heating, and overall environmental conditions, and participants with eastern exposure in particular were less satisfied with the quality and the ability to adjust electric lighting.

Effects of Load Shed on Well-Being, Productivity, and Satisfaction: Comparison between Building 1 and Building 2.

The following results compare the responses of occupants on the control days (no load shedding) with those on the days during which load shedding was implemented. Data was pooled across the days of collection across morning and afternoon responses since the number of responses for each point of data collection was too small for reliable statistical analysis. In all analyses higher numbers correspond to better or more desirable outcomes.

In both Building 1 and Building 2 we found large and, in a number of cases, statistically significant changes between control and load shedding days on items that address well-being, productivity, and satisfaction. Most interestingly the direction of the changes was consistent within each building but strikingly different between the sites. Specifically, overall and on an overwhelming number of items, occupants of Building 1 rated the environment as getting better whereas occupants in Building 2 rated the environment as getting worse (see Figures 9, 10, 11).

For the well-being items (see Figure 9), on every item except self-reported stress, occupants in Building 1 saw the environment as improving on load shedding days while occupants in Building 2 saw the environment as becoming less positive. Occupants in Building 1 felt more pleasant and alert, rated their physical and mental health more positively, and were better able to concentrate and less fatigued, while those in Building 2 felt the opposite (statistical significance is indicated with *). Occupants indicated feeling slightly (but not significantly) more stress on the load shedding days in each case.

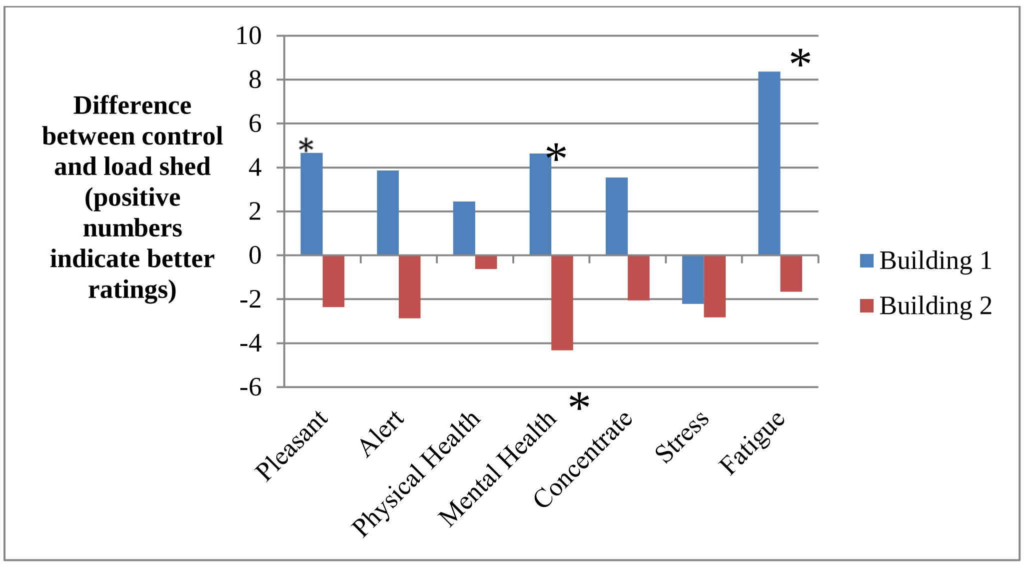

Figure 9. Building 1 & Building 2 – Changes with Load Shedding: Well-being

As shown in Figure 10, occupants of Building 1 rated themselves as having higher work quality, being more productive (both at statistically significant levels), and being more satisfied with their work (though not reaching statistical significance) on load shedding days. By contrast, occupants in Building 2 rated themselves as having lower work quality, being less productive (both at statistically significant levels), and being less satisfied with their work (though not reaching statistical significance) on load shedding days.

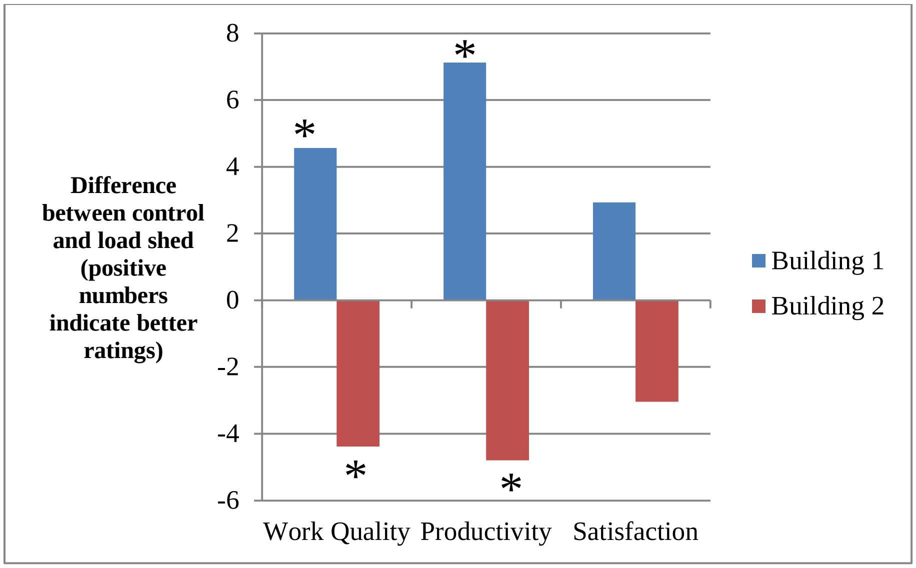

Figure 10. Building 1 & Building 2 – Changes with Load Shedding: Productivity

Self-ratings of satisfaction with environmental conditions showed more variability, with several items standing out. For Building 1 temperature and temperature adjustability were rated significantly more positively on load shedding days, while for Building 2, air quality and temperature adjustability were rated as significantly less satisfactory on load shedding days (Figure 11).

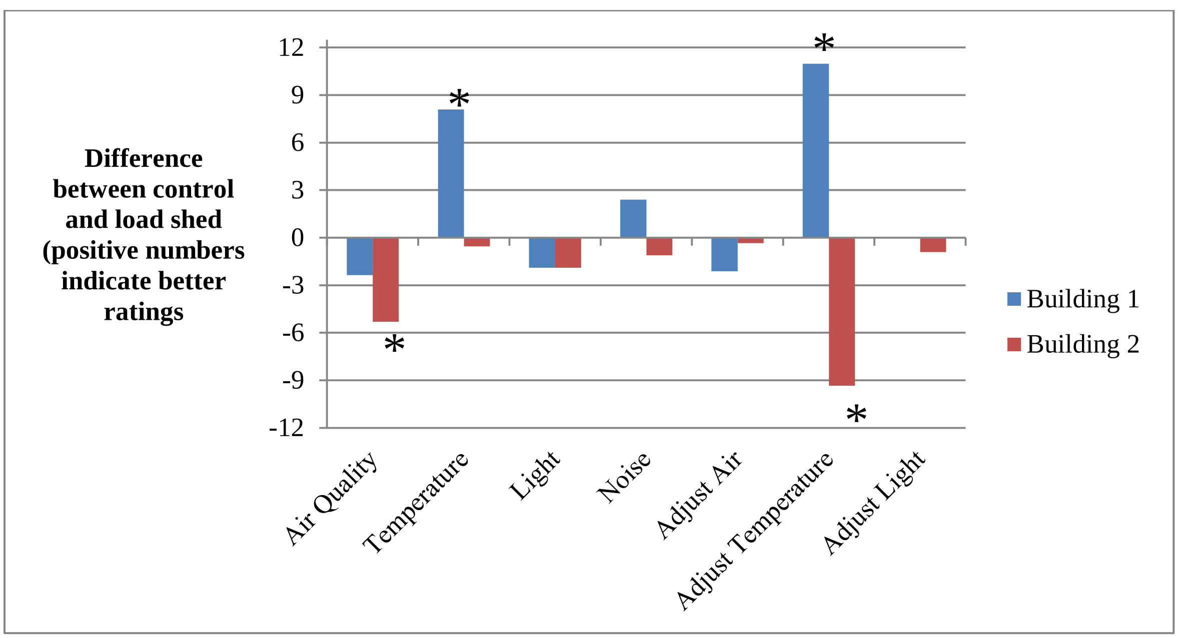

Figure 11. Building 1 & Building 2 – Changes with Load Shedding: Satisfaction

Overall for both buildings, load shedding has a clear effect on well-being, productivity, and satisfaction with one's environment. Yet, in Building 1 load shedding leads to improvements in indicators, while in Building 2 the effects are negative. Confidence in these results is supported by the fact that they are apparent for many variables, that the levels of statistical significance are strong, and that the direction of differences (load-shedding days are better than control days), is the same within the Building in virtually every case.

Accounting for Different Effects of Load Shed across Buildings 1 and 2

To examine the reasons underlying our findings of an opposite effect of load shedding in the two buildings, we took a closer look at how the changes in temperature during the load shed interacted with participants' needs and preferences.

Building 1 – Changes during Load Shed

First, we observed that, at baseline, participants fell into one of three categories: those who indicated that actual temperatures were lower than they desired ("too cool") comprised the largest block (39.5%), while 31.6% felt that actual temperatures were higher than desired ("too warm"), and 28.9% felt temperatures were as desired (Table 2). As one might expect, those who indicated that ambient temperature was at desired levels were significantly more satisfied with temperature than were those who were either too hot or too cold (Table 3).

Perceived and desired temperature

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1.00 Too cold	15	31.9	39.5	39.5
	2.00 OK	12	25.5	31.6	71.1
	3.00 Too hot	11	23.4	28.9	100.0
	Total	38	80.9	100.0	
Missing	System	9	19.1		
Total		47	100.0		

Table 2. Differences between Perceived and Desired Temperature

	Temperature Differential	Satisfaction with Temperature
Baseline	**F (2,35) = 10.552*****	**OK > Too Hot & Too Cold**
Control Days	**F (2,30) = 5.373***	**OK > Too Hot & Too Cold**
Load Shed Days	**F(2,23) = 1.960, ns.**	**OK & Too Cold > Too Hot (ns)**

- **= P<.05 ***= p<.001**

Table 3. Perceived Temperature Differential as Predictor of Thermal Satisfaction during Baseline, Control Days, and Load Shed Days

However, once the load shed was implemented, we see that the pattern of satisfaction changed across participants (Figure 12).

Those who felt the temperature was just right at baseline continued to be satisfied, and those who were too hot continued to be less than satisfied on load shedding days. However, those who were too cool at baseline were much more comfortable during the load shed, as the building warmed up. In fact, their levels of satisfaction became indistinguishable from those who had been satisfied at baseline. In other words, those who were too hot remained unhappy, those who were satisfied remained satisfied, and those who were too cool became significantly more satisfied on load-shed days.

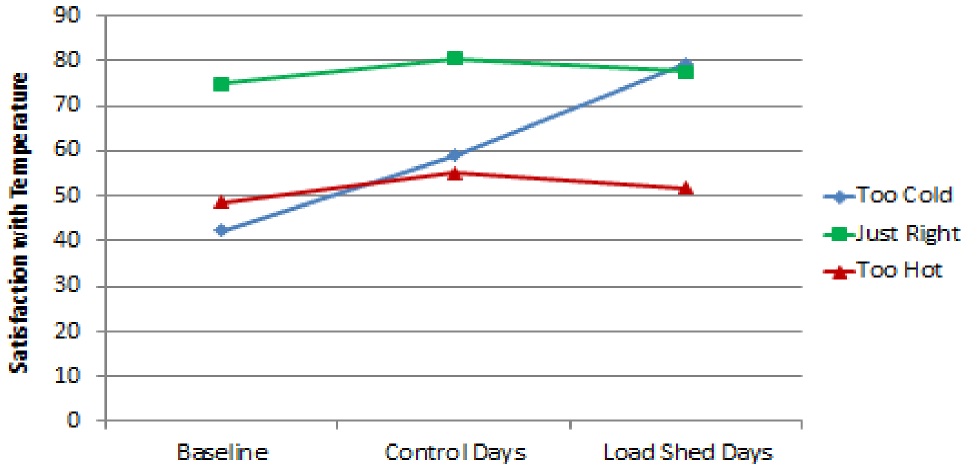

Figure 12. Load Shedding: Temperature (Building 1)

Given the difficulty in controlling or accounting for many possible variables that could affect outcomes in this environment, we need to note that there may be explanations other than the presence or absence of load shedding. For instance, there could be an unmeasured extraneous variable that accounts for these differences, such as positive or negative organizational events (a celebration or work crisis), a meteorological event (a storm or temperature swing) or other condition, even though attempts were made to monitor such events.

The data, however, strongly suggests that responses across a wide range of variables and many respondents were more positive on load-shedding days, when temperature was allowed to rise beyond ordinary set points. This suggests that the normal conditions were, in fact, not optimal, and therefore reduced levels on load shedding days come closer to what the occupants actually desired.

Building 2 – Changes during Load Shed

To examine whether the process observed in Building 1 was replicated in Building 2, we again examined responses among three categories of respondents: those who indicated that actual temperatures were as desired were the largest block (43.1%), while 31% felt that actual temperatures were higher than desired ("too warm"), and 25.9% felt temperatures were lower than desired ("too cool") (see Table 4).

Table 4. Difference between Perceived and Desired Temperature

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1.00 Too cold	15	21.1	25.9	25.9
	2.00 Just right	25	35.2	43.1	69.0
	3.00 Too hot	18	25.4	31.0	100.0
	Total	58	81.7	100.0	
Missing	System	13	18.3		
Total		71	100.0		

Yet, in Building 2 there were no significant baseline differences in thermal satisfaction based on rating of actual versus desired temperature (see Table 5), nor did we observe a statistically significant effect for load shedding (see Figure 13). This may be because the error variance for these subjects (aspects of scores not accounted for by the independent variable) is higher for Building 2 occupants than it was for Building 1 occupants. There are, however, similar changes between the groups of subjects who initially indicated the space was "too warm", "too cool", and "ok" even though these differences are too small to reach significance. That is, as the building temperature warmed up during load shedding, those who felt too warm on control days moved toward being less satisfied, and those who felt too cool on control days trended toward being more satisfied.

Table 5. Perceived Temperature Differential as Predictor of Thermal Satisfaction

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4.568[a]	2	2.284	.888	.417
Intercept	966.784	1	966.784	375.733	.000
tempdiff.split.0	4.568	2	2.284	.888	.417
Error	141.518	55	2.573		
Total	1181.000	58			
Corrected Total	146.086	57			

a. R Squared = .031 (Adjusted R Squared = -.004)

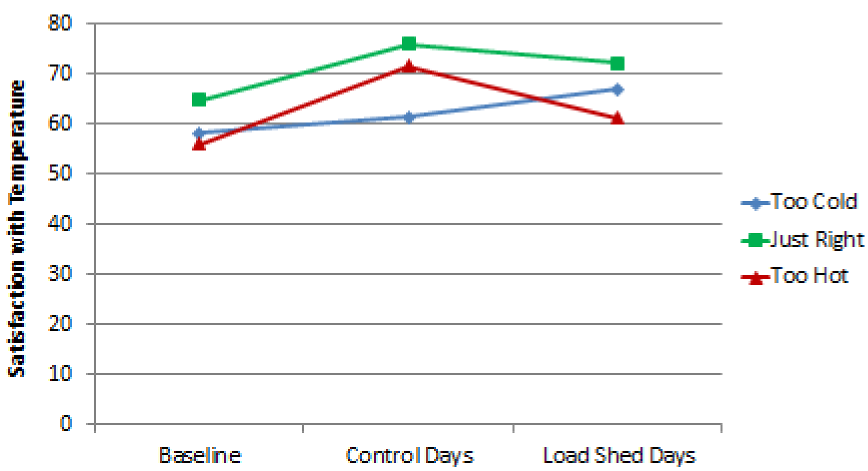

Figure 13. Load Shedding: Temperature (Building 2)

These findings suggest that Building 1, or at least substantive areas within it, was experienced by occupants as overcooled prior to load shedding. Those who felt this building was cooler than preferred were the single largest block of occupants. Reducing energy use during load shedding created a higher set point for the cooling level of the building, making it warmer overall and hence more closely approaching desired levels for many users. In Building 2, the largest block of users was those who felt the building temperature during control days was about right. Changes during load shedding that resulted in making the building warmer, therefore, were more likely to lead to increased dissatisfaction.

Importantly, the difference in response also likely stems from the type of load shed implemented. As shown in Table 1, load sheds differed drastically between the two buildings. During the period of this study the managers of Building 1 were in the process of updating and improving the control systems for their HVAC and lighting systems. These improvements provided them with sophisticated, fine-grained control to make subtle adjustments to the settings, creating a more optimal environment. Building 2, on the other hand, made no comparable changes, had limited building system controls, and implemented load shedding in a more blunt manner, relying on completely turning off the HVAC system. Whereas Building 1 was able to adjust the cooling set point degree by degree, Building 2, as noted above, simply shut off cooling systems and ventilation. Adequate ventilation can be particularly important in how occupants perceived the quality of their thermal environment, and we observed that satisfaction with air quality decreased significantly during load shed in Building 2. Therefore, our findings offer evidence for the sensitive and powerful response of building users to the type of environmental change taking place.

CONCLUSION AND RECOMMENDATIONS

In drawing conclusions we need to be careful to take into account the differing contexts of these buildings. First, they have different functions and populations. Building 2 is owner-occupied by employees of a scientific research organization. Building 1 is occupied by a single tenant whose employees are mostly engineers. Building 1 has much more sophisticated control systems and a superior building envelope, allowing it much better control over internal conditions, whereas Building 2 consists of a series of interconnected buildings of various ages, different envelopes, and varying control systems, over which operators have much less control, reducing their ability to adjust for changing conditions, areas with different kinds of sun exposure, etc.

The most important finding suggested by this analysis may be that all load shedding is not the same. Load shedding may be much better suited for buildings that have sophisticated controls and high-tech envelopes, in which operators can tailor adjustments at a fine-grained level so that the load shedding is not seen as a drastic change. Load shedding may be a more risky strategy in buildings with older systems and less control over operations.

A second important finding relates to the extent to which these (and many other) buildings may be over-cooled in summers. Especially given that occupants preferred somewhat warmer temperatures (Building 1), reducing the extent of over-cooling, where it occurs, could save energy – not only during load-shedding events but on a regular basis.

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