The Effect of Ramps in Temperature and Electric Light Level on Office Occupants: A Literature Review and a Laboratory Experiment

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ABSTRACT

When electricity demand has the potential to exceed supply, brownouts or blackouts may occur. Utilities may take steps to deliver additional power, or to reduce demand. The latter case may involve commercial buildings shedding load when prompted by the electrical utility. For example, lighting may be dimmed, and (in the cooling season) setpoint temperatures increased. However, this may degrade the indoor environment relative to prevailing operational guidelines. Although this may be a reasonable alternative to a blackout, it is still desirable to minimize negative effects on occupants. We reviewed the literature on the effect of steady changes (ramps) in temperature and illuminance from electric light on occupants. Results related to temperature suggest that changes typically associated with load shedding (around 1.5 ^{o}C over 2-3 hours) are unlikely to be detected by occupants, and if detected, would likely be acceptable in the circumstances. Studies of rapid changes in illuminance (of the order of 10-100 lx/s) suggest that illuminance can decline by up to 20% without being detected. With slower rates of change (1 lx/s or less), greater reductions in illuminance may remain undetected, and acceptable.

However, studies to date have focused on detectability and acceptability of ramps, little is known about the wider effects on occupants. Further, existing studies have examined ramps in temperature and lighting independently, rather than in combination. We conducted a controlled laboratory study to address these shortcomings. Sixty-two Participants spent a day in a full-scale office laboratory, completing questionnaires and standard office tasks. One group of participants was exposed to a simulated load shed in the afternoon: workstation illuminance was reduced by 2 %/min, and temperature increased by ~1.5 ^{o}C over a 2.5 hour period; another group experienced no load shed. Analyses suggest that the group experiencing the simulated load shed experienced both positive and negative effects on satisfaction or performance. On balance, our findings suggest that load shedding typical of current suggested practice is a reasonable response to peak power emergencies. Indoor environment conditions may drift from recommended practice, but this is unlikely to create substantial hardships for occupants.

Introduction

Buildings use a lot of energy to maintain temperature and lighting levels within acceptable limits: heating, cooling, ventilating, and lighting buildings accounts for about one-third of the world's energy use (IEA 2005). Of particular recent concern is the demand for electrical power at peak use times (typically summer afternoons), and the ability of the electrical utility to meet this demand – if peak demand exceeds supply blackouts or brownouts may occur.

As part of the general desire to make buildings more energy efficient, building managers are making better use of energy management and control systems (EMCS) to monitor and control energy use in buildings (West, Elliot & Johannesen 1997). An EMCS can be highly responsive during peak demand times, reducing power demand quickly over short periods of time to help avoid blackouts (Meier 2004). Such actions are often referred to as load shedding strategies (or demand control; West, Elliot & Johannesen 1997), which have been found to reduce peak demand by around 30% (LRC 2005; Piette et al. 2005). One strategy is temperature drifts/ramps, in which the setpoints for air conditioning are raised[1]. Due to the thermal mass of the building, a step change in setpoint will result in the space temperature rising steadily for up to several hours[2]. Another strategy is light switching or dimming. Dimming is likely more acceptable to occupants because illuminance is reduced smoothly and continuously from the usual lighting requirements (IESNA 2000; LRC 2005).

Therefore, although load shedding can be effective in offsetting a peak demand crisis, it creates the potential for conditions to deviate from recommended temperature and lighting standards (e.g. ASHRAE 2004; IESNA 2000). This may result in an indoor environment that is uncomfortable or unacceptable to occupants, and might impair their performance. In the first part of this paper we review the existing literature on the effects on people of exposure to steady ramps in temperature and lighting levels. The second part of the paper describes a laboratory experiment to address some of the gaps in knowledge revealed by the literature review. The ultimate goal is to provide guidance such that when ramps in environment conditions as induced by load shedding are necessary, they are enacted in a way that is least uncomfortable and disruptive to office workers.

Literature Review

After an extensive literature search, we found 20 studies that were relevant to the purposes of our review. These studies examined either temperature ramps or lighting ramps; there were no studies that examined ramps in temperature and lighting acting simultaneously.

Effects of Exposure to Steady Ramps in Temperature Levels

We reviewed eleven studies on the effects of steady cyclic or linear ramps in temperature on occupant detectability, acceptability, or task performance. These studies are briefly described below. Note that the studies where the rate of change of temperature was similar to that likely achieved in a load shedding scenario are mentioned first in each section; studies with very rapid temperature changes may provide additional supplementary information, but are not given the same weight when drawing conclusions. All studies were conducted in environmental chambers, with the exception of Brager, Paliaga & de Dear's (2004) field study on acceptability.

Detectability. In a study by Griffiths and McIntyre (1974), participants (N=32*)[3] recorded their thermal comfort every hour for six hours while the temperature varied above or below 23°C by

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[1] In much of North America, peak demand occurs on hot summer afternoons, and therefore the focus is to reduce cooling demand. In winter peaking regions where heat is provided electrically there may be a desire to reduce heating demand by allowing temperatures to fall.

[2] Another strategy is load shifting, that is, using electrical power during periods of low demand to offset demand for power during high demand periods. One example of this is pre-cooling in the morning to defer demand for cooling in the afternoon; see: http://news.uns.purdue.edu/UNS/html4ever/2006/060117.Braun.energy.html, and http://drrc.lbl.gov/drrc-pubs3.html.

[3] A * after the number of study participants indicates they had no expectation that ramping would occur.

1.5, 3, or 4.5°C at rates of 0.5, 1.0, or 1.5°C/hr. Results indicated that participants detected change even at the lowest ramping rate.

Sprague and McNall (1970) studied the effects of quick, cyclic temperature ramps. Participants (N=192*) engaged in sedentary activity while the temperature fluctuated around an average of 25.6°C at a maximum rate of 0.18°C/min and maximum peak-to-peak amplitude of 3.3°C. Participants evaluated their thermal sensation every 7.5 minutes for three hours. Findings revealed no significant correlation between temperature change rate and thermal sensation votes.

Nevins et al. (1975) exposed sedentary participants (N=18*) to quicker cyclic temperature ramps from an initial temperature of 25°C at a rate of 0.3°C/min and peak-to-peak amplitude of 5°C. Participants measured their thermal comfort and sensation every 5 minutes for two hours. Participants were comfortable at 24.4 to 25.3°C, and felt neutral[4] at 24.3 to 26.4°C.

Wyon et al. (1971; also see Wyon 1977) examined even quicker cyclic temperature ramps from an initial point of 25°C at a rate of 0.5°C/min. In contrast to the previous studies, participants (N=8*) could reverse the ramp direction when they felt "too hot" or "too cold". Two hours of mental work (performing calculations) were followed by two hours of rest. Findings revealed that wider temperature swings went undetected by participants when working (Mdn = 9.2°C) than when resting (Mdn = 5.6°C). The authors suggested that large but rapid temperature changes are not detected because skin temperature will lag behind air temperature and temperature extremes may not be experienced for long enough to be detected.

Acceptability. Berglund & Gonzalez (1978a) exposed participants (N=36*) to linear temperature ramps above or below an initial value of 25°C at rates of 0.5, 1.0, or 1.5°C/hr over a 4-hour period (~ amplitude of ramp = ±2, 4, or 6°C). Participants engaged in sedentary activities and walked slowly for 5 minutes every half-hour. Participants judged thermal acceptability every half-hour. Ramps of ±2, 4, or 6°C were acceptable at rates of 0.5, 1.0, and 1.5°C/hr, respectively. In a later study, Berglund & Gonzalez (1978b) extended their testing sessions to 8.5 hours with linear ramps from 23 to 27.8°C at a change rate of 0.6°C/hr. Findings indicated that conditions were acceptable to more than 80% of participants (N=24*) up to about 27°C.

Brager, Paliaga & de Dear (2004) conducted a field study in a naturally ventilated office building in San Francisco. The temperature in 38 workstations was recorded over a two-week period in both warm and cool seasons. Occupants judged thermal acceptability several times a day. The indoor temperature in the warm season ranged from 19.7 to 32.9°C, and from about 17.5 to 30.6°C in the cool season. The daily trend followed an inverted U-shape, with temperature increasing in the morning, remaining steady from noon until approximately 2 p.m., and then declining for the remainder of the day; rates were 0 to ±3.0°C/hr. Findings revealed that temperature limits between 19.4 and 26.4°C, and 18.1 and 25.1°C, at a rate of ±1.5°C/hr were acceptable to 80% of the occupants in the warm and cool season, respectively.

Given that core body temperature cycles over 24 hours, Fanger, Hojbjerre & Thomsen (1973) hypothesized that people might prefer temperature fluctuations as opposed to a constant temperature. With initial temperature at 25.6°C, participants (N=16) engaged in mental work (e.g., reading or studying) for an 8-hour period. Every ten minutes the participants indicated their thermal preference and the temperature was adjusted accordingly. Findings revealed no preference for fluctuations around a mean value of 24.5°C. In a subsequent study, Fanger, Hojbjerre & Thomsen (1974) investigated whether temperature preferences changed from

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[4] "neutral" refers to the sensation of being in thermal balance with the environment – heat loss equal to heat gain – this is not necessarily the same as feeling thermally "comfortable".

morning to evening (N=16); again, initial temperature was set at 25.6°C. Similar results were obtained, with no preferred deviations around a mean value of 25.2°C. These findings suggest that constant temperatures are preferred.

Task performance. Wyon et al. (1973; also see Wyon 1977) hypothesized that a constant temperature would create a monotonous climate, increasing fatigue, and decreasing arousal and task performance. Participants (N=16*) were exposed to cyclic ramps around a mean of 24.5°C at rates of 0.25, 0.5, 0.75 and 1.0°C/min and peak-to-peak amplitudes of 2, 4, 6, and 8°C over two 4-hour periods. Irrespective of change rates, performance (speed and accuracy of math calculations) was poorest at peak-to-peak amplitudes of 2°C, and best at peak-to-peak amplitudes of 8°C.

Wyon, Andersen & Lundqvist (1979) examined the effects of slower cyclic temperature ramps on performance (speed and accuracy of various cognitive tasks). Participants (N=76*) were exposed to temperature ramps between 20 and 29°C at a rate of 3 or 4°C/hr from an initial temperature of 20 or 23°C during three successive 50-minute periods. Sentence comprehension increased when temperature increased from 26 to 29°C, and decreased from 26 to 23°C, recognition memory increased when temperature increased from 24 to 26°C, and cue utilization increased when temperature increased from 23 to 25°C and decreased from 23 to 20°C.

Effects of Exposure to Steady Ramps in Lighting Levels

We reviewed nine laboratory experiments in simulated offices that examined the effects of linear ramps in lighting levels on detectability, acceptability, satisfaction and task performance.

Detectability. Kryszczuk and Boyce (2002) asked participants (N=16) to observe a black target against a white background, in some cases while performing a mental distraction task (verbal subtraction calculations). The illuminance level on the target was reduced over periods of 3.33-120 seconds from 1090 lx (~ change rate = -9 to -337 lx/s) or 475 lx (~ change rate = -4 to -134 lx/s) until participants indicated that they detected a change. On average, illuminance declined by about 20% before being detected, irrespective of mental distraction or change rate.

Shikakura, Morikawa & Nakamura (2003), exposed participants (N=55) to lighting ramps between the range of about 560 and 1000 lx from an initial level of 750 lx (desktop illuminance) over durations of 0 (instantaneous change), 2, 8, or 16 seconds (~ change rate = -190 to +250, -95 to +125, -24 to +31, or -12 to +16 lx/s, respectively). When not engaged in office tasks, changes in lighting levels were undetected between 693 and 808 lx, or ±8% around the initial level. However, this range expanded to 633 and 913 lx when participants performed office tasks (concentration, communication, and computer-based (VDT) work), suggesting that changes of roughly ±20% will remain undetected when working. The change rate had no effect on the findings reported.

Acceptability. Tenner, Begemann & van den Beld (1997) studied participants (N=20) engaged in their own work for two 8-hour days. Participants set the initial preferred light level each day and were able to adjust the level to a maximum of 830, 1660, or 3100 lx (desktop illuminance). Fifteen minutes after the initial level was set, the light began to dim by 8% every 3 minutes (~ change rate = 0 to -0.37, 0 to -0.74, or 0 to -1.38 lx/s, respectively). The lighting switched off if

20% of the maximum level was reached. For maximum light levels of 830, 1660, and 3100 lx, participants on average allowed light to dim by approximately 30%, 40%, and 60%, respectively, before intervening.

In Newsham et al. (2002), participants (N=10*) completed various tasks and satisfaction questionnaires for 2.7 hours. Participants set the initial light level from 12 to 100% of maximum light output (~75 to 630 lx for desktop illuminance), and were able to adjust the level throughout the session. Twenty minutes after the start of the session, the experimenters dimmed lights by 1% of full output every 2 minutes (or -0.05 lx/s). Light levels fell by 13-80% before occupants intervened. Occupants' satisfaction did not appear to suffer as a result of the dimming.

Akashi, Neches & Bierman (2003) dimmed lighting from an initial level of 500 lx on the target to 420, 340, 260, 180, 100 or 20 lx over 10 seconds, or left the level unchanged at 500 lx (change rate = 0 to -48 lx/s). The authors also examined effects of task type (no task, paper word puzzles, or VDT word puzzles), font size (6- or 12-point font), and bias toward energy conservation. Participants (N=24) detected change after a 15-20% reduction from the initial illuminance level. Eighty percent of the non-biased participants accepted up to a 20% reduction, while 80% of the biased participants accepted up to a 54% reduction. Change rate, task type, and font size showed little effect.

Mood, arousal, & task performance. Vallenduuk (1999) studied the effects of constant (1200 lx) vs. variable lighting (between 200 and 2100 lx; ~ change rate = ±0.18 lx/s). Participants (N=33^)[5] completed tasks and questionnaires over an 8-hour period. Mood was measured by positive and negative words selected from word groups. Arousal was measured by the time to count to ten. Task performance was measured with visual/motor and cognitive tasks. Participants in the variable lighting condition had a more positive mood and were more aroused.

Laboratory Study

We designed a laboratory study to address some of the shortcomings of previous research. Specifically, our study examined the effects of lighting and temperature ramps acting together, the effect of ramps on a broad range of occupant satisfaction and task performance outcomes, and, to a limited degree, the interaction with the proximity of windows.

Methods

Setting. The experimental space was 12.2 m x 7.3 m x 2.7 m, with an exterior wall facing west, with two small windows. The space contained six typical 'cubicle'offices of 2.83 m x 2.22, panel height 1.68 m. The space had a dedicated HVAC system and, as part of another study on personal control, air was delivered via 10 nozzles in the ceiling (one in each corner, and one per cubicle). Electric lighting was fluorescent with two components: 14 2-lamp prismatic lens luminaires on the perimeter; and 6 pairs (one pair per cubicle) of 3-lamp suspended direct-indirect luminaires, one lamp (up-light) was mounted above the other two lamps (down-light). Figure 1 shows a photograph of the space.

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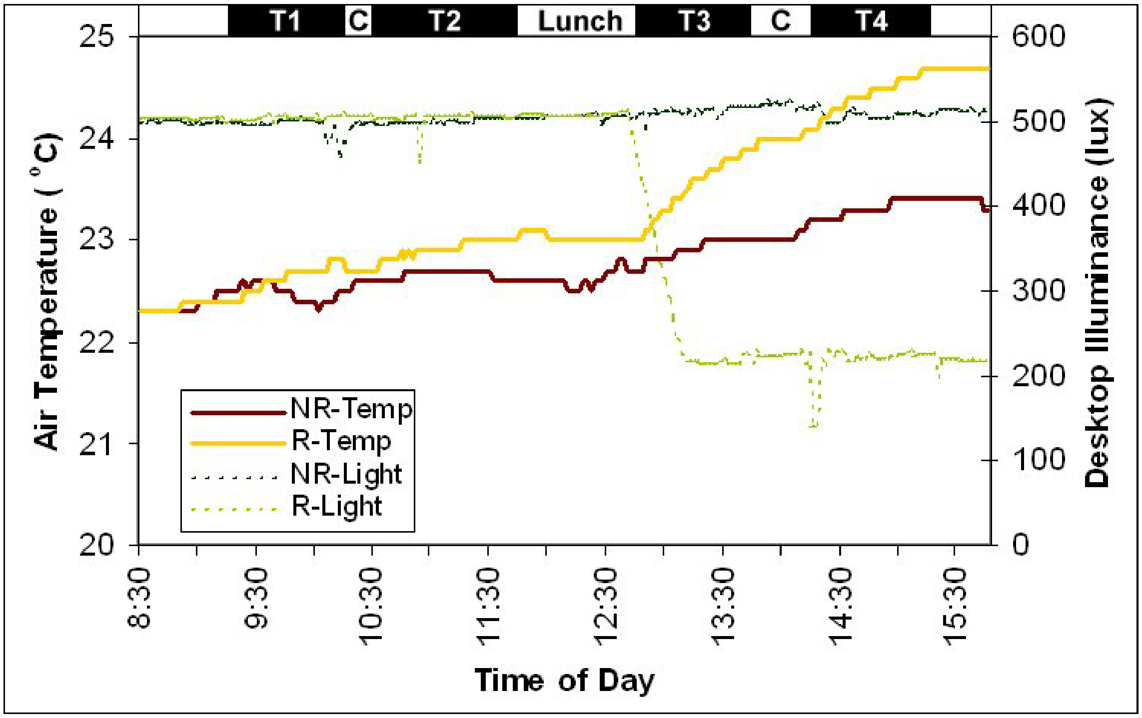
[5] A ^ after the number of study participants indicates that the reference does not indicate whether the participants had an expectation that ramping would occur.

Figure 1. Photograph of Experimental Space

Participants. Participants were recruited from a local temporary-employment agency. Up to six people participated on a testing day, between 9 am and 4 pm. Up to two participants were seated with the small windows to their backs (W), and up to four participants had no immediate access to a window view (NW). During the day they undertook a variety of satisfaction questionnaires and simulated office tasks. The day was divided into four sessions: T1, between morning arrival and mid-morning break; T2, between mid-morning break and lunch; T3, between lunch and mid-afternoon break; and T4, between mid-afternoon break and the end of the afternoon. Session T1 included on-screen instructions, questionnaires and practice tasks, the remaining sessions had very similar content, featuring questionnaires and the tasks that were practiced in T1. On each day, one of four experimental conditions prevailed, of which two are relevant to this paper: no ramping (NR), or ramping (R) initiated at the beginning of session T3. There were 31 participants in each gender-balanced group, ranging in age from 18 to 60.

Experimental conditions. In the NR condition, the direct component of the direct-indirect luminaire was fixed at a level that, in combination with the fixed perimeter and indirect lighting, delivered a minimum of ~400 lx (mean ~490 lx) on the desktops. The corner air supply nozzles were fully open, and the other nozzles were at half flow (total flow rate ~350 ls^{-1}, ~25% outdoor air). Supply air temperature was 18^{o}C, resulting in a room temperature of ~22.5^{o}C. In the R condition, ramping was initiated when the participants returned to the space following the lunch break. The direct component of the direct-indirect luminaire was reduced by 2% of full output per minute, to a minimum 15% output. The other electric lighting components were maintained at constant output to assure adequate minimum light levels throughout the space. To simulate the effect of reduced chiller operation, the supply air setpoint was raised from 18^{o}C to 24^{o}C in a single step; the supply air temperature reached 24 ^{o}C ~30 minutes later. The air temperature in the test space increased by ~1.5°C over the following 2.5 hours[6]. The rate of change of temperature differed by ±0.3°C/hr depending on external climate and internal gains on the day. Figure 2 shows measured desktop illuminance and air temperature in a typical NW cubicle on a typical R and NR day.

Figure 2. Typical Temperature and Lighting Profiles on R and NR Days: the Arrangement of Works Sessions across the Day is also Shown



Results

Analysis strategy. We conducted a series of analyses of variance (anovas) or multivariate analyses of variance (manovas) using the data from the tasks and questionnaires. Each analysis looked at between-subject effects: r vs. Nr, and w vs. Nw. For outcomes measured at several times during the day, within-subject time-of-day effects were tested. The interactions of these effects were tested in a series of contrasts. Table 1 shows the significant univariate effects involving r vs. Nr, the principle interest of this paper.

Summary and discussion. Table 1 shows some outcomes that were negatively affected by ramping, and others that show improvements. All effects were small to medium in size, in terms

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[6] An alternative approach would be to adjust the room setpoint temperature up to 24 °C. If this is done with a VAV system, the supply air temperature will stay the same and the airflow rate will be reduced, and the general room air temperature will rise. This might be a more common approach in practice, and may be perceived differently by occupants than the approach we took. However, from an experimental design point of view, we did not want to confound the effects of flow and temperature, and, from an ethical point of view, we did not want to risk exposing our participants to outside air flow rates lower than recommended practice.

of fraction of variance explained ($\eta^2_{partial}$). There were four outcomes interpreted as negatively affected by ramping. For those participants seated near windows, ramping reduced the number of five-letter anagrams solved, and increased the time taken to rate fictional resumes; note that these effects included performance from session T2, before ramping was imposed. On a vigilance task, for those seated near windows, the time taken to respond to a prompt tended to decrease between T2 and T3, but the decrease was less under ramping conditions. Finally, participants under ramping conditions and seated away from windows experienced an increase in distraction from temperature changes from T3 to T4, whereas those under non-ramping conditions experienced a decrease. There were four outcomes interpreted as improved by ramping. Participants in the R group were more satisfied with their performance over the entire day. The time taken to read and rate magazine articles decreased more between T2 and T3 for the R group. As a measure of motivation we looked at the time spent trying to solve an impossible five-letter anagram, with higher values indicating greater motivation. Motivation decreased from T2 to T3 for the NR group, whereas it increased for the R group. Finally, for those seated away from windows, short-term memory improved from T3 to T4 for the R group, whereas it stayed constant for the NR group.

Note, participants were explicitly asked about satisfaction with lighting and temperature, and detection of changes. For lighting satisfaction the trends were in the expected direction between the R and NR groups at T4 (Means: R=3.54; NR=3.86; scale 0 (v. dissat.)-6 (v. sat.)), and between T2 and T4 for the R group (Means: T2=3.72; T4=3.54), however, the differences were not statistically significant (and are therefore not shown in Table 1) despite the large difference in illuminance shown in Figure 2. Previous research has demonstrated a large variability in individual preferred illuminance (Boyce et al. 2003; Newsham & Veitch 2001), with an expectation for a larger number of people satisfied at the pre/non-ramping illuminance level. Responses to the thermal sensation question indicated that participants were cooler than neutral at T2 (Means: R=34.0; NR=32.8; scale 0 (cold) to 100 (hot)), though the temperature was not atypical of office building setpoints (e.g. Brager, Paliaga & de Dear 2004; Piette et al. 2005) or recommended practice (ASHRAE 2004). Therefore, the general rise in temperature in the afternoon, which was exacerbated by ramping (see Figure 2), generally improved thermal sensation at T4 (Means: R=51.4; NR=39.5). In this context, the trends were in the expected direction, but were not statistically significant. To compare detection, we looked at the responses at the end of T3, the session during which the biggest changes occurred. Participants were asked “Have you noticed any changes in electric lighting level (or temperature) since the beginning of the session?”; response options were “No” (0), “Yes, small changes” (1), and “Yes, large changes (2)”. Trends were in the expected direction (Lighting Means: R=0.59; NR=0.52; Temperature Means: R=0.93; NR=0.78), but were not statistically significant. This suggests that the changes induced by these ramps were not detected compared to the reference case. These results suggest that the ramp rates we used were neither detectable, nor dissatisfactory (unacceptable), consistent with most prior research in the field, with the exception of Griffiths and McIntyre (1974).

Negative effects of ramping on performance and satisfaction might have been expected based on degradation of the indoor environment compared to established standards. In this experiment it is arguable that in thermal terms ramping actually improved conditions. It is possible ramping would be perceived more negatively if the pre-ramping temperature is higher, and if the post-ramping illuminance is lower. Positive effects might have been expected based on previous research in the literature review suggesting an inherent preference for some variation in indoor environment. Overall, we saw both positive and negative effects in approximately equal measure for ramping conditions that we considered typical of likely practice.

Table 1. Significant Effects from Analyses of Task and Questionnaire Outcomes (Brief Descriptions of the Tasks are Given in the Table Footnotes)

Effect	F-test	$\eta^2_{partial}$	Means (s.d.)			
Satisfaction with Performance during the day (0-4)						
R vs. NR (main effect)	$F_{1,117}$=5.87*	0.048	NR=2.17 (0.72)		R=2.62 (0.72)	
Anagram Solving, (fraction correct, 0-1)						
R vs. NR, W	$F_{1,117}$=6.12*	0.050	NR-W=1.00		R-W=0.71 (0.21)	
Time to Rate Resumes, (s)						
R vs. NR, W	$F_{1,92}$=8.25**	0.082	NR-W=26.5 (12.4)		R-W=44.4 (12.3)	
Time to Rate Magazine articles, (s)						
R vs. NR, for T2 vs. T3	$F_{1,92}$=7.58*	0.076	NR-T2=141.2 (39.0)	NR-T3=138.2 (38.0)	R-T2=152.3 (39.2)	R-T3=125.4 (38.1)
Motivation, (s)						
R vs. NR, for T2 vs. T3	$F_{1,71}$=4.42*	0.059	NR-T2=78.9 (30.0)	NR-T3=64.0 (27.2)	R-T2=61.4 (24.3)	R-T3=67.3 (22.3)
Vigilance, (s)						
R vs. NR, for T2 vs. T3, W	$F_{1,80}$=6.00*	0.070	NR-W-T2= 34.5 (20.6)	NR-W-T3= 15.7 (5.7)	R-W-T2= 25.0 (9.4)	R-W-T3= 22.0 (8.6)
Temperature Change Distraction, (0-2)						
R vs. NR, for T3 vs. T4, NW	$F_{1,103}$=6.07*	0.056	NR-NW-T3= 0.56 (0.62)	NR-NW-T4= 0.28 (0.46)	R-NW-T3= 0.47 (0.72)	R-NW-T4= 0.65 (0.61)
Serial Recall Memory, (correct digits/s)						
R vs. NR, for T3 vs. T4, NW	$F_{1,103}$=6.05*	0.055	NR-NW-T3=0.47 (0.22)	NR-NW-T4=0.48 (0.26)	R-NW-T3=0.53 (0.34)	R-NW-T4=0.71 (0.42)

* = $p<0.05$, ** = $p<0.01$; For MANOVAs, univariate effects shown only if multivariate effects significant.

Satisfaction with Performance during the day was the mean of 4 questions on a 5-point scale from Strongly Disagree to Strongly Agree (see Boyce et al. 2003).

Anagram Solving, participants were asked to solve five-letter anagrams (based on Aspinwall & Richter 1999; Sandelands, Brockner & Glynn 1988).

Time to Rate Resumes, participants read three fictional resumes for a fictional job opening, and rated applicants on skills, competence, intelligence, and assigned a starting salary. The measure was the time taken to complete the ratings, after reading the resumes (based on a task in Veitch & Newsham 1998).

Time to Rate Magazine articles, participants read short magazine articles, and rated the article on whether it was interesting, grammatically correct, well-written, and biases. The measure was the time taken to read the article and complete the ratings (based on a task in Boyce et al. 2003).

Motivation, participants were asked to solve impossible five-letter anagrams. The measure was the time spent before giving up (based on Aspinwall & Richter 1999; Sandelands, Brockner & Glynn 1988).

Vigilance, at random times during the day, an on-screen icon similar to an e-mail arriving appeared. Measure was the time taken for participants to click on the icon (see Boyce et al. 2003).

Temperature Change Distraction, participants indicated if they had been distracted from their work by changes in temperature, response options were No (0), Yes a little (1), and Yes a lot (2).

Serial Recall Memory, eight digits were presented to participants on-screen one at a time, after 10 seconds they attempted to type back the sequence. Measure was the number of correct digits divided by the time taken to recall them (Banbury et al. 2001).

Conclusions

Here we add the findings of our experimental study to the findings of the literature review to come to some general conclusions regarding the effects of ramps on occupants.

Temperature change rates typical of load shedding scenarios in offices (e.g. 0.5^{o}C/hr over 3 hours) may be detectable by occupants, but are likely to be acceptable. Much more rapid cyclic changes (e.g. 0.3^{o}C/min around a comfortable mean temperature) may go undetected, but are not proposed for practical load shedding applications.

Changes in desktop illuminance of 20% will be undetected, irrespective of change rate. Reductions of perhaps 50% from typical office desktop illuminance (~500 lx) will not be detected if the change rate is particularly slow (< 10 lx/min). The presence of daylight may also mask ramps in electric lighting levels. Lighting studies also suggest greater acceptance if: occupants are informed about the importance of ramping as an energy conservation strategy; occupants are unaware that change will occur; or, occupants have personal control over lighting. These effects have only been studied independently, what the effects would be in combination is unknown. One might expect similar effects on the acceptability of temperature ramps, but there is no published data on such effects.

In terms of task performance, there is no strong evidence that ramps typical of suggested load shedding practice will have a consistent negative or positive effect.

Note that our experiment addressed temperature and lighting ramps acting simultaneously. Our results were consistent with prior studies that looked at temperature and lighting ramps independently, there did not appear to be any strong interaction effects between the ramp types.

On balance, our findings suggest that load shedding in office buildings is a reasonable response to peak power emergencies, provided implementation is designed appropriately. By this we mean that indoor environment conditions should not drift too far from recommended practice and change should be slow (according to the limits above). If this is observed, load shedding is unlikely to create real hardships for occupants. At worst, there may be short-term disturbance, but this is likely to be viewed by all concerned as a reasonable alternative to a blackout. We recommend numerical guidelines for the impact of load shedding practices on indoor environmental conditions be included in utility program design. We also recommend that early implementations be closely monitored. This is because one limitation of existing studies is that 20 of 21 were laboratory experiments. Although laboratory studies allow for greater control of experimental conditions, the generalizability of results to actual work settings is always in question. More data from field studies should be used to finalize program design.

A final note of caution is warranted: there is evidence from the lighting literature that people who experience luminous conditions closer to their own preferred levels do experience a bonus in mood, satisfaction, comfort, and motivation (Boyce et al. 2003; Newsham & Veitch 2001), at least in a laboratory setting. Therefore, plans to use load shedding to save energy dollars even when the alternative is not a blackout should be considered carefully until more is known about the effects of environmental ramps on task performance and organizational productivity in real workplaces.

References

Akashi, Y., Neches, J., & Bierman, A. 2003. Energy savings for load-shedding ballast for fluorescent lighting systems. In Lighting Research Center (Ed.), *Reducing Barriers to Use of High Efficiency Lighting Systems* (Final Report Year 2; pp. 22-40). Troy, NY: Rensselaer Polytechnic Institute. URL: http://www.lrc.rpi.edu/researchTopics/reducingBarriers/pdf/year2FinalReport.pdf

[ASHRAE] American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2004. *Thermal environmental conditions for human occupancy* (ANSI/ASHRAE Standard 55-2004). Atlanta, GA: ASHRAE.

Aspinwall, L. G., & Richter, L. 1999. "Optimism and self-mastery predict more rapid disengagement from unsolvable tasks in the presence of alternatives." *Motivation & Emotion*, 23(3), 221-245. URL: http://www.wkap.nl.

Banbury, S. P., Macken, W. J., Sebastien, T., & Jones, D. M. 2001. "Auditory distraction and short-term memory: Phenomena and practical implications." *Journal of the Human Factors and Ergonomics Society*, 43(1), 12-29.

Berglund, L. & Gonzalez, R. R. 1978a. "Application of acceptable temperature drifts as a mode of energy conservation." *ASHRAE Transactions*, 84(1), 110-121.

Berglund, L. & Gonzalez, R. R. 1978b. "Occupant acceptability of eight-hour-long temperature ramps in the summer at low and high humidities." *ASHRAE Transactions*, 84(2), 278-284.

Boyce, P. R., Veitch, J. A., Newsham, G. R., Myer, M., & Hunter, C. 2003. Lighting quality and office work: A field simulation study (PNNL 14506). Richland, WA, USA: Pacific Northwest National Laboratory. URL: http://irc.nrc-cnrc.gc.ca/fulltext/b3214.1

Brager, G. S., Paliaga G., & de Dear, R. 2004. "Operable windows, personal control & occupant comfort." *ASHRAE Transactions*, 110, 17-35.

Fanger, P. O., Hojbjerre, J., & Thomsen, J. O. B. 1973. "Man's preferred ambient temperature during the day." *Archives des Sciences Physiologiques*, 27, 395-402.

Fanger, P. O., Hojbjerre, J., & Thomsen, J. O. B. 1974. "Thermal comfort conditions in the morning and the evening." *International Journal of Biometeorology*, 18(1), 16-22.

Griffiths, I. D., & McIntyre, D. A. 1974. "Sensitivity to temporal variations in thermal conditions." *Ergonomics*, 17(4), 499-507.

[IEA] International Energy Agency. 2005. URL: http://www.iea.org

[IESNA] Illuminating Engineering Society of North America. 2000. *Lighting handbook: Reference and application* (9th ed.). New York: Illuminating Engineering Society of North America.

Kryszczuk, K. M., & Boyce, P. R. 2002. "Detection of slow light level reduction." *Journal of the Illuminating Engineering Society*, 31, 3-10.

[LRC] Lighting Research Center. 2005. *Energy efficient load-shedding lighting technology* (Project 3.2, Final Report): Lighting Research Center, Troy, NY. URL: http://www.archenergy.com/lrp/demandresp_lighting/deliverable_3.2.10_Load-shed_FINAL-RPT.pdf

Meier, A. 2004. Saving electricity quickly. International Energy Agency website, URL: http://www.iea.org/Textbase/publications/free_new_Desc.asp?PUBS_ID=1043

Nevins, R. G., Gonzalez, R. R., Nishi, Y., & Gagge, A. P. 1975. "Effect of changes in ambient temperature and level of humidity on comfort and thermal sensations." *ASHRAE Transactions*, 81, 169-182.

Newsham, G. R., Marchand, R. G., Svec, J. M., & Veitch, J. A. 2002. "The effect of power constraints on occupant lighting choices and satisfaction: A pilot study." In *Proceedings of the IESNA Annual Conference*, Salt Lake City, UT, 115-131.

Newsham, G. R., & Veitch, J. A. 2001. "Lighting quality recommendations for VDT offices: A new method of derivation." *Lighting Research and Technology*, 33, 97-116.

Piette, M.A, Watson, D.S., Motegi, N., & Bourassa, N. 2005. *Findings from the 2004 Fully Automated Demand Response Tests in Large Facilities*. Report for the PIER Demand Response Research Center (LBNL Report Number 58178). URL: http://drrc.lbl.gov/pubs/58178.pdf.

Sandelands, L. E., Brockner, J., & Glynn, M. A. 1988. "If at first you don't succeed, try, try again: Effects of persistence-performance contingencies, ego involvement, and self-esteem on task persistence." *Journal of Applied Psychology*, 73(2), 208-216.

Shikakura, T., Morikawa, H., & Nakamura, Y. 2003. "Perception of lighting fluctuation in office lighting environment." *Journal of Light & Visual Environment*, 27, 15-22.

Sprague, C. H., & McNall, P. E. 1970. "The effects of fluctuating temperature and relative humidity on the thermal sensation (thermal comfort) of sedentary subjects." *ASHRAE Transactions*, 76, 1-11.

Tenner, A. D., Begemann, S. H. A., & van den Beld, G. J. 1997. "Acceptance and preference of illuminance in offices." In *Lux Europa'97, Proceedings of the 8th European Lighting Conference*, Amsterdam, 131–143.

Vallenduuk, V. 1999. *The effects of variable lighting on mood and performance in an office environment* (Masters Thesis). The Netherlands: Eindhoven University of Technology.

Veitch, J. A., & Newsham, G. R. 1998. "Lighting quality and energy-efficiency effects on task performance, mood, health, satisfaction and comfort." Journal of the Illuminating Engineering Society, 27(1), 107-129.

West, M., Elliot, L., & Johannesen, R. 1997. *Saving money with energy management systems*. Gainesville, FL: University of Florida.

Wyon, D. P. 1977. "Human response to cyclic changes in the thermal environment." *INSERM*, 75, 153-162.

Wyon, D. P., Anderson, I., & Lundqvist, G. R. 1979. "The effects of moderate heat stress on mental performance." *Scandinavian Journal of Work, Environment & Health*, 5, 352-361.

Wyon, D. P., Asgeirsdottir, T., Kjerulf-Jensen, P. K., & Fanger, P. O. 1973. "The effects of ambient temperature swings on comfort, performance and behaviour." *Archives des Sciences Physiologiques*, 27, 441-458.

Wyon, D. P., Bruun, N. O., Olesen, S., Kjerulf-Jensen, P., & Fanger, P. O. 1971. Factors affecting the subjective tolerance of ambient temperature swings. In R. Salmark (Ed.), *Proceedings of the 5th International Congress for Heating, Ventilating and Air Conditioning*, Copenhagen, Vol. 1, 87-107.