NRC Publications Archive
Archives des publications du CNRC

# Individual control of electric lighting in a daylit space

Newsham, G. R.; Aries, M.; Mancini, S.; Faye, G.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.
For the publisher's version, please access the DOI link below./ Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

**Publisher's version / Version de l'éditeur:**
https://doi.org/10.1177/1477153507081560
*Lighting Research & Technology, 40, 1, pp. 25-41, 2008-03-01*

**NRC Publications Record / Notice d'Archives des publications de CNRC:**
https://nrc-publications.canada.ca/eng/view/object/?id=c8afafb3-df25-49f0-bebe-3d9063391f16
https://publications-cnrc.canada.ca/fra/voir/objet/?id=c8afafb3-df25-49f0-bebe-3d9063391f16

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

**Questions?** Contact the NRC Publications Archive team at
PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

**Vous avez des questions?** Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research Council Canada
Conseil national de recherches Canada

# Individual control of electric lighting in a daylit space

NRCC-49453

Newsham, G.R., Aries, M., Mancini, S., Faye, G.

2008-03-01

A version of this document is published in / Une version de ce document se trouve dans:

*Lighting Research & Technology*, 40, (1), pp. 25-41, March 01, 2008

# Individual Control of Electric Lighting in a Daylit Space

G.R. Newsham, M.B.C. Aries, S. Mancini, and G. Faye
National Research Council Institute for Research in Construction
1200 Montreal Rd., Ottawa, Ontario, K1A 0R6, Canada
guy.newsham@nrc-cnrc.gc.ca

## 1 Abstract

Participants (N=40) occupied a glare-free, daylit office laboratory for one day, and were prompted every 30 minutes to use dimming control over electric lighting to choose their preferred light level. Illuminances and luminances were recorded before and after each control opportunity; luminance maps were generated using a calibrated, high-dynamic range digital camera. Although there was a wide variation in chosen light levels between individuals, results showed a significant negative correlation between prevailing desktop illuminance and change in dimmer setting. This indicates that, from the perspective of occupants, daylight does displace electric lighting. Surprisingly, we did not find any luminance-based measure that was as good a predictor of participant dimmer choice as illuminance measured on the desktop. On average, manual dimming control in this situation reduced energy use for lighting by 25% compared to a fixed system delivering 500 lx of electric lighting on the desktop.

## 2 Introduction

Surveys consistently indicate that building occupants both desire more control over their environment, and believe that such control is linked to important health, comfort, and performance outcomes[1-3]. Specific studies of personal control over lighting have consistently demonstrated benefits for building occupants, and energy savings, as detailed below.

### *2.1 Laboratory Studies: with little or no daylight*

Veitch and Newsham[4] conducted a study in an open-plan office laboratory in Canada. Participants had dimming control over three ambient lighting circuits, and on-off control over a task light. Forty-seven matched pairs of participants spent a day completing various simulated office tasks and questionnaires. One of the pair got lighting control at the start of the day, with the other participant receiving the same lighting; no further control was permitted. At the end of the day the second participant used the dimmers to express their own preferred lighting conditions. Individual preferred light levels varied widely[†] (mean desktop illuminance 423 lx, s.d. 152 lx, min. 83 lx, max 725 lx), but on average required 10-15% less power than prevailing energy code recommendations[5]. Newsham and Veitch[6] performed further *post-hoc* analyses on the data from the second participant in each pair. Participants whose daytime light levels were closest to their own preference had significantly better ratings of mood (pleasure), lighting satisfaction, and environmental satisfaction during the day. Newsham et al.[7] conducted a further study in an open-plan office laboratory in Canada, and found lighting

---

[†] Observing large differences between individuals is common to most studies referenced here, but will not be repeated in every study description for succinctness.

control associated with significant improvements in mood, satisfaction, self-assessed productivity, and comfort.

Boyce et al.[8] conducted a study in an office laboratory in the northeastern USA, featuring individual offices with three lighting designs: ceiling-recessed parabolic luminaires delivering 490 lx on the desktop; identical dimmable luminaires with a maximum of 680 lx on the desktop; and a larger number of luminaires with a maximum of 1240 lx on the desktop. For the lower output dimmable system, the mean chosen illuminance was about 10% lower than for the fixed system, translating into energy savings. Offices with control had higher ratings of lighting quality and comfort, and tasks were rated as less difficult.

In one of a pair of field simulation experiments, Boyce et al.[9,10] exposed over 180 people to one of four different lighting conditions for a day in an open-plan office in the northeastern USA. Two of the four conditions had some form of manual control. In one condition (N=33), occupants had three-level switching control over a desk lamp, with fixed ambient lighting. In another condition (N=56), occupants had dimming control over the down portion of a direct/indirect luminaire suspended over the middle of their workstation. For those with dimming control the mean desktop illuminance (435 lx, s.d. 171 lx, min. 243 lx, max 1075 lx) was lower than recommended practice, with concomitant energy savings. Individual control was also associated with improved comfort, and people with dimming control showed more sustained motivation over the workday, and improved performance on a measure of attention.

### *2.2 Laboratory Studies: with daylight*

Halonen and Lehtovaara[11] studied 20 participants during three hours in an office laboratory in Finland. Every 15 minutes participants had the possibility to adjust dimmable, ceiling-based luminaires. Measurements were made both with and without daylight. The mean chosen electric lighting level did not vary with daylight, it remained around 500 lx, even with daylight > 1000 lx.

Tenner et al.[12] conducted a study in a north-facing office in which participants (up to N=10, in the Netherlands) worked for at least two days. Participants had dimming control over ceiling-mounted prismatic luminaires and could use it at any time; 15 minutes after a setting was made the system dimmed by 8% every 3 minutes until the participant again intervened. Several maximum electric light levels were tried, but the lowest one, 830 lx, is closest to that of the other work referenced here. In that case, during Spring, when mean desktop illuminance from daylight was ~1050 lx, the mean chosen electric light contribution was ~550 lx. During Winter, when mean desktop illuminance from daylight was ~675 lx, the mean chosen electric light contribution was ~625 lx.

Begemann et al.[13] studied the dimming preferences of 170 participants occupying a north-facing office in the Netherlands for one day each. Ceiling-based prismatic luminaires allowed for desktop illuminance from electric lighting to be varied from 200 – 2000 lx; these lights were automatically switched off every hour to force a choice from the participants. On average, participants chose 800 lx of electric lighting over a wide variety of daylighting conditions. Nevertheless, people working near the back of the office chose average electric lighting levels 25% higher than those working nearer the window, where average daylight was about three times higher.

Laurentin et al.[14] used an east-facing office laboratory in France. Thirty participants worked at three identical, adjoining open-plan workstations arranged perpendicular to the window; they spent 30 minutes at each desk. Participants had dimming control over ceiling-mounted luminaires and a wall-washer, and could choose desktop illuminance from electric lighting in the range 0 – 1200 lx. There was a large difference in the mean daylight available between workstations: near window ~500 lx, middle of room ~250 lx, far from window ~100 lx. However, on average, there was little difference in the electric lighting chosen between workstations, the mean illuminance on the desktop from electric sources was 150-200 lx.

In Zinzi et al.[15], 30 participants occupied an office laboratory with electrochromic (EC) windows facing north and west. Participants could manually control the EC window transmission, a 50% transmission blind on the west window, and the output of ceiling-recessed parabolic luminaires. Data were gathered over a one-hour period in the afternoon. The mean desktop illuminance due to daylighting was 466 lx, and the mean illuminance added electrically was 113 lx.

### *2.3 Field Studies*

Maniccia et al.[16] collected data from 58 individual offices in a Colorado building, each with dimming control over recessed parabolic luminaires. Lighting energy savings between 7 and 23% were attributed to the manual controls.

Jennings et al.[17] focused on the perimeter offices of a large office building in San Francisco. Manual control over recessed parabolic luminaires was available in two forms: bi-level switching of a 3-lamp luminaire (N=30), or continuous dimming (N=7). Lighting energy savings of 23% and 9% were attributed to the two manual control options, respectively.

Moore et al.[18] studied the use of individual lighting controls in 14 UK office buildings with recessed parabolic luminaires, three of which offered dimming control to individuals. Data showed that mean chosen illuminance in winter, without daylight, was below 500 lx in all 3 buildings. The mean power use of the lighting systems was ~50-60% of the maximum available.

### *2.4 Summary and Research Hypotheses*

Studies in laboratories with little or no daylight are consistent in finding that personal dimming control results, on average, in lighting energy savings relative to a fixed systems designed to prevailing recommended practice. One might expect that adding daylight would lead an occupant to dim electric light levels further. This is supported by the reviewed field studies, and by some laboratory studies, but not all.

Several authors have reflected on this issue and the relationship to the design of automatic lighting control systems. Typical automatic daylight harvesting systems are designed to deliver a constant desktop illuminance throughout the day. However, several studies have shown that, given a free choice, people in daylit spaces do not use manual controls to maintain constant desktop illuminance. This has led to suggestions that occupant preferences are not driven by desktop illuminance, but by a desire to balance luminance or illuminance ratios[11], or by time-of-day effects[13].

Given this prior work, we designed an experiment in a daylit office laboratory in which occupants had manual dimming control over electric lighting to test the following hypotheses:

1. Occupants do not use manual controls to maintain a constant desktop illuminance.
2. There is a negative correlation between prevailing light levels and dimmer level choice; i.e., higher light levels prior to using a dimmer will predict a lowering of the dimmer level, and vice versa.
3. There are photometric variables that are better predictors of manual control actions than desktop illuminance.
4. Manual control of electric lighting in a daylit space leads to greater energy savings than in a space without daylight.

## 3 Methods and Procedures

### *3.1 Office design and ambient conditions*

The experiment took place in a dedicated daylighting laboratory located in Ottawa, Canada (45$^{o}$ N and 76$^{o}$ W). 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$^{o}$ 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). A Rosco neutral density filter, nominal transmittance 25%, was applied to the interior of the windows, to yield a total visual transmittance of approximately 20%. This transmittance was chosen so that the resulting sky luminance would be <2500 cd/m$^2$, a value that research suggests would result in only a small minority of occupants wanting to lower a window blind[19,20]. This was desirable because we did not want to confound lighting control and blind control in this experiment, and therefore blinds were removed from the rooms. To further ensure that blinds were not required the participant was seated towards the back of the room; the experiment was conducted in the period April 24 – July 6, 2006, when no direct sun reached the occupant[†].

For this experiment, each of the two offices was furnished as a shared office for two occupants, with desks arranged perpendicular to the window, and the main viewing direction at 45$^{o}$ 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 window covered and no electric lighting). Table 1 summarizes the materials and reflectances of the furnishings. The ventilation system delivered building air at ~22°C to each room at a rate of ~125 ls$^{-1}$.

The participant occupied the desk towards the back of Room A. Room B was identical to Room A, but with additional photometric measurement equipment (see Figure 2). This enabled detailed data about the lighting conditions at the participant’s seating location to be gathered at the same time that the participant experienced them.

The lighting system in each room consisted of four 300 x 1200 mm (1x4-foot) “paracube”-louvered luminaires operated on electronic dimming ballasts by a custom

---

[†] There were sunpatches nearer the windows, as shown in Figure 1.

lighting control system. The lamps were 3500 K, 80 CRI T8 fluorescents. The occupant could change the electric light level through a slider on their computer screen. The output from the luminaires was linear with slider position, and the lighting conditions in the two rooms were always identical to within 3%. The maximum desktop illuminance from electric lighting was 700 lx, and the minimum was 0 lx.

### *3.2 Photometric and Energy Measurements*

Illuminance, interior and exterior temperature and humidity conditions, and lighting and supplementary heating energy use, were recorded every 30 seconds.

The additional photometric equipment in Room B included a vertical illuminance sensor at the approximate location of the occupant's eyes, a Hagner luminance meter pointed to a reference point on the south wall, and a digital camera calibrated as a luminance camera (yielding pixel-by-pixel luminance measurements), also at the approximate location of the occupant's eyes. The digital camera (Canon EOS Digital Rebel XT 350D) was equipped with a wide-angle lens (EF-S 10-22mm f/3.5-4.5 USM) and was triggered from the central control computer. The ISO-number and aperture were set at 100 and F4.0 respectively, and four photos at different shutter speeds (1/2, 1/15, 1/30, and 1/60 second) were taken at each measurement time. Photosphere software[21] was used to create High Dynamic Range (HDR) images from the four photos. A calibration procedure conducted in the rooms demonstrated that the luminance values extracted from the HDR images were accurate[†] within 14% over a range of 1-1750 cd/m$^2$. The photos also provided information about the exterior sky conditions. Table 2 describes the photometric measures used later in this paper; Figure 3 shows a typical digital camera image showing areas for which mean luminance was calculated.

### *3.3 Participants and Tasks*

Participants were recruited from a temporary employment agency; one participant attended the laboratory on each testing day. There were 40 participants (20 male, 20 female), ranging in age from 18 to 59; all participants reported having normal or corrected-to-normal vision. Participants wore their own clothing, and were not given instructions on what to wear, except the general instruction that the day would be similar to normal office work.

During the day the participants performed computer- and paper-based office tasks. The tasks consisted of typing reports, and entering data into spreadsheets and databases. Each participant did similar work, but it was not standardized between participants. Performance on this work was not scored, but it ensured that participants spent the day in a typical office experience, particularly with regard to visual targets.

### *3.4 Procedure*

The experimental session started in a reception area between 8:30 and 9:00am. The initial instructions, including the signing of a consent form, and all breaks occurred in this space. The participants then proceeded to the laboratory, where they conducted the day's work as assigned by the researcher.

---

[†] In principle, more photos than four can produce more accurate luminances in static luminance fields, however, the extra time to take more photos allows for bigger changes in sky conditions, which would reduce accuracy.

Initially, the electric lighting was set at a level typical of recommended practice (dimmer setting 50%, mean ${}^{e}E_{desk}$ ~320 lx, mean ${}^{tot}E_{desk}$ ~500 lx). After the researcher explained the dimming control, the participant started working at the initial level. They were told that they could only change this level when invited to by the researcher, which occurred every 30 minutes, beginning at 9:15. The researcher took luminance photos in Room B just before and just after inviting the participant to choose their preferred dimming level. Breaks were scheduled from 10:20 – 10:35, and 14:20 – 14:35, in between invitations to use the dimmer and the associated measurements. Lunch was scheduled from 12:15 – 13:00, and there were no dimming choices and associated measurements at 12:15 and 12:45.

At the end of the day the participants completed a short questionnaire, which included items on how they used the controls, and on their satisfaction with various aspects of the indoor environment. We also collected demographic information, and information on light sensitivity[22], and chronotype[23], chosen because they might help predict lighting choices.

# 4 Results

## *4.1 Available Daylight*

Figure 4 shows data for the prevailing desktop illuminance due to daylight, ${}^{d}E_{desk}$. These data are from each of the 12 measurement times over all participants. The low transmission window ensured that daylight alone very rarely provided the typical recommended value of 500 lx, implying that electric lighting would often be used. Although this daylight level was low, it was glare-free without the use of shades, this was achieved in a somewhat artificial way because of the desire in the experimental design to avoid confounding lighting and shade control. Nevertheless, photometrically, the room may not be that different from a more conventional perimeter space with a diffusing blind lowered against glare[24].

## *4.2 Chosen Illuminance*

Figure 5a shows, mean, maximum and minimum ${}^{tot}E_{desk}$ across all 40 participants, at each measurement time during the day, after the participants had the opportunity to change the dimmer setting. There was a wide range of individual preferences for desktop illuminance at each time of day. Nevertheless, the overall mean ${}^{tot}E_{desk}$ was 551 lx (s.d. 227), close to typical recommended practice.

Figure 5b, which shows mean, maximum and minimum ${}^{tot}E_{desk}$ across all measurement times, for each of the 40 participants. The means are not clustered around the typical recommended practice level of 500 lx, or any other value. Further, there is great variation within individuals around their own mean, many participants chose illuminances that differed by more than 25-50% at various times of the day. For the range of available daylight shown in Figure 4, participants could have used electric lighting to maintain a constant level all day, but they did not. Given what we know about the sensitivity and adaptability of the visual system, this might not be surprising. For example, Newsham and Mancini[25] in a laboratory study in Canada found that only 20% of participants used controls to intervene when light levels were reduced by 35% from their preferred setting over a period of around 20 minutes. Newsham & Mancini's study was done in a space with little daylight, and the authors suggested that sensitivity to changes would be reduced further in daylit spaces. Nevertheless, it is important to note that participants in the current study did not exhibit complete inertia, in total, of the 480 opportunities to change the dimmer, changes were made on 295 occasions (145 increases, and 150 decreases).

### *4.3 Photometric Predictors of Dimmer Choices*

We used regression analysis to look at whether dimmer choices were influenced by aspects of the photometric environment. We had dimmer settings and a wide variety of photometric variables for 12 measurement times during the day. This gave 480 data points per regression (12 times x 40 participants); in fact, the data set was twice this size because we had data both before and after the occasions when participants were invited to use the controls. Each participant contributed multiple data points, therefore the points were not independent and simple regressions, though often used with this kind of data, are, strictly, inappropriate. The relatively new statistical technique of Hierarchical Linear Modelling (HLM, or mixed regression)[26,27] accounts for the within-subject effects in this kind of analysis, and was previously applied to lighting research by Newsham et al.[28]. Conceptually, HLM consists of creating separate regression lines for each participant, and then testing the distribution of regression weights (slopes and intercepts) against the null hypothesis that the average regression weight equals zero. The technique also produces a single best-fit regression line across all data points. In the terminology of HLM, dimmer choice was the outcome variable, photometric values were level-1 predictors (yielding an overall relationship between photometric values and dimmer choices), and characteristics of the participant were included as potential level-2 predictors (to investigate which characteristics might have led to differences in choices between participants).

We initially conducted a large set of simple linear regressions to identify candidate photometric predictors, which were then used in subsequent, more complex, HLM analyses. For the outcome variable, we focussed on change in dimmer setting at each measurement point[†]. For level-1 photometric predictors, we used values measured just before the participant was invited to use the controls. For illuminance-based predictors we tried ${}^{tot}E_{desk}$ and ${}^{d}E_{desk}$. In general, ${}^{tot}E_{desk}$ was the better predictor, suggesting that people are not sensitive to the source of light when determining the adequacy of the light level; in this manner they are more similar to closed-loop than open-loop automatic control systems. We also tried ${}^{tot}E_{ceil}$ as the closest analogue to a commercial photosensor location. Knowing that the eye responds to luminance, not illuminance, we were interested in testing whether luminance-based predictors would perform better than illuminance-based predictors. We tried many luminance-based measures: averages over certain areas (e.g. desk, window, wall) and ratios of these; percentage of pixels above/below certain thresholds; the luminance of the 2nd, 10th, 25th, 75th, 95th etc. percentile pixel, and their ratios; the final set of measures is described in Table 2. For level-2 predictors we tried gender, photophobia/philia, and ratings on the early-late scale. None of the level-2 predictors were significant, and so the final analyses were restricted to level-1 predictors.

---

[†] Absolute dimmer setting is obviously not appropriate for regression, consider desktop illuminance as a predictor, for example. Because of the high contribution of electric light to total light, there would be a high correlation between dimmer setting and light level even for random settings.

The results of the final HLM analyses are shown in Table 3. The intercept and slope values define the best-fit linear regression line through the data points. The proportion of variance explained is a measure of effect size; i.e., how much of the variance in the outcome variable is explained by the predictor. A value of zero indicates that the predictor has no correlation to the outcome, whereas a value of one indicates perfect correlation. Cohen[29] suggested the following guidelines for interpreting effect sizes: 0.01 is a small effect, 0.09 is a medium effect, and 0.25 is a large effect. As a benchmark, field studies of thermal comfort[30] typically find that the proportion of variance in individual thermal sensation votes explained by physical and demographic variables is around 0.10-0.15.

The relationship involving ${}^{tot}E_{desk}$ is shown in Figure 6, the solid line shows the best-fit line through the individual data points from the HLM analyses. On average, a higher illuminance just before participants were invited to use the dimmer resulted in a lower dimmer setting, and vice versa. But there was a lot of spread around the average line, and on 185 of 480 occasions there was no change in the dimmer setting no matter what the illuminance (indicated by the points on the x-axis). The way a perfect closed-loop photosensor would perform in this room is shown by the dashed line, assuming it was controlling to the mean illuminance chosen by participants (550 lx). The relationship involving the best luminance-based predictor, $I_{P75}$:$I_{P25}$, is shown in Figure 7.

A repeated-measures ANOVA showed a significant quadratic time-of-day effect on ${}^{tot}E_{desk}$ (multivariate: $F_{11,29}=4.12$, $p=0.001$, $\eta^2_{partial}=0.61$; quadratic: $F_{1,39}=35.5$, $p<0.001$, $\eta^2_{partial}=0.48$), but there was no significant effect on chosen electric light level, ${}^{e}E_{desk}$, indicating that the effect on total luminance was due to the natural variation in daylight, as shown in Figure 4b. A time-of-day effect on electric lighting preference had been suggested by Begemann et al.[13], but was later withdrawn in a re-analysis by Tops et al.[31].

### *4.4 Energy Use*

Figure 8 compares the energy use per 7-hr day of the lighting system in Room A for six scenarios, as described in Table 4. The "500 lx from Electric" is typical of recommended practice, and will be the basis of comparison for this analysis. The analysis shows that a perfect closed-loop photosensor, in this room and over this time period, would have reduced lighting energy use by 38% relative to typical practice, this is consistent with previous research on daylight harvesting systems[24,32,33]. On average, the individual control option saved 25%, though the range of individual preferences meant that some people used more lighting energy than typical practice. The "Actual Choice" option accounts for all dimmer changes, it would be reasonable to expect that in practice over the longer term, people would adjust light levels less frequently. The "Start of Day Choice" and "End of Day Choice" option reflect this, but Figure 8 shows that overall these options do not differ substantially from "Actual Choice" in terms of energy use.

### *4.5 Questionnaire Responses*

Given that participants had individual control of electric lighting, it is not surprising that satisfaction with light level was rated highly (scale 0 (very unsatisfactory) to 6 (very satisfactory), mean=4.95, s.d.=1.03). Satisfaction with glare was also high (mean=4.70, s.d.=1.45), only 10% of ratings were below the mid-point of the scale, which confirms that our efforts to control glare without window blinds were successful.

There was a specific open-ended question regarding drivers for electric lighting choices: “What was your strategy when using the lighting control? For example, were you trying to light a particular part of the room? Were you responding to changes in daylight?”. The responses to this question are summarized in Table 5, based on key words or phrases. Twenty-one people agreed with the specific prompt in the question that they responded to changes in daylight, but only four specifically indicated that they increased electric lighting as daylight decreased, and vice versa (the others did not indicate how daylight influenced them). The other reasons given cannot be related to energy use, but rather to comfort and visibility; only three participants indicated an underlying preference for different light levels at different times of the day.

## *5* Discussion

Given what we know about the sensitivity and adaptability of the visual system, it should not come as a surprise that many people do not maintain constant illuminance over time. And given previous research on preferred levels, it is not surprising that we observed a wide range of preferences between individuals. Nevertheless, typical automatic daylight harvesting systems are designed to maintain the same, constant illuminance for all – clearly this is not the environment that people choose for themselves. The dimmer and questionnaire data do show that participants were sensitive to the prevailing illuminance when choosing electric lighting levels. But in Figure 6 the slope of the solid black line is much lower than the slope of the dashed line, indicating that, on average, people are much less sensitive to changing illuminance than a closed-loop photosensor would be. An automatic controller that mimicked this aspect of the behaviour of people would have a much wider deadband. The energy implications of this would depend on the daylight conditions at the particular site: the system would not dim down as rapidly when the illuminance increased above the central setpoint, nor would it increase as rapidly when the illuminance fell below the setpoint. Complaints associated with daylight harvesting systems have been recorded[32,34], some of which have been associated with systems that change light level too frequently. A wider deadband derived from the kind of analysis conducted in this paper might ease some of these complaints. However, it would require an acceptance that the system would then allow light levels to fall below typically prescribed minimums. In this laboratory study we used the somewhat artificial protocol of prompting people to use the dimmer control every 30 minutes. One might expect that this would result in a greater sensitivity to lighting conditions than would be the case in a field setting. In a field study in Switzerland of a manually controlled lighting system with free control choice, Lindelöf and Morel[35] observed relative insensitivity to desktop illuminance over a range of ~ 200-2000 lx, suggesting that a wide deadband would be acceptable.

This experiment is part of a larger effort to explore the potential of a luminance-based lighting control system[36,37] to deliver a lit environment well-matched to occupant preference. None of the luminance-based measures we tried was a better predictor of control actions than ${}^{tot}E_{desk}$. This was surprising, although the design of the experimental space, which eliminated glare without shading, did suppress the range of possible luminances, and it is possible that this reduced the predictive power of luminance-based measures. Nevertheless, remember that ${}^{tot}E_{desk}$ was actually measured on the desktop in Room B, and therefore was not affected by the position of the participant or any of their work materials. In practice, this is not possible, and the photosensor is typically placed on the ceiling and a calibration to desktop illuminance is performed[†]. ${}^{tot}E_{ceil}$ was a substantially worse predictor than ${}^{tot}E_{desk}$ in our study. A commercial ceiling-based photosensor might perform better than ${}^{tot}E_{ceil}$ because it might have an angular response function and shielding better designed to correlate with desktop illuminance. We speculate that a commercial sensor would perform somewhere between ${}^{tot}E_{desk}$ and ${}^{tot}E_{ceil}$. It is also true that the position of the camera, from which luminance-based measures were derived, would not be practical in a real setting, a more likely location might be on the back wall, facing towards the occupant. Given these considerations, it is likely that there are practical luminance-based predictors that perform as well as a practical desktop illuminance predictor. $I_{P75}$:$I_{P25}$ was highly correlated with ${}^{tot}E_{desk}$ (r=0.77), however, $I_{desk}$ had an even higher correlation with ${}^{tot}E_{desk}$ (r=0.91), though it was not as good a predictor of control actions as $I_{P75}$:$I_{P25}$, suggesting that $I_{P75}$:$I_{P25}$ does represent useful information beyond that related to the desktop. We are continuing to develop a prototype system based on a low-cost CMOS (camera) detector, and to test its performance using control variables such as $I_{P75}$:$I_{P25}$.

Figure 8 showed that savings due to individual control were about one-third less than those calculated for a perfect closed-loop photosensor. However, individual control is likely cheaper to implement: there is no requirement for sensors, their calibration, or control logic, though there would be costs associated with providing the computer desktop interface. In a real setting, individual control would likely yield additional savings due to manual switch-off for unoccupied periods[38]. Further, individual control provides benefits for environmental satisfaction (and possibly other occupant benefits) as described in the Introduction, which cannot be delivered by automatic control systems. These considerations illustrate that simple energy savings alone should not be the only factor in determining the most effective lighting control system.

## 6 Conclusions and Implications for Practice

As with all research, the results of this study must be interpreted with due consideration for the context in which it was done. Nevertheless, our results do accord with those in other published studies, providing confidence in these conclusions. With reference to the specific hypotheses at the start of the paper:

1. *Occupants do not use manual controls to maintain a constant desktop illuminance.*
   This hypothesis was supported, desktop illuminance after each control opportunity varied widely both between individuals, and for a single individual over the day. This suggests that automatic controls designed to maintain constant illuminance are likely to be less desirable to occupants than manual control.

---

[†] Advances in wireless technology might allow illuminance sensors to be positioned closer to the desktop than is currently typical.

2. *There is a negative correlation between prevailing light levels and dimmer level choice.*
   This hypothesis was supported, but the slope of the best-fit regression line was not as steep as for a close-loop automatic controller. This implies that, from the perspective of the occupant, glare-free daylighting can displace electric lighting. This is good news for energy efficiency programs, and contradicts some prior research suggesting a preference for higher electric light levels in the presence of daylight.
3. *There are photometric variables that are better predictors of manual control actions than desktop illuminance.*
   This hypothesis was not supported, illuminance actually measured on the desktop was a better predictor than any of the many luminance-based predictors we tried. However, there may be practical, luminance-based predictors that are as good as practical, desktop illuminance sensors. A camera-based luminance detection system may also be used for occupancy detection and safety purposes, though there are serious privacy concerns to be addressed for such applications.
4. *Manual control of electric lighting in a daylit space leads to greater energy savings than in a space without daylight.*
   This hypothesis was supported, energy savings relative to a typical fixed system were 25% in this space, compared to around 10% for manual control in spaces without daylight. This further supports the assertion that occupants accept that daylighting displaces electric lighting. This finding also demonstrates that substantial energy savings are achievable with relatively simple manual control.

## 7 Acknowledgements

This work was financially supported by the Climate Change Plan for Canada, Technology and Innovation R&D Initiative, and the National Research Council. The authors would like to extend their thanks to Roger Marchand and Chantal Arsenault for their technical development of the experimental space, and to Tina Chen and Sophie Boissard for their work on a pilot study that helped to refine the experiment described in this paper. This work was part of a collaboration with Francis Rubinstein of Lawrence Berkeley National Laboratory, and we are also grateful to Steve Selkowitz for facilitating this collaboration. We have also collaborated with Jens Christoffersen of the Danish Building Research Institute in the development of this work. Finally, we are grateful for the continuing support of Morad Atif (NRC).

## 8 References

1 Steelcase. 1999. Office workers believe quality of lighting affects productivity and creativity. Steelcase Workplace Index Survey, 2 pages.

2 Bordass, W.; Bromley, K.; Leaman, A. 1993. User and Occupant Control in Buildings. Proceedings of the International Conference on Building Design, Technology and Occupant Well-Being in Temperate Climates, Brussels.

3 Roulet, C.-A.; Johner, N.; Foradini, F.; Bluyssen, P.; Cox, C.; Fernandes, E.; Muller, B.; Aizlewood, C. 2006. Perceived health and comfort in relation to energy use and building characteristics. Building Research & Information, 34 (5), 467-474.

4 Veitch, J.A.; Newsham, G.R. 2000. Preferred luminous conditions in open-plan offices: Research and practice recommendations. Lighting Research and Technology, 32, 199-212. URL: http://irc.nrc-cnrc.gc.ca/pubs/fulltext/nrcc43061/

5 Canadian Codes Centre. 1997. Model National Energy Code of Canada for Buildings. Ottawa, ON, Canada: National Research Council.

6 Newsham, G.R.; Veitch, J.A. 2001. Lighting quality recommendations for VDT offices: a new method of derivation. Lighting Research and Technology, 33 (2), 97-116. URL: http://irc.nrc-cnrc.gc.ca/pubs/fulltext/nrcc44481/

7 Newsham, G.; Veitch, J.; Arsenault, C.; Duval, C. 2004. Effect of dimming control on office worker satisfaction and performance. Proceedings of the IESNA Annual Conference (Tampa, USA), 19-41. URL: http://irc.nrc-cnrc.gc.ca/pubs/fulltext/nrcc47069/

8 Boyce, P.R.; Eklund, N.H.; Simpson, S.N. 2000. Individual Lighting Control: Task Performance, Mood, and Illuminance. Journal of the Illuminating Engineering Society, 29 (1), 131-142.

9 Boyce, P.R.; Veitch, J.A.; Newsham, G.R.; Jones, C.C.; Heerwagen, J.; Myer, M.; Hunter, C.M. 2006a. Lighting quality and office work: two field simulation experiments. Lighting Research and Technology, 38 (3), 191-223.

10 Boyce, P.R.; Veitch, J.A.; Newsham, G.R.; Jones, C.C.; Heerwagen, J.; Myer, M.; Hunter, C.M.. 2006b. Occupant use of switching and dimming controls in offices. Lighting Research and Technology, 38 (4), 358-378.

11 Halonen, L., Lehtovaara, J. 1995. Need of individual control to improve daylight utilization and user satisfaction in integrated lighting systems. Proceedings of the 23rd session of the CIE (New Delhi, India), 200-203.

12 Tenner, A.D.; Begemann, S.H.A.; van den Beld, G.J. 1997. Acceptance and preference of illuminances in offices, Proceedings Lux Europa (Amsterdam, the Netherlands).

13 Begemann, S. H. A.; van den Beld, G. J.; Tenner, A. D. 1997. Daylight, artificial light and people in an office environment, overview of visual and biological responses, International Journal of Industrial Ergonomics, 20 (3), 231-239.

14 Laurentin, C.; Berrutto, V.; Fontoynont, M.; Girault, P. 1998. Manual control of artificial lighting in a daylit space. Proceedings of the 3rd International Conference of Indoor Air Quality, Ventilation and Energy Conservation in Buildings (Lyon, France), 175-180.

15 Zinzi, M. 2006. Office worker preferences of electrochromic windows: a pilot study. Building and Environment, 41, 1262-1273.

16 Maniccia, D.; Rutledge, B.; Rea, M.S.; Morrow, W. 1999. Occupant Use of Manual Lighting Controls in Private Offices. Journal of the Illuminating Engineering Society, 28 (2), 42-56.

17 Jennings, J.D.; Rubinstein, F.M.; DiBartolomeo, D.; Blanc, S.L. 2000. Comparison of control options in private offices in an advanced lighting controls testbed. Journal of the Illuminating Engineering Society, Summer, 39-60.

18 Moore, T.; Carter, D.J.; Slater, A.I. 2002. A field study of occupant controlled lighting in Offices. Lighting Research and Technology, 34 (3), 191-205.

19 Clear, R.D.; Inkarojrit, V.; Lee, E.S. 2006. Subject responses to electrochromic windows. Energy and Buildings, 38 (7), 758-779.

20 Christoffersen, J.; Wienold, J. 2005. Monitoring Procedure for assessment of user reaction to glare, Report ECCO-DBUR-0303-01, Energy and Comfort Control for Building management systems (ECCO-Build), EU Commission (Contract No: ENK6-CT-2002-00656), 70 pp.

21 Ward, G. 2005. Photosphere Quick Start Guide, Photosphere 3.1. URL: www.anyhere.com

22 Bossini, L; Martinucci, M; Paolini, K; Castrogiovanni, P. 2005. Panic-Agoraphobic Spectrum and Light Sensitivity in a General Population Sample in Italy. Canadian Journal of Psychiatry, 50 (1, Jan), 39-45.

23 Bohle, P.; Tilley, A. J.; Brown, S. 2001. Psychometric evaluation of the Early/Late Preferences Scale. Ergonomics, 44(10), 887-900.

24 Lee, E.S.; Selkowitz, S.E. 2006. The New York Times Headquarters daylighting mock-up: Monitored performance of the daylighting control system, Energy and Buildings, 38(7), 914-929.

25 Newsham, G.R.; Mancini, S. 2006. The Potential for demand responsive lighting in non-daylit offices. Leukos, 3, (2), 105-120.

26 Bryk, A.S.; Raudenbush, S.W. 1992. Hierarchical Linear Models, Sage Publications (Newbury Park, CA, USA).

27 Hox, J.J. 1995. Applied Multilevel Analysis, TT-Publikaties (Amsterdam, The Netherlands).

28 Newsham, G.R.; Richardson, C.; Blanchet, C.; Veitch, J.A. 2005. Lighting quality research using rendered images of offices, Lighting Research and Technology, 37 (2), 93-115.

29 Cohen, J. 1988. Statistical power analysis for the behavioral sciences (2nd ed.). Hillsdale, NJ: Erlbaum.

30 Schiller, G.; Arens, E.; Bauman, F.; Benton, C.; Fountain, M.; Doherty, T. 1988. A field study of thermal environments and comfort in office buildings. ASHRAE Final Report No. 462-RP, 77 pages + appendices.

31 Tops, M.; Tenner, A.D.; van den Beld, G.J.; Begemann, S.H.A. 1998. The effect of the length of continuous presence on the preferred illuminance in offices. Proceedings of the CIBSE National Lighting Conference, 6 pages.

32 Heschong Mahone Group. 2006. Sidelighting photocontrols field study. Report #06-152, prepared for the Northwest Energy Efficiency Alliance. URL: http://www.nwalliance.org/research/reports/152.pdf

33 Galasiu, A.D.; Atif, M.R. 2002. Field-performance of daylight-linked lighting controls and window blinds: a pilot study. Proceedings of 5th European Conference on Energy-Efficient Lighting - Right Light 5 (Nice, France), 255-268.

34 Rea, M.S.; Rutledge, B.; Maniccia, D. 1998. Beyond daylight dogma. Proceedings of Daylighting '98 (Ottawa, Canada), 215-222.

35 Lindelöf, D.; Morel, N. 2006. A field investigation of the intermediate light switching by users. Energy and Buildings, 38 (7), 790-801.

36 Sarkar, A.; Mistrick, R.G. 2006. A novel lighting control system integrating high dynamic range imaging and DALI. Leukos, 2(4), 307-322.

37 Glennie, W. L.; Thukral, I.; Rea, M. S. 1992. Lighting control: feasibility demonstration of a new type of system. Lighting Research and Technology, 24(4), 235-242.

38 Pigg, S.; Eilers, M.; Reed, J. 1996. Behavioral aspects of lighting and occupancy sensors in private offices: a case study of a university office building. Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings (Pacific Grove, USA), 8.161-8.170.

**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 |

**Table 2. Photometric Measures and nomenclature**

| Abbreviation | Description |
|---|---|
| ${}^{tot}E_{desk}$ | Total illuminance on the desk at the back of the room, mean of the two sensors LWDNS and LWDNN in Figure 2 (lx) |
| ${}^{e}E_{desk}$ | Illuminance on the desk at the back of the room due to electric light only (lx). Based on a nighttime calibration between dimmer setting and desktop illuminance |
| ${}^{d}E_{desk}$ | Illuminance on the desk at the back of the room due to daylight only (lx) = ${}^{tot}E_{desk}$ - ${}^{e}E_{desk}$ |
| ${}^{tot}E_{ceil}$ | Total illuminance on the ceiling at the back of the room, LWCN in Figure 2 (lx) |
| PCTL40 | Percent pixels in the HDR image less than 40 cd/m$^2$ (%) |
| $I_{P25}$ | Luminance of the 25th percentile pixel in the whole image * (cd/m$^2$) |
| $I_{P75}$:$I_{P25}$ | Ratio of the luminances of the 75th and 25th percentile pixels in the whole image |
| $I_{desk}$ | Mean luminance of the top of the desk at the back of the room (cd/m$^2$) |
| $I_{sky}$:$I_{backwall}$ | Ratio of the mean luminance of the sky (as seen by the participant) to the mean luminance of the rear part of the interior wall behind the participant's computer screen |

*i.e. arrange the luminances of all pixels from the calibrated camera image in ascending order, the luminance that is 25% of the way from the bottom of the list is the 25th percentile.

**Table 3. Results of the HLM analyses, outcome variable was change in dimmer level. Each line shows a separate regression model, using the predictor variables indicated. All relationships shown were significant at the *p*<0.01 level.**

| Predictor | Intercept | t (d.f. = 39) | Slope (or Coefficient) | t (d.f. = 39) | Proportion of Variance Explained* |
|---|---|---|---|---|---|
| ${}^{tot}E_{desk}$ | 29.8 | 5.58 | -0.054 | -5.76 | 0.36 |
| ${}^{tot}E_{ceil}$ | 23.4 | 4.74 | -0.142 | -4.78 | 0.19 |
| PCTL40 | -18.6 | -4.46 | 0.446 | 4.60 | 0.17 |
| $I_{P25}$ | 21.2 | 4.63 | -0.722 | -4.70 | 0.20 |
| $I_{P75}$:$I_{P25}$ | -49.6 | -5.55 | 13.909 | 5.42 | 0.31 |
| $I_{desk}$ | 26.1 | 4.38 | -0.294 | -4.42 | 0.27 |
| $I_{sky}$:$I_{backwall}$ | -23.9 | -4.61 | 0.514 | 4.66 | 0.23 |

*Note, in this analysis the proportion of variance explained refers to variance at level-1, at the level of the individual ratings. The total variance at level-1 is calculated using a 'random intercept model' that is, an HLM model with no predictors; call this $\sigma_1^2$. We then add the level-1 photometric predictor, which reduces the unexplained level-1 variance to $\sigma_2^2$. The proportion of variance explained at level-1 is then $(\sigma_1^2 - \sigma_2^2)/\sigma_1^2$.

**Table 4. Lighting control options for energy analysis.**

| | |
|---|---|
| Dimmer@100% | Electric lighting fixed at full output, providing $^{e}E_{desk}$ = 700 lx |
| 500 lx from Electric | Electric lighting fixed at output providing $^{e}E_{desk}$ = 500 lx |
| Actual Choice | Derived from actual dimmer settings made every 30 minutes |
| Start of Day Choice | If each individual's first dimmer choice had prevailed over their whole day |
| End of Day Choice | If each individual's final dimmer choice had prevailed over their whole day |
| Perfect Photosensor: | If the dimmer was adjusted every 30 minutes to provide $^{tot}E_{desk}$ = 500 lx |

**Table 5. Reasons given for using lighting controls.**

| **Reason** | **Frequency** |
|---|---|
| Responded to changes in daylight | 21 |
| Comfort (visual) | 13 |
| Visibility of tasks | 7 |
| High light level preference | 4 |
| Low light level preference | 2 |
| Time of day influence | 3 |
| Glare control | 2 |

## Figure Captions

Figure 1. The daylighting laboratory. Room A (occupant's room); Room B (measurement room).

Figure 2. Plan of daylighting lab test rooms: the grey circles show horizontal illuminance sensors at desk level (h=75cm), the white circles show ceiling mounted illuminance sensors, the black ovals show illuminance sensors vertically mounted on the interior (h=119cm) and exterior (h=340cm) walls, and the white oval is a vertical sensor at eye-height (119cm). The rectangles at $45^{\circ}$ are the locations of the computer screens, the locations of luminance measures are also shown (spot meter (h=87cm) and digital camera (h=119cm)).

Figure 3. Typical digital camera image showing areas for which mean luminance was calculated.

Figure 4a. Frequency histogram and descriptive statistics of desktop illuminance due to daylight.

Figure 4b. Mean variation of desktop illuminance due to daylight over the day; quadratic trend shown by dotted line.

Figure 5a. Mean, maximum and minimum total desktop illuminance across all 40 participants, at each measurement time during the day.

Figure 5b. Mean, maximum and minimum total desktop illuminance across all measurement times, for each of the 40 participants.

Figure 6. Dimmer changes vs. total desktop illuminance before choice, for all participants and control opportunities. The best-fit linear regression from HLM analyses, and the theoretical performance of a perfect closed-loop photosensor control are also shown.

Figure 7. Dimmer changes vs. Ratio of the luminances of the 75th and 25th percentile pixels before choice, for all participants and control opportunities. The best-fit linear regression from HLM analysis is also shown.

Figure 8. Lighting energy use under six scenarios. The error bar on "Actual Choice" indicates the standard deviation of the energy use of 40 individuals.

Figure 3

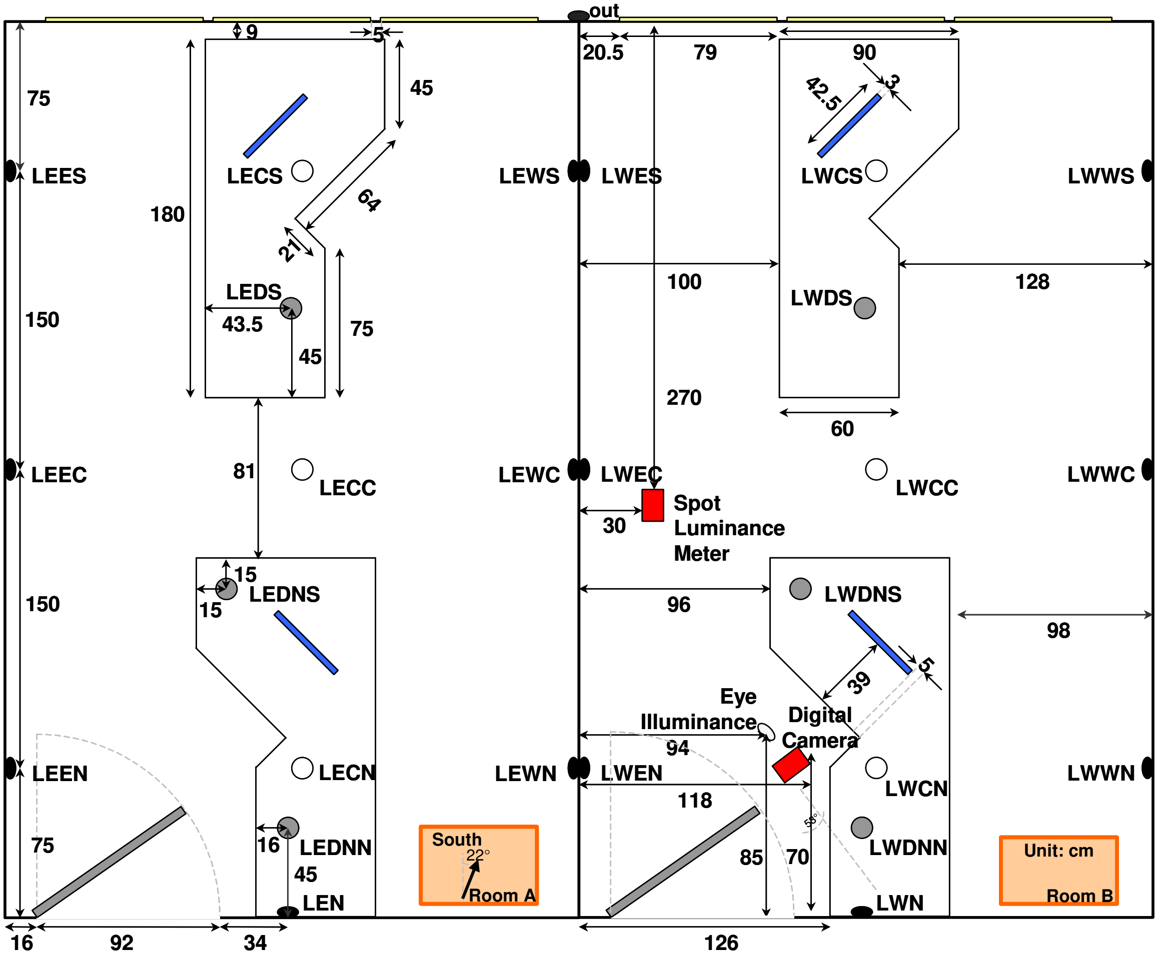

out
9
5
45
75
LEES
LECS
LEWS
LWES
20.5
79
90
42.5
3
LWCS
LWWS
180
64
21
100
128
LEDS
43.5
LWDS
150
75
45
270
60
LEEC
81
LECC
LEWC
LWEC
LWCC
LWWC
Spot
Luminance
Meter
30
15
15
LEDNS
150
96
LWDNS
98
39
5
Eye
Illuminance
Digital
Camera
94
LEEN
LECN
LEWN
LWEN
118
LWCN
LWWN
58°
75
16
LEDNN
45
LEN
South
22°
Room A
85
70
LWDNN
LWN
Unit: cm
Room B
16
92
34
126

Figure 4.

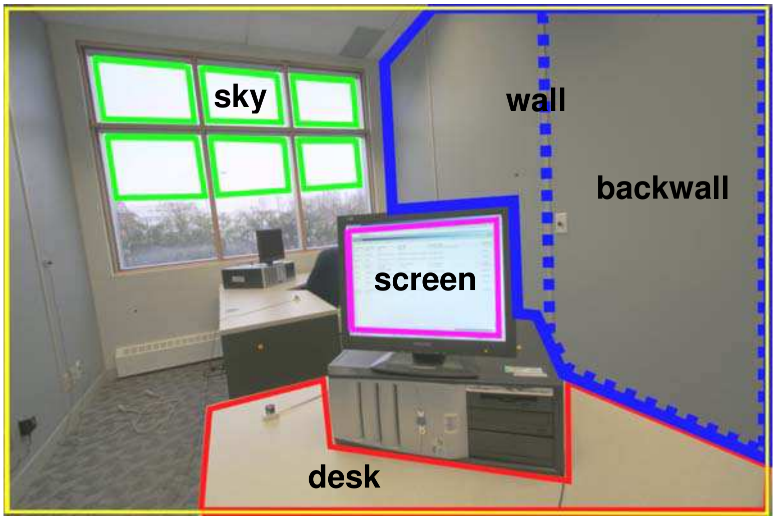
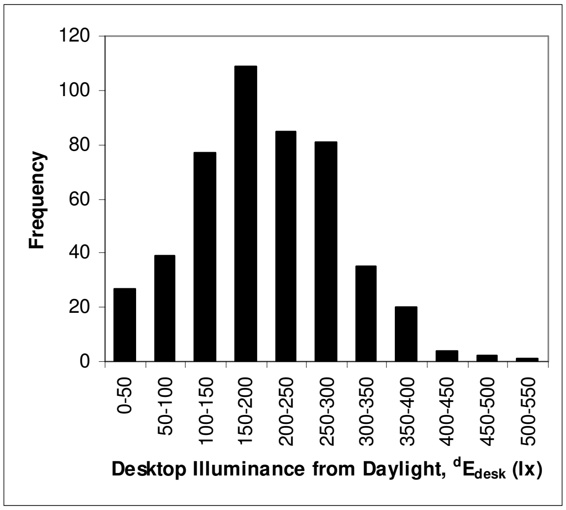
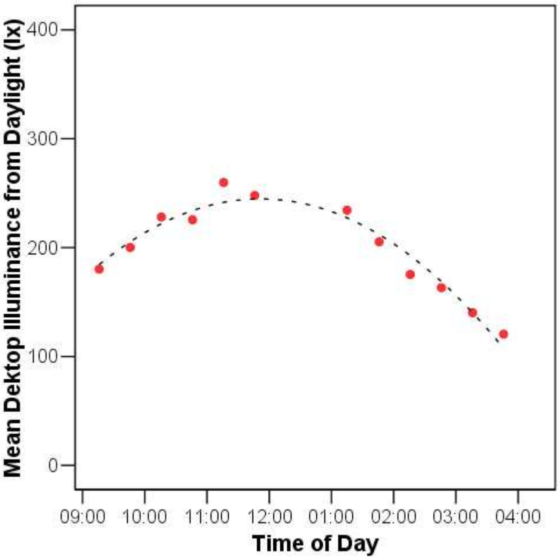


**Figure 3.**





Mean =198 lx; median = 196 lx; s.d. = 95 lx

**Figure 4a.**

**Figure 4b.**

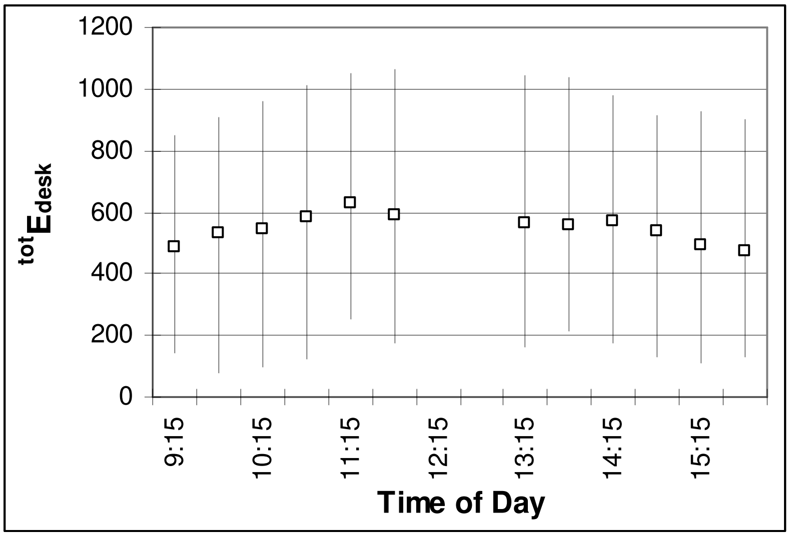

1200
1000
800
600
400
200
0
$^{tot}E_{desk}$
9:15
10:15
11:15
12:15
13:15
14:15
15:15
Time of Day

Figure 5a.

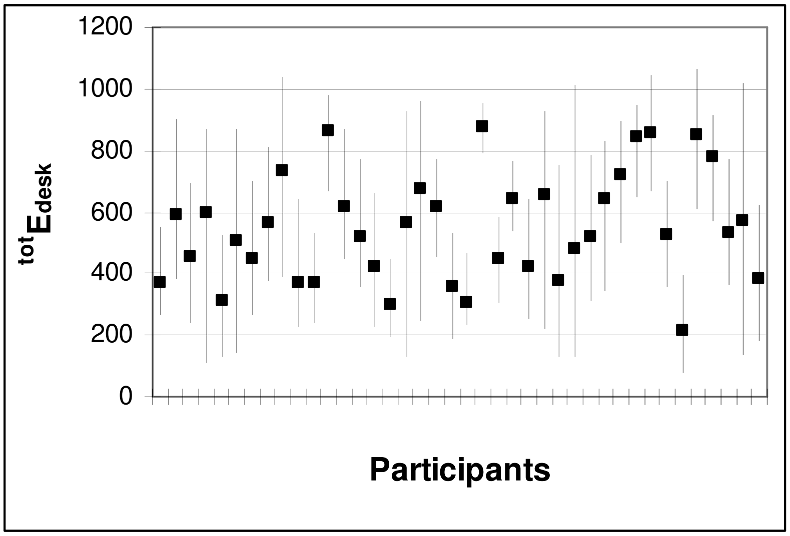


**Figure 5b.**

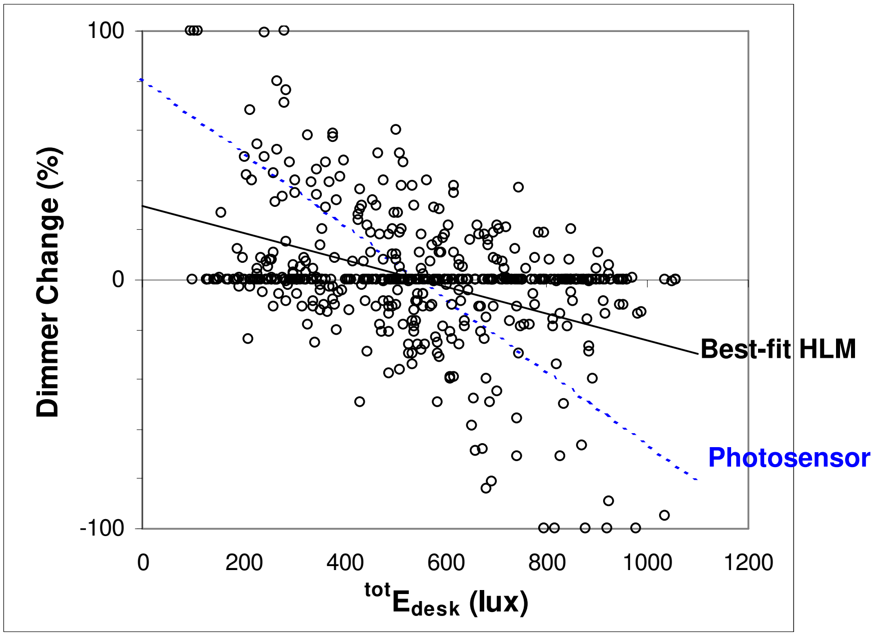

100
0
-100
Dimmer Change (%)
0
200
400
600
800
1000
1200
$^{tot}E_{desk}$ (lux)
Best-fit HLM
Photosensor

Figure 6.

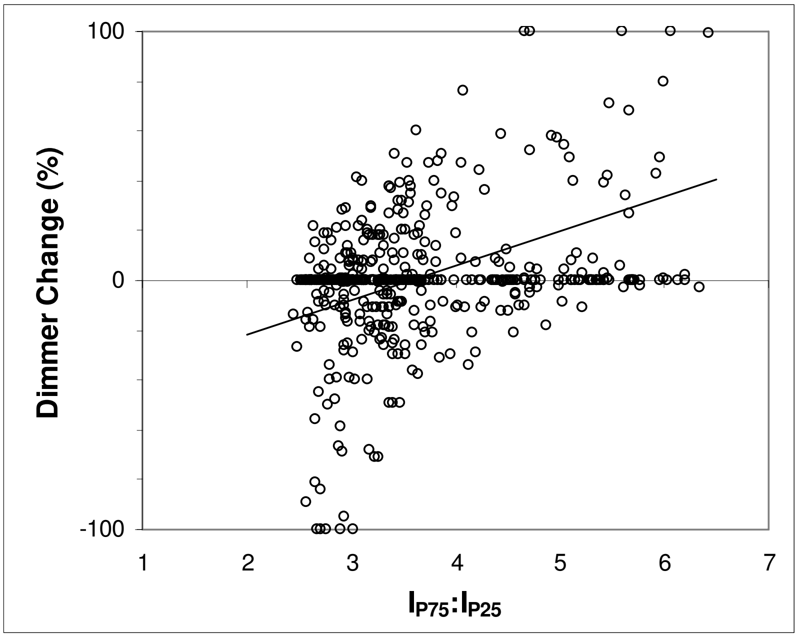


**Figure 7.**

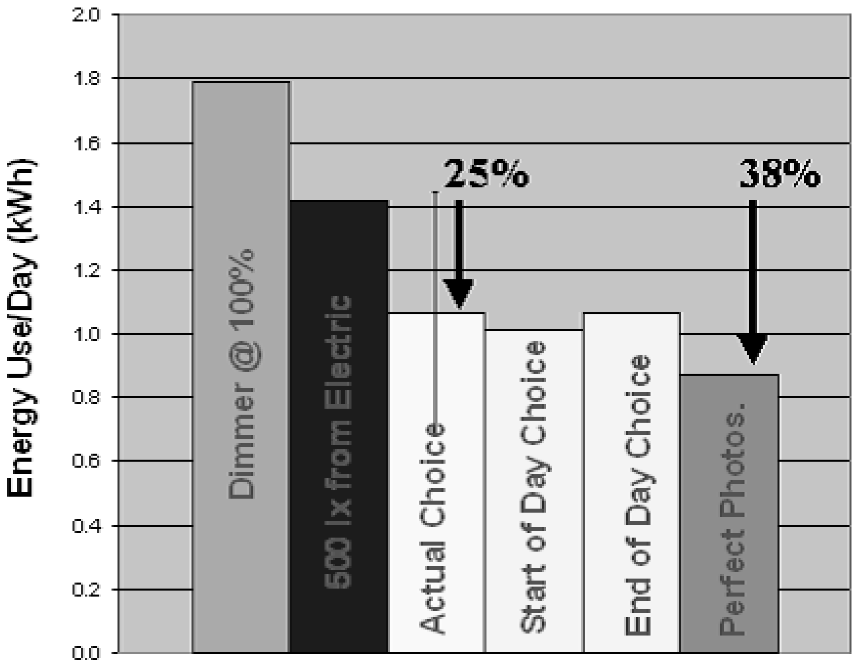

Energy Use/Day (kWh)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
25%
38%
Dimmer @ 100%
500 lx from Electric
Actual Choice
Start of Day Choice
End of Day Choice
Perfect Photos.

**Figure 8.**