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Detection and Acceptance of Demand-Responsive Lighting in Offices with and without Daylight

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Abstract – Participants (N=33) in an office laboratory were exposed to an initial baseline electric lighting level of 400 lx on the desktop. The electric lighting was dimmed smoothly over 10 seconds. During the dim, and for 30 seconds afterwards, the participant performed a computer-based proofreading task. The participants indicated if they had noticed the change, and whether the lighting conditions were acceptable. This was repeated over multiple trials, with dimming from 0 to 80%, and with or without daylight. The level of dimming not noticed by occupants was 20% with no daylight, 40% with relatively low prevailing daylight, and 60% with high prevailing daylight (or, alternatively, an amount which represents 20% of total light level). The level of dimming that resulted in conditions that were still acceptable was 40% with no or low daylight, and 80% with high prevailing daylight. These results may be used to develop guidelines for using lighting in demand response actions. They suggest that dimming lights can contribute large electricity demand reductions during periods of grid stress without major inconvenience to occupants.

Keywords – Demand Response, Load Shedding, Energy Management, Comfort

1. Introduction

1.1 Load Shedding and Demand-Responsive Buildings

Demand for grid electricity is not constant, rather it varies according to daily and seasonal cycles. Peak demand tends to occur on hot summer afternoons, when demand for cooling in residential and commercial buildings is at its highest. Electrical utilities must have access to enough generated electricity to meet this peak demand, even though this capacity is not required for most hours of the year. This challenge is generally met on the supply side, in other words, the utility will start generators for peak-time use only, or import premium-priced power from other jurisdictions. Even given these options, there is concern in some locations that there may not be enough supply to meet peak demand, in such cases blackouts will occur.

As a result of this concern, there is growing interest in addressing this issue, at least partially, on the demand side [Piette et al., 2005; DRCC, 2006; Rowlands, 2005], that is, reducing the peak demand for electricity at critical times by eliminating electricity use (“load shedding”), or shifting it to non-peak times. In principle, this is relatively straightforward to do, all one needs is control equipment that can respond to some kind of prompt from the utility. Rosenzweig et al. [2003] estimated that a reduction of only 2-5% in system-wide demand at peak times could reduce the spot price for electricity by 50% or more.

In commercial buildings, which represent 45% or more of the US summer peak electricity demand [Kiliccote et al., 2006; Rubinstein & Kiliccote, 2007] load shedding and shifting can be achieved with a modern energy management and control system (EMCS)¹. For thermal loads, one strategy is pre-cooling, in which the building is over-cooled in the morning, and the building thermal mass carries some of this “coolth” to the afternoon to delay the need for cooling during the hottest part of the day. Another strategy is simply to raise the thermostat setpoint [Piette et al., 2005]. Lighting, which constitutes 30-45% of electricity demand in commercial buildings [IEA, 2006] can also participate in such load shedding, by switching or dimming.

Amrani Joutey et al. [2006] simulated summer demand response in French office buildings. They assumed an increase in the thermostat setpoint of 1 °C, and lighting reductions of 25%, and predicted demand reductions of 20-30%. Similarly, Kiliccote et al. [2006] simulated summer afternoon demand response in the new New York Times office tower. They assumed more aggressive parameters: overnight pre-cooling, an increase in the thermostat setpoint of up to 3.3 °C, and lighting reductions of 50% in the core and 70% at the perimeter. This reduced demand for electricity by around 45%. Rubinstein & Kiliccote [2007] estimate that the potential demand response from lighting in commercial buildings in California is at least 1 GW (a figure supported by ADM [2007]), although the actual number of luminaires currently installed with the necessary control gear is very small. However, Southern California Edison has recently conducted several demand response trials that might help stimulate market share growth [SCE, 2005a; SCE, 2005b; ADM, 2007].

However, by definition, the above demand response strategies create 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. Indeed, Kiliccote et al. [2006] stated that “Occupant comfort under these sequences is still not understood”, and SCE [2005b] and ADM [2007] noted potential problems when lighting was dimmed too aggressively. It would certainly be preferable if demand response strategies did not disrupt building occupants. Switching lighting will obviously be noticed by occupants, and may cause dissatisfaction [Boyce, 1984]. However, smooth changes in lighting characteristic of dimming systems may be much more acceptable. In this paper we summarize the literature with respect to smooth temporal changes in light level², and present new data to guide practitioners on the magnitude of lighting load sheds that may be applied without hardship to occupants of daylit and non-daylit offices.

1.2 Detection of Temporal Changes in Light Level

Detection of temporal changes at relatively high frequencies has featured in vision research for several decades. Much of this research was aimed at finding the frequency of output fluctuation of fluorescent lighting that would not be perceived as flicker. For

¹ In practice, there are challenges [Piette et. al, 2005].

² A more detailed description of many of these sources is available in Newsham & Mancini [2006].

example, in Kelly [1961] participants looked through an artificial pupil into a wide, almost uniform light field. The luminance was varied sinusoidally above and below a base adaptation luminance. Kelly's data show a tendency towards frequency insensitivity below 1.6 Hz, and suggest the limit of detection at very low frequencies (equivalent to a unidirectional ramp) to be about a 15% reduction in light level.

Several studies have explored sensitivity to temporal changes in light level under conditions more characteristic of demand response. A series of studies in a small, windowless office laboratory at the Lighting Research Centre culminated in that of Akashi & Neches [2005]. In one study, initial desktop illuminance was 500 lx and illuminance was decreased linearly by 16% to 96% over 10 seconds³; no-change trials were also included. Participants (N=20) conducted word puzzles on paper or computer screen at two font sizes (6- or 12-point font). At the completion of each 10-second exposure participants were asked to indicate if they had perceived a change in illuminance. A second study (N=26) followed the same basic procedure, except that initial desktop illuminance was 300 lx. The results showed that 50% of participants detected a 15-25% change in light level. Participants were also asked if the change was acceptable. The results showed that 50% of participants found a reduction in light level of 55-80% to be acceptable, and that 80% of participants found a reduction in light level of 30-50% to be acceptable.

Shikakura et al. [2003], exposed participants in a windowless office laboratory to smooth lighting reductions from an initial desktop illuminance of 750 lx. The largest reduction presented was ~25%, and the reduction was carried out over periods of up to 16 seconds. In the initial experiment, participants (N=10) had no task to do during the lighting change, but in a second experiment participants conducted a paper-based task and an interview (N=14), and a computer-based task (N=9). With no task, 50% of participants detected an 8% change in light level, and there was no effect of dimming rate. Conducting a task reduced the sensitivity to changing light levels: 50% of participants detected a 20% change in light level when the change took 8 seconds.

In the above studies the participants were aware that the lighting level might change in the short term. This might not be the case in a real demand-response situation, and this prior expectation was removed in Newsham et al. [2006], in which two groups of participants (N=31 per group) completed various tasks and satisfaction questionnaires over a typical workday in a six-person office laboratory with little daylight. Participants in one group were exposed to constant indoor environment conditions: desktop illuminance ~ 500 lx. The second group received the same illuminance conditions in the morning but just after lunch the lights were dimmed at 2% of full output every minute, to a minimum desktop illuminance of ~ 200 lx. Results suggested that occupants did not detect this 60% reduction in light level, and that there was no overall net effect on mood, satisfaction, or task performance. A further group (N=30) had access to personal dimming control at all times during the day [Newsham & Mancini, 2006], and could

³ Earlier work had established that dimming rate from 3.33-120 seconds (Kryszczuk and Boyce [2002]), and dimming curve shape (Akashi & Neches [2004]), had no effect.

therefore override the experimenter-imposed dimming. In this experiment, the principal measure used was the point at which participants intervened. Results showed that 20% of participants intervened after a reduction in desktop illuminance of ~35% from their initial preferred level, and 50% of participants intervened after a reduction in desktop illuminance of ~50%. These studies suggest that the lack of expectation of slow dimming as part of a conventional workday substantially reduced sensitivity to lighting changes.

All of the above studies were conducted in spaces with little or no daylight⁴. One would expect that sensitivity to changes in electric lighting would be reduced in the presence of daylight [SCE, 2005b], simply because the same change in electric lighting would represent a smaller change in total light level. Most office buildings are occupied during the day, and perimeter workstations receive substantial daylight contributions. Therefore, it may be of practical significance to know the effect of daylight in choosing demand response scenarios likely to be acceptable to occupants. The experiment described in this paper contributes new knowledge in this area by quantifying the daylight effect.

2. Methods and Procedures

2.1 Office design and ambient conditions

The experiment took place in a dedicated daylighting laboratory located in Ottawa, Canada (45° N and 76° W), and was conducted in the period 19th February – 23rd March, 2007. The laboratory (see Figure 1) featured two identical private offices, and a control room where a researcher monitored the data collection system. The façade faced SSE (22° from true South). Both offices had identical double-glazed windows of conventional clear glass with a low-e coating, overall transmittance ~80%. The window covered 64% of the area of the exterior wall (window 2.3 wide x 1.8 m high, and ranging from 1 m from the floor, up to the ceiling). The experiment was conducted after 2 pm when the sun's position was lower and further west, this ensured that direct sunlight did not reach the participant during daylight trials, and therefore confounding shading for glare control was unnecessary. An opaque roller blind was used to create the non-daylit condition (see Figure 1b); in this condition the daylight contribution to desktop illuminance was <10 lx.

Both offices were furnished as shared offices for two occupants, with desks arranged perpendicular to the window, and the main viewing direction at 45° to the window (Figure 2). Each desk had a computer and flat 15" LCD monitor (screen luminance ~140 cd/m², measured on a white screen with blinds down and no electric lighting). Table 1 summarizes the materials and reflectances of the furnishings. Temperature and ventilation was regulated to typical levels by the general building HVAC system. Participants occupied the desk on the west side of each room (see Figure 2). This enabled the participation of two participants at the same time under the same conditions.

The electric lighting system consisted of four 1x4-foot “paracube”-louvered luminaries operated on electronic dimming ballasts by a custom lighting control system. The lamps

⁴ Tenner et al. [1997] dimmed electric lighting by 8% every 3 minutes, and measured at what point occupants with personal controls intervened. This was done in spaces with and without daylight. However, data for only four participants in each setting is presented, and therefore general conclusions cannot be drawn.

were 3500 K, 80 CRI T8 fluorescents. The lighting conditions in the two rooms were always identical to within 3%. The maximum desktop illuminance contribution from electric lighting was ~650 lx, and the minimum was ~100 lx.

2.2 Photometric and Energy Measurements

Illuminance at multiple locations (see Figure 2 for the location of the sensors), and interior temperature were recorded every second during each trial.

2.3 Participants and Tasks

Thirty-nine participants (20 male, 19 female) were recruited from a temporary employment agency. Two participants of the same sex were scheduled to attend the laboratory on each testing day, although on 7 days only one participant attended. The recruitment criteria required that the participants were between 18 to 55 years of age and had normal or corrected-to-normal vision.

During the experiment the participants performed a computer-based proofreading task. The task consisted of reading a short article (18-23 lines) on screen, which was also presented on paper on a document holder next to the screen, and identifying single-character typographical errors. There were six errors in each article, on six different lines. Participants were informed that they would be asked to complete a questionnaire regarding the content of the articles at the end of the testing session. The primary purpose of this task was to keep the participants' attention on representative office work, rather than looking directly at the light sources. Nevertheless, two aspects of performance were scored: a) how many errors were correctly identified; and, b) accuracy of recall of the information in the articles.

2.4 Procedure

The experimental session started in Room A between 2:00 and 2:30 pm. The initial instructions, including the signing of a consent form, and a demonstration of an example trial occurred in this space. Participants were told that during such trials "the light level in the room may or may not change". The participants then were seated in their randomly assigned room (A or B). Due to the design of the control system, if there was a single participant, they occupied Room B. Data collection began around 2:45 pm, and lasted for about an hour.

All participants were exposed to 42 trials, 30 in the daylit condition, followed by blind closure, and then 12 trials in the non-daylit condition. The design of each trial was modeled on the protocol used by Akashi & Neches [2005]. Each trial began with the electric lights raised to full output for 10 seconds, this was designed to prevent direct comparison between the lighting conditions at the end of one trial and the beginning of the next. The electric light level was reduced to the design baseline level of 400 lx desktop illuminance for 20 seconds, during this period the proofreading article appeared on screen. This was followed by one of six dimming regimes. The first possibility was a no-change regime (0% dimming). In four other regimes nominal unidirectional dimming of 20%, 40%, 60%, or 80% from baseline occurred, in all cases dimming was linear over 10 seconds (a time period typical of the most rapid demand response sought by utilities),

the lower level was maintained for the remainder of the trial. The sixth regime was a “sawtooth” dimming pattern, in which the electric lighting was dimmed down by 20% over 10 seconds, and back up over 10 seconds, a cycle which was then repeated. In all cases, the proofreading task remained on screen for 40 seconds after the dimming began. The participant was then asked the following questions on screen: a) did you notice a change in the lighting level during the last minute? and, b) were the lighting conditions during the last minute acceptable? When both participants had completed the questions, the next trial began. Figure 3 shows the timeline of a trial graphically. Participants repeated each of the six regimes five times in the daylit condition, and two times in the non-daylit condition; the trials were presented in randomized order within each daylit/non-daylit condition. The extra repetitions in the daylit condition were designed to address the variability introduced by the natural changes in daylight.

At the end of the day the participants completed a short questionnaire on paper, which included the questions on the content of the articles they read during testing, and an opportunity to provide any comments on their participation in the study.

Figure 1. The daylighting laboratory. (a) shows the set-up for a daylit condition, and (b) for a non-daylit condition. Note that the photograph of the daylit condition was taken three hours before the experimental trials began; during the trials direct sunlight did not reach the occupant’s location.

Table 1. Room surface materials and reflectances

	Material	Colour	Reflectance
Desk Top	Formica	Medium grey	0.54
Chair Fabric	Fabric	Royal blue	0.38
Wall	Vinyl	Mid grey	0.38
Carpet	Nylon	Black-grey pattern	0.10 – 0.16
Ceiling	Acoustic tile	White	0.89

Figure 3. Timeline of the experimental trials, showing the electric lighting levels, and participant tasks.

3. Results

3.1 Analysis Strategy

For the unidirectional dimming patterns, the general experimental design was 5 (dimming levels) x 2 (daylight condition) within-subjects. Separate ANOVAs were conducted for the outcome variables lighting change noticed, and lighting conditions acceptable. Each outcome variable was the mean response to multiple repetitions of a particular condition. For example, a participant was exposed to the 60% electric light reduction in the presence of daylight five times, if he/she said they noticed a change in light level during three of the trials, the outcome variable was 0.6. Each analysis looked at specific contrasts on the dimming level variable for each daylight condition, specified *a priori*: the response at each dimming level compared to the no-change regime. This identifies the dimming level at which the outcome variable changed significantly compared to constant electric lighting.

In addition, we compared 20% unidirectional dimming to the 20% sawtooth. In this case the experimental design was 2 (dimming types) x 2 (daylight condition) within-subjects.

In a subsequent analysis we tested whether the effect of daylight differed depending on the amount of illuminance from daylight. We calculated desktop illuminance from daylight prevailing during the practice trial⁵ as an indicator of general daylight levels on that day. We then conducted a median split on the sample, based on this measure (median = 1343 lx) to create two groups labelled LD=below median prevailing daylight; and, HD=above median prevailing daylight. This was used in a new series of ANOVAs on the trials with daylight, with the designs: 5 (dimming levels) within-subjects x 2 (daylight level) between-subjects; and, 2 (dimming types) within-subjects x 2 (daylight level) between-subjects.

Although task performance was scored, it was not a variable of primary interest. An initial descriptive analysis suggested no differences between experimental conditions, and no further explorations were conducted.

3.2 Data Cleaning

We examined the variation of the external light level, measured every second on the vertical exterior wall of the laboratory, during a single trial. If this variation was greater than 20% for the majority of the 30 daylight trials, then all data for that day were removed from the sample, because of the elevated risk of false-positives (those reporting a change in lighting when there was no change in electric lighting). Data for three days (six participants) were removed, leaving a final sample of 33.

3.3 Photometric Conditions

Data collection during the actual trials allowed us to check if the illuminances and dimming regimes were realised at the nominal design levels. Table 2 shows that the mean baseline illuminance, and the mean dimming levels across all trials, were a little lower than their design nominal values. The very low standard deviations indicate that

⁵ Note that daylight level, on average, fell after the practice trial, as the afternoon progressed.

the actual electric lighting conditions were very similar in trials with the same nominal conditions.

Table 2. Design nominal values of baseline desktop illuminance from electric light and dimming levels, and the actual values achieved across all trials.

	Design Nominal Value	Actual Mean Value (s.d.)
Baseline Illuminance	400 lx	385 lx (7)
Dimming level	20 %	17.6 % (0.45)
	40 %	36.3 % (0.39)
	60 %	57.4 % (0.66)
	80 %	76.7 % (0.56)

The daylight contribution to desktop illuminance is shown in Figure 4. These data are based on the mean daylight contribution during a single daylit trial, thus providing 30 data points for each participant. Figure 4 shows, for each participant, the mean of these 30 values, as well as the minimum and maximum value. The grand mean over all participants was 898 lx (s.d. = 389; median = 926). Only two participants commented that they found the daylit condition uncomfortably bright, suggesting that the methods we used to limit glare were successful.

Figure 4. Mean, maximum and minimum total desktop illuminance across all measurement times, for each of the 33 participants.

3.4 Daylit vs. Non-daylit Condition

Table 3 shows the result of the analysis for the unidirectional dimming regimes, with whether the lighting changes were noticed as the outcome variable. There were no significant effects on this outcome in the analysis of 20% unidirectional vs. sawtooth dimming. Table 4 shows the result of the analysis for the unidirectional dimming regimes, with whether the lighting conditions were acceptable as the outcome variable.

Table 5 shows the result of the analysis for the unidirectional vs. sawtooth dimming, with whether the lighting conditions were acceptable as the outcome variable.

Table 3. Results of the overall ANOVA and contrasts, for daylight condition and nominal dimming level, on lighting change noticed, empty cells indicate non-significant tests.

Effect	Contrast	Statistical test	η^2_{partial}
Dimming level		$F_{4,128} = 56.01^{***}$	.64
Daylight condition		$F_{1,32} = 23.79^{***}$	.43
Dimming level x Daylight condition		$F_{4,128} = 9.69^{***}$	.23
Dimming level (non-daylit)	17.6% vs. 0%		
	36.3% vs. 0%	$F_{1,32} = 11.15^{**}$	.26
	57.4% vs. 0%	$F_{1,32} = 81.26^{***}$	.72
	76.7% vs. 0%	$F_{1,32} = 118.6^{***}$	.79
Dimming level (daylit)	17.6% vs. 0%		
	36.3% vs. 0%	$F_{1,32} = 4.24^*$	.12
	57.4% vs. 0%	$F_{1,32} = 14.17^{**}$	.31
	76.7% vs. 0%	$F_{1,32} = 23.64^{***}$	.43

* = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$

Table 4. Results of the overall ANOVA and contrasts, for daylight condition and nominal dimming level, on light conditions acceptable, empty cells indicate non-significant tests.

Effect	Contrast	Statistical test	η^2_{partial}
Dimming level		$F_{4,128} = 31.38^{***}$	.50
Daylight condition		$F_{1,32} = 24.86^{***}$	.44
Dimming level x Daylight condition		$F_{4,128} = 10.73^{***}$	.25
Dimming level (non-daylit)	17.6% vs. 0%		
	36.3% vs. 0%		
	57.4% vs. 0%	$F_{1,32} = 17.73^{***}$	.36
	76.7% vs. 0%	$F_{1,32} = 57.76^{***}$	.64
Dimming level (daylit)	17.6% vs. 0%		
	36.3% vs. 0%		
	57.4% vs. 0%	$F_{1,32} = 7.03^*$	.18
	76.7% vs. 0%	$F_{1,32} = 6.26^*$	.16

* = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$

Table 5. Results of the overall ANOVA and contrasts, for daylight condition and dimming type, on light conditions acceptable, empty cells indicate non-significant tests.

Effect	Contrast	Statistical test	η^2_{partial}
Dimming type			
Daylight condition			
Dimming type x Daylight condition		$F_{4,128} = 5.95^*$	.16
Dimming type (non-daylit)	unidirectional vs. sawtooth (17.6% dim)	$F_{1,32} = 4.41^*$	.12
Dimming type (daylit)	unidirectional vs. sawtooth (17.6% dim)	$F_{1,32} = 4.62^*$	.13

* = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$

3.5 High vs. Low Daylight Condition

Table 6 shows the result of the analysis for the unidirectional dimming regimes, with whether the lighting changes were noticed as the outcome variable. There were no significant effects on this outcome in the analysis of 20% unidirectional vs. sawtooth dimming. Table 7 shows the result of the analysis for the unidirectional dimming regimes, with whether the lighting conditions were acceptable as the outcome variable. Table 8 shows the result of the analysis for the unidirectional vs. sawtooth dimming, with whether the lighting conditions were acceptable as the outcome variable.

The trends tested in Tables 3 and 6 are shown graphically in Figure 5, the trends tested in Tables 4 and 7 are shown graphically in Figure 6, the trends tested in Tables 6 and 8 are shown graphically in Figure 7. The Figures combine results for conciseness, but remember that the non-daylit curve was drawn from the whole sample, whereas the two daylight conditions are from the median split samples. Figures 5 and 6 also show comparison data from other similar studies.

Table 6. Results of the overall ANOVA and contrasts, for daylight level and nominal dimming level, on lighting change noticed, empty cells indicate non-significant tests.

Effect	Contrast	Statistical test	η^2_{partial}
Dimming level		$F_{4,124} = 12.47^{***}$	.29
Daylight level			
Dimming level x Daylight level			
Dimming level (low-daylight)	17.6% vs. 0%		
	36.3% vs. 0%		
	57.4% vs. 0%	$F_{1,16} = 10.07^{**}$	.39
	76.7% vs. 0%	$F_{1,16} = 20.59^{***}$	.56
Dimming level (high-daylight)	17.6% vs. 0%		
	36.3% vs. 0%		
	57.4% vs. 0%		
	76.7% vs. 0%	$F_{1,15} = 6.04^*$	.29

* = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$

Table 7. Results of the overall ANOVA and contrasts, for daylight level and nominal dimming level, on lighting conditions acceptable, empty cells indicate non-significant tests.

Effect	Contrast	Statistical test	η^2_{partial}
Dimming level		$F_{4,124} = 6.14^{***}$	.17
Daylight level			
Dimming level x Daylight level		$F_{4,124} = 6.55^{***}$	.17
Dimming level (low-daylight)	17.6% vs. 0%		
	36.3% vs. 0%	$F_{1,16} = 6.94^*$	.30
	57.4% vs. 0%	$F_{1,16} = 11.52^{**}$	.42
	76.7% vs. 0%	$F_{1,16} = 13.02^{**}$	.45
Dimming level (high-daylight)	17.6% vs. 0%		
	36.3% vs. 0%		
	57.4% vs. 0%		
	76.7% vs. 0%		

* = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$

Table 8. Results of the overall ANOVA and contrasts, for daylight level and dimming type, on light conditions acceptable, empty cells indicate non-significant tests.

Effect	Contrast	Statistical test	η^2_{partial}
Dimming type		$F_{1,31} = 4.72^*$	.13
Daylight level			
Dimming type x Daylight level			
Dimming type (low-daylight)	unidirectional vs. sawtooth (17.6% dim)		
Dimming type (high-daylight)	unidirectional vs. sawtooth (17.6% dim)	$F_{1,32} = 4.62^*$	.13

* = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$

LD	.71 (.26)	.56 (.28)	.38 (.28)	.29 (.25)	.25 (.26)
HD	.55 (.38)	.53 (.35)	.45 (.37)	.36 (.37)	.36 (.28)
ND	.98 (.09)	.89 (.21)	.55 (.42)	.29 (.35)	.27 (.38)

Figure 5. Mean fraction of occasions that a change in lighting was noticed, by size of reduction from baseline, and amount of prevailing daylight. ND=non-daylit; LD=below median prevailing daylight; HD=above median prevailing daylight. Open symbols indicate fractions that did not differ significantly from the no-change case (0% reduction) for that daylight condition, whereas closed symbols indicate a significant difference. The table shows the mean (s.d.) of the outcome for each point on the graph. For comparison, the closest equivalent data has been transcribed from graphs presented in Akashi & Neches [2005] (non-biased sample, VDT task, 12 point font, for baseline illuminance 300 and 500 lx) and Shikakura et al. [2003] (VDT task, 8 second dimming, for baseline illuminance 750 lx).

LD	.56 (.39)	.66 (.33)	.78 (.27)	.89 (.14)	.92 (.17)
HD	.89 (.22)	.84 (.26)	.83 (.28)	.89 (.23)	.85 (.25)
ND	.21 (.33)	.48 (.38)	.76 (.36)	.80 (.33)	.79 (.35)

Figure 6. Mean fraction of occasions that lighting conditions were acceptable, by size of electric light reduction from baseline, and amount of prevailing daylight. ND=non-daylit; LD=below median prevailing daylight; HD=above median prevailing daylight. Open symbols indicate fractions that did not differ significantly from the no-change case (0% reduction) for that daylight condition. The table shows the mean (s.d.) of the outcome for each point on the graph. For comparison, the closest equivalent data has been transcribed from graphs presented in Akashi & Neches [2005] (non-biased sample, VDT task, 12 point font, for baseline illuminance 300 and 500 lx).

Figure 7. Mean fraction of occasions that lighting conditions were acceptable, by dimming type, and amount of prevailing daylight. ND=non-daylit; LD=below median prevailing daylight; HD=above median prevailing daylight. The table shows the mean (s.d.) of the outcome for each point on the graph.

3.6 Change in Total Desktop Illuminance

So far we have presented the data in terms of change in electric light contribution to desktop illuminance. Of course, in the daylit condition, the change in total desktop illuminance will be a function of the change in electric lighting, the baseline electric light level, and the prevailing daylight contribution to desktop illuminance. Therefore, we have replotted the outcome data from Figures 5 and 6, with change in total desktop illuminance on the x-axis; this is shown in Figures 8 and 9. Table 9 shows the mean (and s.d.) for change in total desktop illuminance, for both the low and high daylight conditions.

Table 9. Change in total desktop illuminance, for both the high and low daylight conditions, relative to the nominal change in electric light level.

Design Nominal Change in Electric Light Level	Mean (s.d.) Change in Total Light Level for LD group	Mean (s.d.) Change in Total Light Level for HD group
20 %	7.0 % (1.3)	4.4 % (0.4)
40 %	14.8 % (2.5)	9.2 % (0.9)
60 %	23.1 % (4.0)	14.7 % (1.5)
80 %	30.8 % (5.5)	19.6 % (2.0)

Figure 8. Mean fraction of occasions that a change in lighting was noticed, by size of reduction in total desktop illuminance, and amount of prevailing daylight. ND=non-daylit; LD=below median prevailing daylight; HD=above median prevailing daylight. Open symbols indicate fractions that did not differ significantly from the no-change case (0% reduction) for that daylight condition.

Figure 9. Mean fraction of occasions that lighting conditions were acceptable, by size of reduction in total desktop illuminance, and amount of prevailing daylight. ND=non-daylit; LD=below median prevailing daylight; HD=above median prevailing daylight. Open symbols indicate fractions that did not differ significantly from the no-change case (0% reduction) for that daylight condition.

4. Discussion

This study was conducted in a space with a specific geometry and lighting design that might not be representative of all office types. Nevertheless, overall our results conform with expected trends: sensitivity to electric light reduction increases as the size of the reduction increases, and decreases as the amount of prevailing daylight increases. Further, for any given electric lighting reduction, the lighting was acceptable more often than the change was not noticed. Our data from the non-daylit case may be compared to those of Akashi & Neches [2005] and Shikakura et al. [2003], as shown in Figures 5 and 6. The results are quite similar, although the fraction of occasions a change was noticed in our study was lower, for changes in electric lighting $> 20\%$. On the other hand, the number of false-positives in our study was markedly higher. In our study, false-positives were reported in 27% of trials, in the other studies, for similar conditions, the rate of false positives was 10% or less. Only for paper-based tasks in small font did Akashi & Neches' false positive rate approach 25%. We suggest two possible explanations for the above differences. First, Akashi & Neches' [2005] noticing question was worded differently, referring to "whether illuminance ... was higher, lower, or identical to the initial illuminance level". Similarly, Shikakura et al. [2003] asked participants to "evaluate[d] the lighting change using three alternatives of 'changed', 'unchanged', or 'cannot determine'." These different wordings might have been interpreted differently compared to our question. Second, in our non-daylit case, the opaque blind did allow some daylight to leak around the edges, as shown in Figure 1b. Even though the effect on desktop illuminance was very small (< 10 lx), luminance changes near the window might have been more perceptible. We asked participants "did you notice a change in the lighting level during the last minute?", this question was not specific to electric lighting, and changes in luminance at the blind edges might have led people to answer 'yes' to this question even when electric lighting did not change. For this reason, we did expect false-positives in our daylit condition to be higher than in our non-daylit condition, and this trend is apparent for the high-daylight case in Figure 5.

Figure 6 shows that the fraction of participants accepting a given, non-daylit, lighting condition was generally higher for Akashi & Neches [2005] than for our experiment. The curve shapes are very similar, and the difference in mean data appears to be a vertical offset. Again, a likely explanation is a difference in the wording of the acceptability questions. We asked if the lighting conditions were acceptable, whereas Akashi & Neches [2005] asked "whether the illuminance change was acceptable". Thus, even when the lighting was constant, the lighting was considered acceptable in our study in only 79% of trials, which is not unusual for a non-daylit North American office with this type of lighting [Boyce et al. 2006]. For Akashi & Neches, the acceptability of a change, when no change had happened, was, unsurprisingly, very high ($>95\%$).

Akashi & Neches [2005] suggested limits for demand response dimming based on absolute fractions of participants noticing/accepting a change. Rather than referring to absolute targets, we have based our limits on the dimming levels that are not significantly different in terms of noticing/accepting than the case with no dimming. An absolute target might seem more straightforward, but it has its problems. First, one must define an

appropriate target. Often 50% of people noticing is used as a threshold, however, we would suggest that, at least for initial demand response, 50% represents an inappropriate level of disruption to occupants. How about 20% of people noticing? In our data, more than 20% of people said they noticed a change in the non-daylit situation even when there was no change, so that is clearly inappropriate too. Overall, our approach, in referencing results to the no-change case, should represent the greatest reduction possible with the least risk to occupant comfort.

We propose that the data on fraction noticing and the fraction accepting may be used to define two stages of demand response, depending on the level of grid stress. The level of prevailing daylight, which may imply different zones in the same building, or the same zone in a building at different sky conditions, can then be used to modify the proposed dimming level. The first level of response should be dimming by amounts that are not even noticed by occupants: 20% with no daylight, which may be increased to 40% with low prevailing daylight, and 60% with high prevailing daylight. In our study, we defined low daylight as less than 1343 lx on the desktop due to daylight at mid-afternoon, in cases with substantially lower, but non-zero daylight, it might be prudent to interpolate our data and choose 30% dimming as a limit. The second level of response, when more dimming is required, should involve dimming by amounts that may lead to light levels noticeably lower, but are still acceptable: 40% with no or low daylight, and 80% with high prevailing daylight. These suggestions could be incorporated into guidelines for building operators by utilities and other entities seeking to promote demand response.

These reductions are somewhat less aggressive than those modelled by Kiliccote et al. [2006]. However, in the present study dimming was enacted over 10 seconds and participants were well aware that lighting levels might change in the short-term. The work of Newsham et al. [2006] and Newsham & Mancini [2006] suggest that dimming enacted over longer periods, and with no immediate expectation of light level reductions, could increase the level of dimming not noticed by building occupants in non-daylit settings. Alternatively, providing an expectation of light level reductions along with an explanation (to which the building occupants are sympathetic) of why it is necessary might increase the magnitude of reduction tolerated.

When the reduction in electric lighting is expressed in terms of the change in total light level (Figure 8), it appears that people are more sensitive to a given percentage change in lighting at higher light levels. In our study, a 20% reduction in total light level in the non-daylit case required a 20% reduction in electric light level, whereas a 20% reduction in total light level in the high-daylit case required an 80% reduction in electric light level. Electric light was delivered from overhead, whereas daylight came from the side, and the colour-temperature of the two sources were different. These differences might have contributed to the effect seen in Figure 8. It is interesting to note in Figure 8 that the change in total light level that differed significantly in noticability compared to the no-change case was about 20% for all three daylight conditions. It might be possible to use this as a general guideline for all situations.

The sawtooth dimming pattern might have application where dimming ballasts are used on the demand side to help maintain grid supply frequency at exactly 60 Hz in response to grid-wide load variation [Pearson, 2006], or to offset variability in supply from renewable generators such as wind [Blackwell, 2006]. In such cases it might be necessary for light levels to increase as well as decrease over short time scales, and we tested whether a sawtooth change of 17.6% in electric light would be more noticed/accepted than a unidirectional change of the same magnitude. There was no effect of this dimming type difference on the change being noticed, but there was a statistically significant effect on the acceptability of the lighting conditions, as shown in Figure 7. There was an interaction with daylight condition, the sawtooth was more accepted with no daylight, but less accepted with daylight present. However, these effects are small in practical terms, suggesting that very low frequency cyclic changes of this magnitude may be utilized. In addition, we tested a single sawtooth regime, others may apply in various practical situations, and there is certainly scope to explore such effects further.

5. Conclusions

The results of this study support the idea that dimmable office lighting can make a substantial contribution to demand response without great inconvenience to occupants. In this study, lights were dimmed smoothly over 10 seconds, both with and without daylight. Our results suggest two stages of demand response, depending on the level of grid stress:

- Level 1, dimming electric lighting by amounts not noticed by occupants:
 - o 20% with no daylight
 - o 40% with low prevailing daylight (defined in this study as <1343 lx on the desktop due to daylight at mid-afternoon)
 - o 60% with high prevailing daylight
 - o or, an amount which represents 20% of total light level
- Level 2, dimming by amounts that may lead to light levels noticeably lower, but are still acceptable:
 - o 40% with no or low daylight
 - o 80% with high prevailing daylight

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