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The Effect of Power Constraints on Occupant Lighting Choices and Satisfaction: A Pilot Study

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ABSTRACT

Several recent studies have provided evidence that individual lighting control results in occupant satisfaction benefits. As part of a larger series of pilot studies, we examined the use of individual controls under various lighting power constraints. The studies took place in a mock-up open-plan office space, in which participants spent around two hours doing typical office tasks and answering satisfaction questionnaires. Participants were offered control over lighting circuits via virtual dimmers on their computer screen. The effect of power constraint varied depending on how the constraint was applied. When the constraint was obvious to the participant there were negative satisfaction effects, but when the constraint was hidden there were no apparent satisfaction penalties. One of the hidden constraints we applied was similar to a load shedding situation, whereby lighting is slowly dimmed to avoid peak load problems. We reduced light level slowly (1% of maximum output every 2 minutes) after participants had made their initial lighting level choices. Participants were not conscious of the dimming, allowing the illuminance to fall by 40-50% (typically) before choosing to increase light levels. Therefore, as a method of avoiding peak load-induced power outages this method has promise. These pilot study findings have important implications for practice, and warrant a larger future study.

1. INTRODUCTION

Surveys consistently indicate that building occupants both desire more control over their environment, including lighting, and believe that such control is linked to important health and performance outcomes [Steelcase 1999; Bordass & Leaman, 1993]. Newsham & Veitch [2001] found satisfaction benefits when people received the lighting levels they preferred. And several recent laboratory and field studies have demonstrated that individual lighting control is associated with satisfaction benefits and energy savings [Boyce et al., 2000; Jennings et al., 2000; Carter et al., 1999; Maniccia et al., 1999]. The energy savings can be anywhere from 10-80%, with the larger savings generally associated with available compensating daylight. These savings result from the fact that a majority of people choose light levels lower than a typical fixed system would provide during occupancy, and have the ability to switch their own lighting off when leaving their workspace.

Modern networked lighting control systems offer occupants individual control over their own lighting, but also provide building managers with overriding control. With such a system, some interesting demand-side management techniques are available. For example, the system could provide the occupant with feedback on their own energy use or power demand. Feedback about energy consumption has been shown to be effective in reducing energy use, both in homes and organisations [Brandon & Lewis, 1999; Siero et al., 1996].

In addition, the building manager, in conjunction with the local electrical utility, sometimes finds it desirable to reduce the peak electrical demand of the building. This is done to either to avoid excessive peak demand charges, or, in periods of system-wide high demand and short supply, to avoid power outages. This practice is sometimes referred to as “load shedding”. One method is to slowly dim building lighting in anticipation of a peak demand crisis; lighting is targeted because many other devices, such as computers, cannot continue to operate reliably with reduced power. This strategy has been employed in several commercial buildings [Wood, 1999].

Even when applied in emergency situations, it would be desirable to ensure that such power constraints imposed minimal distractions and satisfaction penalties on occupants. In an era of increasingly sophisticated control systems and expanding utility deregulation, it is conceivable that the imposition of lighting power constraints will become more commonplace. It will certainly be tempting to use lighting power constraints as a general energy saving measure in non-emergency situations. Yet, to our knowledge, there has been little or no scientific study of the effect on building occupants. As part of a larger series of pilot studies [Newsham et al., 2001], we examined occupant use of individual lighting controls under various constraints, and occupant satisfaction with the resulting luminous conditions. The scope of the project was limited, and the number of participants prevented statistical hypothesis testing. Rather, we use the results to point us in the direction of larger future studies.

2. METHODS & PROCEDURES

2.1 The Experimental Space

The experiment was conducted in a mock-up office space 7m x 4.9m (20’ x 16’) and 2.75m (9’) high, with a standard suspended ceiling T-bar system. Within this space were two workstations 2.7m x 2.9m (8’ 9” x 9’ 6”), and a corridor area. The workstations are formed using two of the outside walls of the room and two 1.7m (67”) height partition walls; the partitions enclose free-standing desks, and support an overhead storage bin. See Figure 1 for the spatial layout of the experimental space and Figure 3 for a photograph. Fabrics and finishes for the room and workstations are shades of grey and beige, chosen to minimise chromatic effects in the luminous environment. Measured surface reflectances are shown in Table 1.

Mirrors stretch across the width of each of the full-height walls, extending from the ceiling down to a depth of 0.45m (18”). These mirrors serve two purposes:
1. To create a general feeling of a larger space; we would like to be able to extend the results from this space to larger office spaces.
2. The mirrors allow for the possibility of apparent distant light sources viewable as glare images in the computer VDT screen.

There was a control station external to the experimental space. The control station allowed override control of all lighting circuits, provided for data acquisition, and housed the lighting switchgear.

2.2 The Lighting Control System

On-off control is provided via mechanical relays located in the control station. All dimming ballasts operate on a 0-10 V DC dimming signal.

For the studies described in this paper, the luminaires were laid-out as shown in Figure 1. Identical luminaires have the same letter code, and are described by this letter code in Table 2. Thus the lighting was entirely workstation-mounted (recessed prismatic fixtures, used in related work, remained installed in the ceiling, but switched off). Although not common, workstation-based lighting has been proposed for open-plan offices because of its flexibility and potential for energy savings. First, luminaires are only placed where there are occupants who need lighting. Second, workstation-based lighting is much more easily adapted to individual control. Tiller et al. [1995] demonstrated energy savings of over 50% in a Canadian Government building when an existing ceiling-based system was replaced by a workstation-based system with on-off control over individual luminaires. Newsham et al. [2001] compared the performance of a workstation-based system to a more conventional ceiling-based system.

The participant occupied the right-hand workstation, as shown in Figure 1; the left-hand workstation was always unoccupied. There were five independent lighting circuits available to the participant. The desk lamp and the undershelf task lamp (labelled D and T respectively in Figure 1 and Table 2), took one circuit each. The indirect fixtures (labelled I) were distributed on three circuits: the two fixtures behind the participant were on one circuit; the indirect fixture to the participant's left was on a second circuit; and, the two indirect fixtures on the partition directly in front of the participant were on a third circuit. In the latter case, the fixtures in front of the participant were wired such that only the lamps on the side of the fixture nearest the participant were under their control.

2.3 Lighting Control Scenarios

Four different lighting control scenarios are examined in this paper. Scenario 3 offered the occupant unconstrained control over the output of all five lighting circuits. Scenarios 5 and 6 both examined whether light output constraints, resulting in lower energy consumption, are acceptable to occupants if accompanied by the provision of individual control. Scenario 7 was designed to examine the effect of load shedding[1]. We were interested in studying whether occupants noticed the externally imposed gradual dimming, and whether the dimming would lead to a reduction in satisfaction with the lighting. A relatively slow rate of dimming was chosen to explore how far the reduction in light level could go before participants responded. More detail on each scenario is given in Table 3.

The interface for lighting control available to occupants on their computer screens is shown in Figure 2. Data (reported elsewhere [Newsham et al., 2001] indicated that the participants found the interface easy to use, and were able to use the system to create the lighting they desired.

2.4 Participants

Participants were recruited primarily from students on work terms at our organisation. They were required to have familiarity with Windows™-based computers, and to have corrected-to-normal vision (we relied on self-report, we did not test vision). The reward for participation was a Can$50 credit for logo merchandise from our organisation. Participants were randomly assigned to scenarios, and participant characteristics, by scenario, are shown in Table 4. On the whole, we were satisfied that the groups of participants assigned to each lighting control scenario were equivalent on the basis of their self-reported demographic data.

2.5 Experimental Procedure

Sessions were scheduled to begin at either 9am or 1pm, and were expected to last a maximum of 2 hours and 40 minutes. Before entering the space participants were briefed on the experiment, and were told it was about office lighting in general. They were informed of their rights as participants, and then asked to sign a consent form. They were then escorted into the experimental space and shown the adjustments they could make to the chair and keyboard tray. We did not allow adjustments to the computer screen brightness, tilt or position. The experimenter explained the tasks to be performed during the session. Finally, the experimenter explained and demonstrated the lighting controls available for the scenario scheduled for that session. Participants were not allowed to change the location of luminaires in any way. For the remainder of the session the participant was guided by instructions presented on the computer screen, with appropriate audio alarms. They were invited to choose an initial preferred lighting condition, before proceeding with the tasks.

During the session, participants were asked to complete a number of tasks and questionnaires. The session schedule is shown in Table 5, with each element briefly described below:

Demographic Questions: Sex, Vision Correction, Age, Handedness, and Office Work Experience.

[1] This work was part of a larger pilot study featuring seven control scenarios. Scenarios 1,2 & 4 did not involve power constraints and are therefore not described in this paper.

Any Work: During this period participants were free to work on tasks of their own choosing including the Encarta task (described below), computer work they brought with them, reading they brought with them, or reading the magazines provided.

Encarta Search task: Microsoft® Encarta® DVD Encyclopedia was installed on the computer in the occupied workstation. Participants were given a booklet of general knowledge questions derived from other sources, and were asked to use the Encarta package to find the answers. The purpose of this task was to ensure that the participant spent some time on a task that combined pencil-and-paper work with computer work prior to answering the Satisfaction Questions (described below); performance on this (or any other work done during the session) was not measured.

Satisfaction Questions: Four questions were asked three times during the session. Multiple administration was chosen because it was possible for lighting conditions to vary during the session. Each question was on the same seven-point scale from "Very Unsatisfactory" through "Neutral" to "Very Satisfactory". These questions were derived from previous research by Veitch & Newsham [2000a].

Workday Experience Questions: The first two questions asked the participants to rate the difficulty of the questionnaires and the Encarta task on a five-point scale from "Very Easy" through "Neither Easy or Difficult" to "Very Difficult" (note, on this scale a higher value means the task is more difficult; i.e, a worse outcome). The next question asked participants to rate how much the office environment they had experienced during the experimental session influenced their work performance compared to the environments they were used to. This rating was made on a seven-point scale from –30% through 0% to +30%; Veitch and Newsham [1998] found that this measurement was sensitive to changes in lighting conditions.

The next six questions were related to the lighting system and the environment participants experienced during the experimental session. Participants were asked to rate their level of agreement with certain statements. Responses were a five-point scale from "Strongly Disagree" through "Neutral" to "Strongly Agree". The next four questions were related to satisfaction with the workspace on the same five-point scale. The next three questions were related to the lighting control system, again, on the same five point scale.

The next eleven questions were related to general lighting beliefs. These questions were also used by Veitch and Newsham [2000b]. Finally, participants were asked to type open-ended responses to questions about where they placed the question booklet for the Encarta task, the design of the workstation, and any additional lighting changes they would have preferred. The responses to the lighting beliefs and open-ended questions are not reported here, but can be found in Newsham et al. [2001].

The subject matter of each question is shown in Table 7. Responses to all questions were recorded to a text file on the computer, along with the time when that screen of questions was completed.

2.6 Physical Measurements

During the experimental session we recorded illuminance at four fixed positions in the workstation every minute. These positions were chosen to be sensitive to the variety of different lighting choices the participants had available to them.

In addition, all control signals were recorded to a file in a manner that enabled us to recreate the various conditions after the session had been completed. This allowed us to do more detailed photometry at a later date. The measurement points are shown in Figure 3.

We decided that it was impractical to measure all of the conditions that each occupant was exposed to during their session. Instead, we chose to measure the luminous conditions at the time of the same four events in the session for all occupants. These four events were at the completion of the demographic questions, and at the completion of each repetition of the satisfaction questions. Thus, we would always know the lighting conditions at the time the participants expressed their satisfaction with those conditions.

Initial photometric values prevailing when the participant first entered the space are shown in Table 6. Initial dimmer settings for Scenarios 3, 5 and 7 were chosen to match the illuminance on the CPU box.

3. RESULTS

Extensive data were collected in this experiment, and it is tempting to conduct detailed analyses. However, this experiment was intended as a pilot study only. Several control scenarios were studied, but each control scenario involved only a small sample of participants (~10), exposed for a relatively short period (2 hrs). In light of this, detailed statistical analysis of the data is not warranted, lest one over-interpret. Rather, we concentrate on descriptive statistics and a more qualitative interpretation of the data. Our approach is to compare all relevant outcomes, and look for a pattern of differences that might point towards effects with potential for follow-up studies.

Results are summarised in Table 7. When comparing between scenarios we are faced with the question: what constitutes a “difference” in outcomes without enough participants for meaningful statistical testing? We take a somewhat arbitrary approach. For questionnaire responses we look for differences in the median of 1.0 scale points, combined with a difference in the mean of at least 0.5 scale points. With such a small sample size, both measures of central tendency are open to bias, and having a selection criterion for both is a simple attempt to control for this.

In all comparisons, we focus on the conditions at or near the end of the session. We chose this time, as opposed to any other, because it maximised the participant’s exposure to conditions (and it was too labour intensive to examine data at all times for this level of pilot study analysis). For the recurring satisfaction questions we look only at the responses to the third time the questions were asked in each session. For the luminous conditions, we present the values prevailing at the time of the third occurrence of the satisfaction questions.

3.1 How Did Power Constraints Affect Choice and Satisfaction?

We were interested in exploring the suggestion that lower power lighting designs – which with conventional equipment inevitably produce lower overall light levels – might be more acceptable if occupants have control over their lighting. Both Scenarios 5 and 6 imposed a form of power constraint on the occupant. By comparing the outcomes from these scenarios with Scenario 3 we can look at whether satisfaction declined when the power constraint was imposed, and which elements of the luminous environment occupants sacrificed under the power constraints.

It is interesting to note that both Scenarios 5 and 6 produced a higher level of agreement with the statement “I would have liked more control over the lighting” than Scenario 3, which would be expected. In both Scenarios 5 and 6 the average power draw of the lighting system was substantially lower than in Scenario 3, by approximately 58% and 29% respectively. Because this is achieved with the same equipment, the general light levels are also substantially lower in Scenarios 5 and 6.

Looking at the dimmer settings, it appears that participants in Scenario 5 made very little use of Luminaire 17 (see Figure 2 for luminaire numberings). In attempting to meet the very strict power limit, the first sacrifice was the luminaire behind the seated position, despite the fact that this luminaire was used extensively by participants in Scenario 3. This is not surprising, it is the only lighting circuit with four lamps under control, so reducing its output makes a big difference to the power demand.

Secondly, the location of the luminaire means it has less direct influence on the luminous conditions in the field of view. The actual output of Luminaire 17 in Scenario 6 was also lower than that in Scenario 3, by around one-third. Reduced use of this luminaire in Scenarios 5 and 6 is perhaps also manifest in the lower ratings of glare on the computer screen for these scenarios.

Interestingly, the luminous environments in the immediate field of view in Scenarios 5 and 6 are very similar, on average. However, despite the similar luminous environments, the participants in Scenario 5 had consistently lower ratings on several of the questionnaire response scales. Ratings from Scenario 5 are lower than those from Scenario 6 for Satisfaction with Lighting Overall, Encarta Task Difficulty, Self-reported Productivity, Desire for greater Environmental Control, and Workplace Satisfaction. Scenario 5 rates lower than Scenario 3 on many of the same scales, whereas Scenario 6 scores as highly Scenario 3 over the range of ratings examined.

3.2 Do Occupants Notice a Slow Reduction in Light Levels?

Light levels were substantially lower by the end of Scenario 7, compared to Scenario 3. Nevertheless, the questionnaire responses indicate no trend towards a difference in satisfaction between the two scenarios. Open-ended comments made by the participants at the end of the session suggested that none of them were consciously aware of the imposed dimming regime. The evidence suggests that dimming of the type we imposed was not apparent to the participants, and did not disturb them.

As a general indication of the luminous environment experienced by participants, the illuminance monitored on top of the CPU box throughout the experimental session is shown for each participant in Figure 4. Two participants made no change to their lighting during the session, although the illuminance at the CPU dropped by around 80% during that period. One participant reduced the lighting level during the session. The other seven participants behaved as one might expect; they increased the light level at some point during the session. In six of those seven cases, the participant increased the light level only once during the session. The amount by which the CPU illuminance dropped before these participants increased the lighting levels varied between 13% and 60%. Interestingly, when participants did act to increase the light level, in only one case was the illuminance at the CPU restored to at least the same level as it was before the dimming started. Restoration was between 66% and 124% of the original level.

4. DISCUSSION

These comparisons raise some very interesting questions with regard to tolerance for power constraints, which would be valuable to follow up on in future larger studies. Our data suggest that the method of power constraint matters, even if the resulting luminous condition is very similar, as was the case for Scenarios 5 and 6. A constraint that was hidden from the participant (Scenario 6) was much more acceptable than one that was obvious (Scenario 5). Comparison of Scenarios 3 and 6, both of which apparently offered a free choice, shows little difference in terms of satisfaction, even though the absolute light levels were much lower in Scenario 6. This might simply mean that our sample size is too small to see a difference in satisfaction, but it is worth pursuing in future studies.

Several previous studies in psychology point to this general phenomenon: people tend to react negatively whenever some level of control over a situation is so obviously withheld [Brehm, 1966], as was the case in Scenario 5, but not Scenario 6. Scenario 7, like Scenario 6, offered apparently free control over lighting conditions but with a hidden power constraint. Again, satisfaction with conditions in Scenario 7 was not obviously lower than satisfaction in Scenario 3. Furthermore, at the end of the session, satisfaction with Scenario 7 was generally higher than that in Scenario 5 despite the fact that light levels were substantially lower. This is perhaps evidence that absolute light levels are less important than other factors. If this is the case, the potential for energy savings is large, and worthy of further study. Future studies could also explore whether different forms of obvious power constraint would be more acceptable as a route to energy savings; e.g., a virtual power meter with no external maximum power limit, or a virtual dollars-and-cents or greenhouse gas meter, or an approaching peak load penalty indicator.

Data from Scenario 7 indicated that participants did not notice as light levels were reduced at a rate of 1% of full output every 2 minutes. Horizontal illumination levels typically fell to half their initial settings before participants (partially) restored the lighting. However, previous work [Newsham & Veitch, 2001] suggests that providing occupants with the lighting they prefer yields satisfaction benefits. Therefore, we would not propose this kind of dimming as a general energy savings strategy even if people do not perceive the (slow) change. Nevertheless, as an alternative to a power outage, which would be more problematic for occupants than dimmed lighting that did not meet their personal preference, the load shedding approach seems promising.

Future studies might examine different dimming rates, as any commercial load shedding system would likely dim light levels more rapidly than we did in this study (typically 2% per minute). Kryszczuk [2001] notes: “Although the increments and decrements in luminance are [a] fairly well researched and known area in vision science, most of the work has been focused on fast changing stimuli (flicker) or static threshold measurements. Not much is still known about visual processing of slow-changing stimuli.” Kryszczuk reported that participants noticed light level changes after reductions of around 20%, independent of dimming rate. However, the slowest dimming rate in that experiment was equivalent to 50% of maximum per minute, and the participants were told to expect changes in light level; the distraction of completing a mathematical subtraction task did not affect the threshold detection level. The work reported in our paper suggests that slower dimming rates in a more realistic setting can result in much lower detection thresholds.

It would also be interesting to explore similar issues in daylit spaces with daylight-linked dimming systems. Such systems have great potential to save energy by displacing electric light with daylight when daylight is available. One anecdotally-reported barrier to widespread adoption is the distraction of occupants by changing electric lighting levels. Research similar to that described here could identify how rapidly such systems should respond to daylighting to minimise occupant distraction.

5. CONCLUSIONS

To reiterate, it would be wrong to draw firm conclusions from a pilot study of this kind. Rather, we prefer to call the following items “Observations”, and hope that future, larger studies will be able to confirm or refute them:

- The success of power constraints on lighting choices seems to depend on how the constraint is applied. In our study, a constraint that was obvious to the occupant produced a marked trend of dissatisfaction with the lighting, and the working conditions in general, compared to an unconstrained condition. Constraints that were hidden from the occupant produced a workplace that was just as satisfactory as the unconstrained condition, with substantial lighting power reductions.

- Occupants did not notice lighting that was dimmed slowly (1% of full output every 2 minutes). Further, they were just as satisfied with the workplace that featured this dimming as they were with an environment where no dimming took place. This study suggests that load shedding has potential as a satisfactory way of avoiding undesirable, dangerous or costly periods of peak power demand.

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Table 1. Measured surface reflectances.

Object	Material	Colour	Reflectance
Partition	Fabric	Light Grey	0.51
Full-height wall	Painted drywall	Light Grey	0.82
Cover for cabling at bottom of partition and above desktop	Plastic	Dark Beige	0.23
Storage bin	Painted metal	Dark Beige	0.24
Desktop	Veneered particleboard	Light Grey	0.63
Floor	Carpet	Dark Grey	0.15
Ceiling	Gypsum tile	White	0.85

Table 2. Description of the luminaires used.

Letter Code	Description
I	.7' x 4' indirect fixtures, mounted on partitions. 2 x 32W T8 lamps (GE F32T8SP35). Motorola Gold electronic dimming ballast (5-110%).
T	.5' x 2' prismatic lens task lights, mounted under storage cabinet 1 x 17W T8 lamp (GE F17T8SP35). Motorola Gold electronic dimming ballast (5-110%).
D	desk lamp, 1 x 23W dimmable compact fluorescent (Philips SLS D23). This lamp with an integral ballast was controlled with an incandescent dimmer that accepted a 0-10V DC control signal.

Table 3. Description of each of the control scenarios.

Scenario #	Description
3	All lighting provided by workstation-based indirect luminaires and task lights. Participant had a free choice, using the on-screen dimmers, over the light output of fixtures in his/her work area at any time, from 12 – 100 % of maximum light output. Luminaires outside the participant's work area remained at constant output (67%)
5	As Scenario 3, but the participant's lighting choice was constrained such that the total power requirement of the light fixtures could not exceed 85W (1 W/ft^2). Participants ensured this with reference to a virtual power meter on-screen, calibrated to the real power requirement of the system.
6	As Scenario 3, but the dimmer maximum available to the occupant did not correspond to the physical maximum output of the lamp, but rather to 50% of the maximum.
7	As Scenario 3 but 20 minutes after the participant had set their preferred light level the system automatically dimmed all lights (including those outside the participant's work area) by 1% of maximum output every 2 minutes.

Table 4. Summary of participant characteristics.

	Whole Sample	Scenario # 3	5	6	7
Sex					
Male	18	5	5	4	4
Female	22	5	5	6	6
Correction Lenses					
None	15	4	3	4	4
Reading Glasses	2	1	0	1	0
Distance Glasses	17	4	6	3	4
Bi- or Trifocals	0	0	0	0	0
Contact lenses	6	1	1	2	2
Age					
25 or less	35	7	9	9	10
26 to 36	5	3	1	1	0
Office Work Experience					
16 months or less	32	7	8	9	8
17 months or more	40	3	2	1	2

Table 5. Experimental schedule for each participant

Activity	Minutes
Instructions & Lighting Control Demo	~ 20
Demographic Questions	~ 5
Any Work	15
Encarta Search Task	10
Satisfaction Questions (1st time)	~ 5
Any Work	15
Break	~ 15
Any Work	15
Encarta Search Task	10
Satisfaction Questions (2nd time)	~ 5
Any Work	15
Encarta Search Task	10
Satisfaction Questions (3rd time)	~ 5
Workday Experience Questions	~ 15

Table 6. Initial luminous conditions, by Scenario (possible maximums are shown in parentheses).

	Scenario	
	3, 5 & 7	**6**
CPU Illuminance (lx)	493 (667)**	223 (307)
Cubic Illuminance (lx)		
Front	201 (264)	94 (125)
Back	250 (359)	111 (162)
Top	532 (737)	237 (335)
Bottom	59 (84)	27 (39)
Left	213 (303)	98 (137)
Right	209 (290)	94 (133)
Desktop Illuminance (lx)		
Close to VDT (from VDTL & VTDR)	423 (587)	191 (270)
Right of desk, beneath storage cabinet (from DRL & DRU)	444 (609)	202 (296)
Left of desk (from DLL & DLU)	456 (653)	210 (295)
Extreme left of desk (from TLL & TLU)	707 (1056)	338 (467)
Luminance (cd/m^2)		
Right partition (from PRU, PRM & PRL)	50.7 (71.9)	22.3 (32.2)
Left partition (from PLU, PLM & PLL)	59.0 (82.3)	26.2 (37.6)
TRP	95.6 (127.9)	44.5 (67.7)
WRM	77.6 (106.2)	35.5 (48.7)
CLT	111.7 (213.0)	90.9 (107.4)
Power (W)	202 (256)	91 (115)

** maxima in this column assume lighting in non-occupied workstation fixed at initial value, this was not the case for much of the occupied period for Scenario 7.

Table 7. Comparison of outcomes for Scenarios 3, 5, 6,7. Medians are shown, with means in parentheses where appropriate. Shading indicates differences between scenarios on questionnaire responses (criterion: median differs by 1.0 and mean differs by 0.5); superscripts indicate the scenario(s) with lower rating(s) than the scenario with the superscript, for that response.

	Scenario 3 Dimmable, indirect + task lighting	**Scenario 5** As Scenario 3 + 85 W power limit	**Scenario 6** As Scenario 3 + light output halved	**Scenario 7** As Scenario 3 + auto ramp down
Questionnaire Responses				
Satisfaction with workplace (final of 3 ratings)	6.0 [5.2]	5.0 [5.0]	6.0 [5.8]^{5}	6.0 [6.3]^{5}
Satisfaction with light for reading (final of 3 ratings)	6.0	6.0	6.0	6.0
Satisfaction with lighting for computer work (final of 3 ratings)	6.0 [6.1]	6.0 [5.2]	6.0 [6.0]	7.0 [6.6]^{356}
Satisfaction with lighting overall (final of 3 ratings)	6.0 [6.2]^{5}	5.0 [4.9]	6.0 [5.9]^{5}	6.5 [6.5]^{5}
Questionnaire difficulty (higher value means more difficult)	1.0 [1.0]^{5}	2.0 [2.0]	1.0 [1.7]	1.0 [1.3]^{5}
Encarta task difficulty (higher value means more difficult)	3.0 [2.7]	3.5 [3.5]	2.0 [2.5]^{5}	3.0 [2.8]
Self-reported productivity	5.0 [4.9]^{5}	3.0 [3.6]	4.5 [4.5]^{5}	5.0 [5.4]^{5}
Lighting control system allowed me to create conditions I wanted	4.0	3.5	4.0	4.0
Lighting control system was easy to use	5.0	5.0	5.0	5.0
I would have liked more control over the lighting	2.0 [2.2]^{56}	3.0 [3.5]	3.5 [3.3]	2.5 [2.6]^{6}
I would have liked more control over the environment	3.0 [3.1]^{57}	4.0 [3.9]	3.0 [2.9]^{57}	4.0 [3.7]
I was distracted by changes in lighting outside my workstation	2.0	1.5	1.5	1.0
I was disturbed by glare on the computer screen	3.0 [2.6]	1.5 [1.9]^{37}	1.5 [1.8]^{37}	2.5 [2.4]
This workspace helped me get the work done efficiently	4.0 [3.7]^{5}	2.5 [2.6]	3.0 [3.3]	4.0 [3.8]^{56}
I'm very satisfied with this workplace	4.0 [3.6]^{5}	2.0 [3.0]	4.0 [3.5]^{5}	4.0 [4.2]^{5}
Physical layout of workspace is well suited to the tasks	4.0	4.0	4.0	4.0
Compared to other offices, I like this workspace	4.0 [3.7]	3.5 [3.3]	4.0 [3.7]	5.0 [4.6]^{356}
Instructions on how to operate lighting controls were adequate	5.0	5.0	4.5	5.0
Interface for lighting controls was easy to use	5.0	5.0	4.5	5.0
Lighting changed rapidly enough in response to my commands	4.0 [4.1]	5.0 [4.3]^{6}	4.0 [3.6]	4.0 [4.3]
Dimmer Settings (%)				
Luminaire 17	66 [51]	0 [1]	88 [77]*	24 [28]
Luminaire 15	71	68	76*	41 [42]
Luminaire 22	71 [72]	25 [29]	92 [71]*	43 [45]
Luminaire 13	66 [61]	22 [35]	55 [50]*	49 [46]
Luminaire 16	48 [55]	27 [45]	86 [69]*	27 [28]
Cubic Illuminance (lx)				
Front	190 [185]	125 [118]	99 [92]	85 [82]
Back	229 [209]	77 [80]	122 [124]	87 [99]
Top	494 [478]	276 [258]	276 [258]	204 [220]
Bottom	58 [57]	27 [27]	29 [29]	21 [24]
Left	200 [197]	115 [124]	108 [105]	81 [92]
Right	187 [184]	98 [93]	102 [101]	77 [86]
Desktop Illuminance (lx)				
Close to VDT (from VDTL & VTDR)	395 [380]	222 [216]	215 [205]	172 [182]
Right of desk, beneath storage cabinet (from DRL & DRU)	396 [385]	233 [232]	197 [192]	220 [219]
Left of desk (from DLL & DLU)	413 [411]	228 [246]	227 [225]	165 [192]
Extreme left of desk (from TLL & TLU)	583 [627]	288 [430]	385 [355]	244 [291]
Luminance (cd/m^2)				
Right partition (from PRU, PRM & PRL)	46.9 [45.8]	23.2 [23.9]	26.5 [25.5]	19.5
Left partition (from PLU, PLM & PLL)	54.8 [55.2]	32.0 [32.2]	30.9 [29.7]	22.4
TRP	88.9 [82.9]	35.7 [43.9]	31.0 [35.8]	56.4
WRM	73.7 [72.5]	43.1 [41.7]	40.3 [39.0]	31.7
CLT	199.0 [202.4]	157.1 [160.1]	103.0 [93.0]	75.1 [73.7]

Power (W)	190 [179]	82 [73]	137 [123]	112 [117]

** value shown is the dimmer setting as it appeared on the participant's screen, actual lighting output was half of this value*

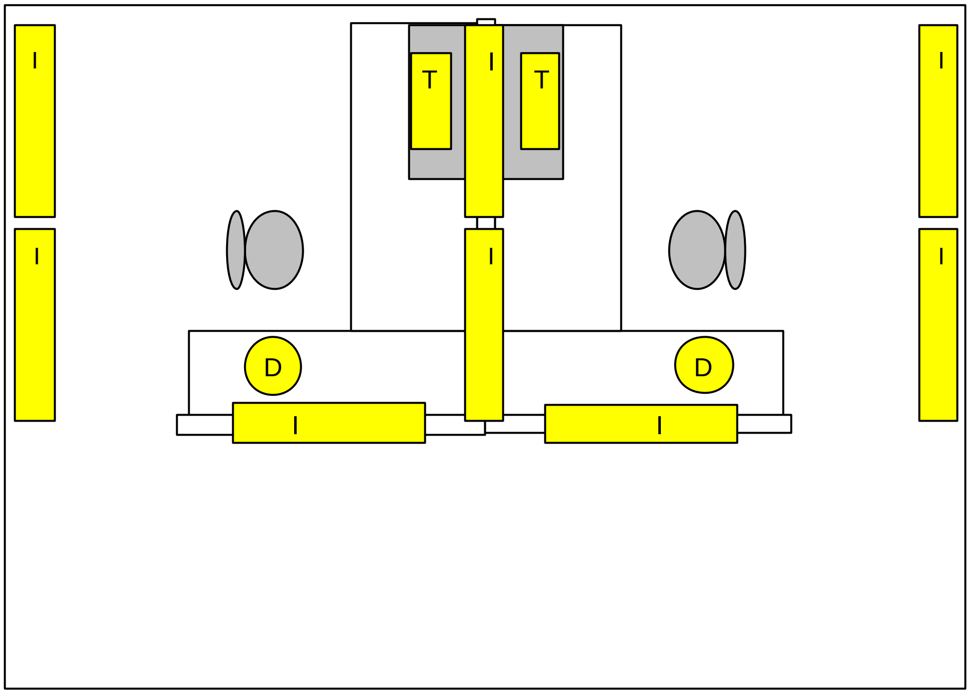

Figure 1. Schematic diagram (plan view) of the current luminaire layout in the experimental facility.

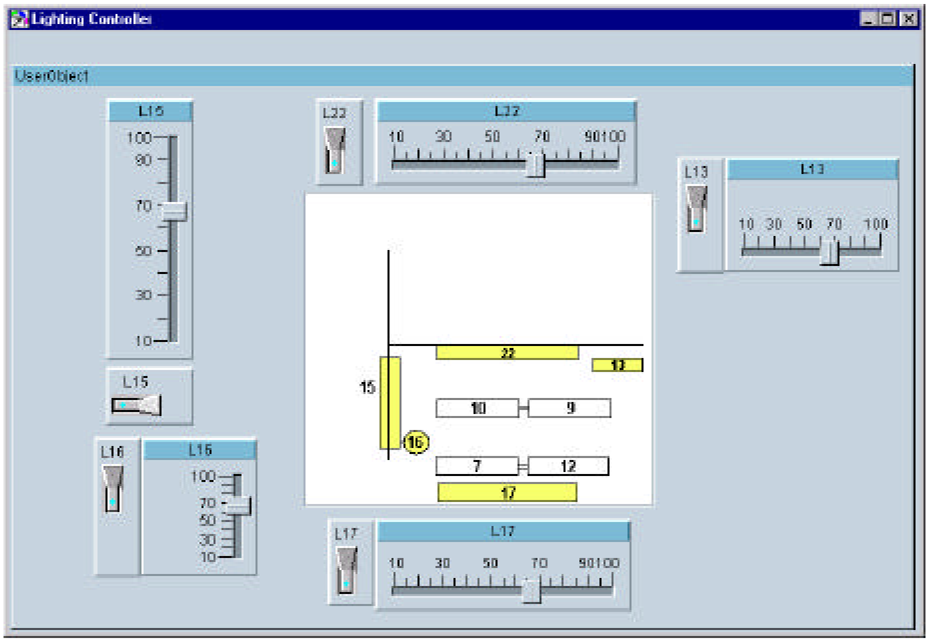

Figure 2(a). Lighting control interface for Scenario 3. Note that luminaire 22 is formed by wiring one lamp from each of two partition-mounted fixtures together on the same dimmable circuit. This allows the participant to control one side (theirs) of the two-lamp fixtures mounted between workstations. The interface for Scenarios 6 and 7 were identical to this one.

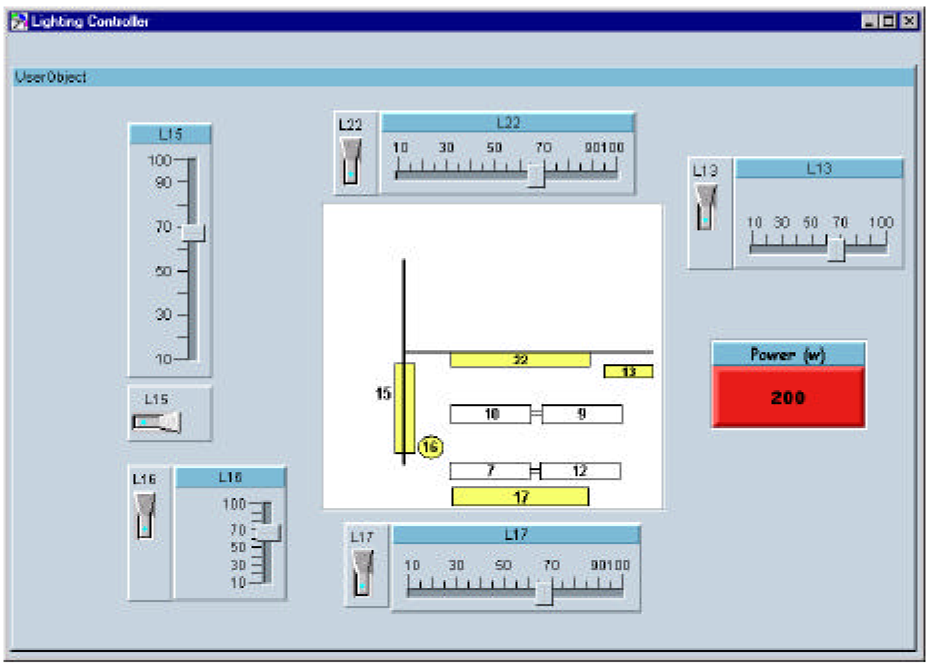

Figure 2(b). The lighting control interface for Scenario 5 was the same as that for Scenario 3, with the addition of a (virtual) power meter. Using pre-defined correlations, the power meter showed the participant the lighting power associated with their lighting choice. They were instructed to choose lighting requiring less than 85W. Power demands higher than this had a red background, power demands that met the criterion had a green background. Shown here are the initial conditions, chosen to match the initial conditions for Scenario 3.

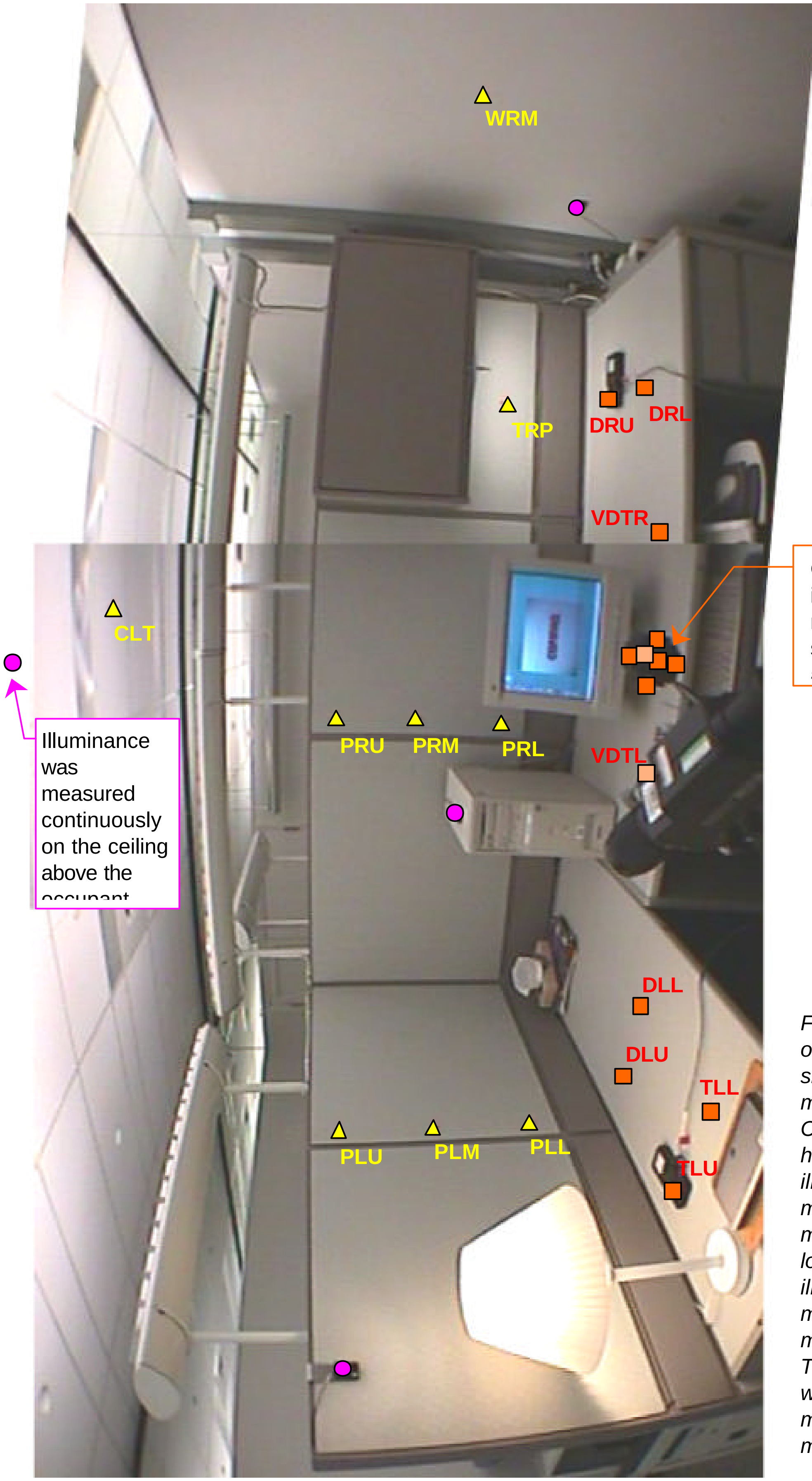

Figure 3. Photomontage of occupied workstation showing photometric measurement points. Circles show locations here continuous illuminance measurements were made. Squares show locations where additional illuminance measurements were made after the session. Triangles show locations where luminance measurements were made after the session.

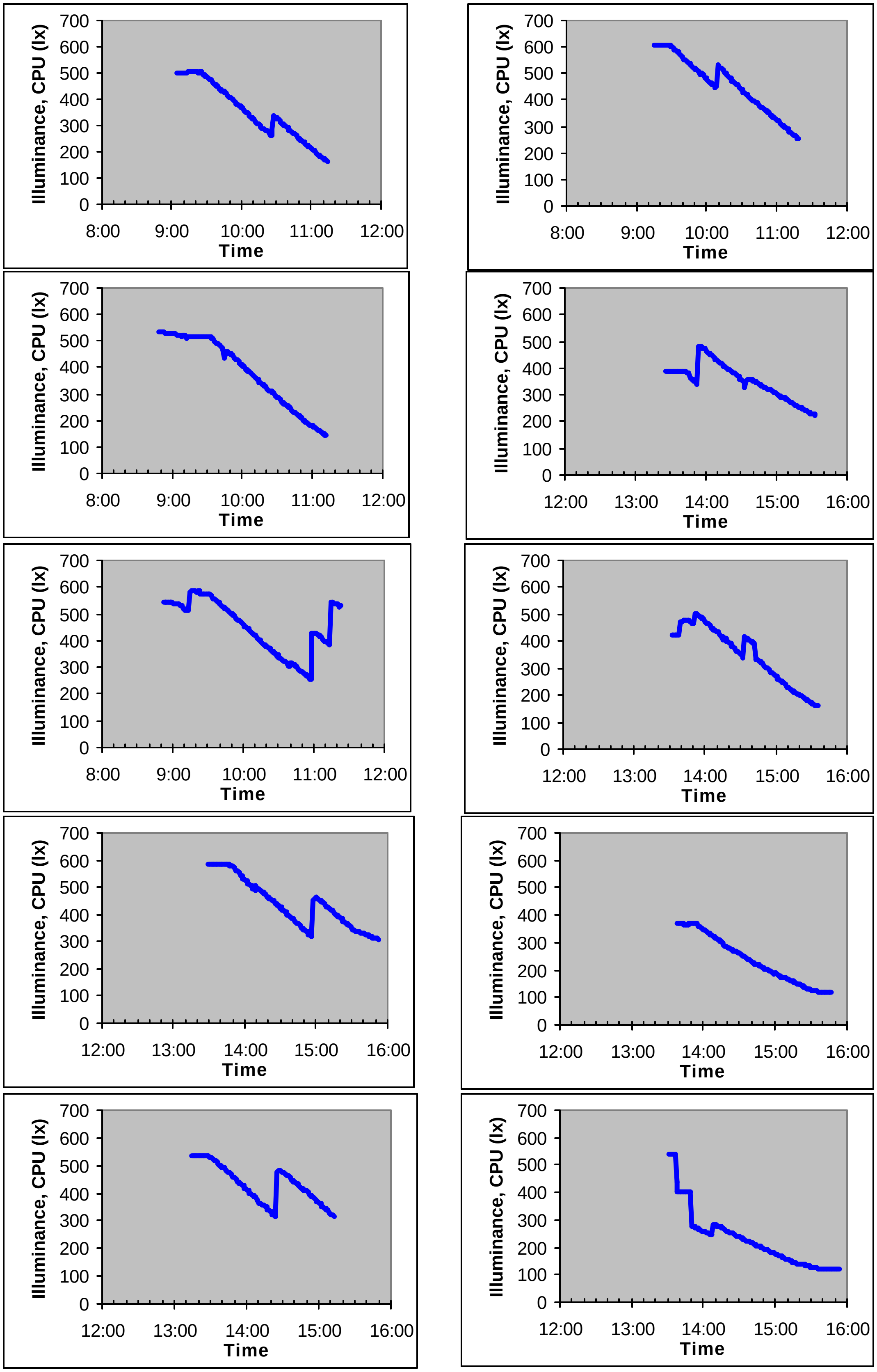

Figure 4. Change of horizontal illuminance on top of CPU box over the experimental session, for each participant in Scenario 7.