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Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/20378016
Research Report (National Research Council of Canada. Institute for Research in Construction); no. IRC-RR-166, 2004-03-17

National Research Council Canada / Conseil national de recherches Canada

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IRC Research Report RR-166

(This report was derived from Client Report #B3208.5, issued in March 2004)

Lighting for VDT workstations 2: Effect of control and lighting design on task performance, and chosen photometric conditions

Guy Newsham, Jennifer Veitch, Chantal Arsenault, Cara Duval

Executive Summary

This experiment was conducted in a mock-up office space laboratory. 118 participants worked for a single day under one of four lighting designs (Figure A). They had no control over the lighting until the second half of the afternoon, when all participants were offered some form of individual dimming control. During this working day participants completed a variety of simulated office tasks and questionnaires related to mood, satisfaction, and discomfort. An earlier report [Newsham et al., 2003] described initial data analysis of questionnaire outcomes and photometric data. In this report we supplement this information with analysis of the task performance data and more detailed photometric data. For completeness, this Executive Summary will summarize the findings of the experiment as a whole.

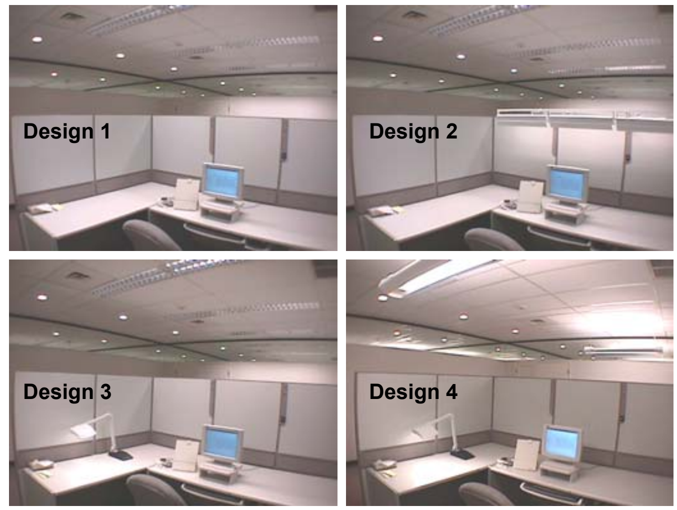


Figure A. The four lighting designs employed in this experiment. Design 1 features ceiling-recessed parabolic system only; Design 2 was the same as Design 1, with the addition of a custom partition-washer; Design 3 was the same as Design 1, with the addition of a task light; Design 4 featured a workstation-specific dimmable direct/indirect fixture and a task light.

Introducing individual lighting control improved ratings of mood, satisfaction and discomfort, but did not improve task performance. We recommend a longer-term study in a real office setting to examine if the mood, satisfaction and discomfort benefits persist, and if benefits to task performance, or other outcomes important to organisations, emerge. Several other studies have demonstrated energy and satisfaction benefits associated with individual lighting controls, a new field study focussed on organisational performance measures might generate results to contribute to a more convincing economic case for adoption of such controls.

Further, our results suggest that is not simply the availability of control that brings benefits to the user, but exercising control to achieve preferred conditions. The participants who made the biggest changes to luminous conditions tended to experience the biggest benefits, those who made little change to luminous conditions experienced little or no benefit (Figure B shows one example).

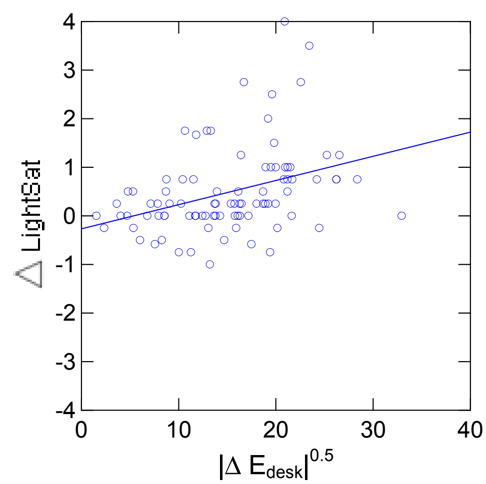


Figure B. The effect of the size of change in desktop illuminance (post-control – pre-control) on the change in rating of Satisfaction with Lighting (post-control – pre-control).

On average, chosen luminous conditions tended to conform to existing recommended practice for office lighting, although individual choices exhibited wide variety. We also saw that many people varied their lighting choices according to the task they were doing. For lighting practice this implies that control systems should be easily accessible, easy to understand, and able to effect substantial changes in conditions.

One of the lighting designs we employed provided a custom partition washer designed to provide additional vertical illumination (Design 2 in Figure A). The hypothesis was that in the modern office, where most tasks are performed on a vertical computer screen, the ability to control vertical illumination in the field of view would be of benefit. We also thought that participants would use less ambient light from ceiling-recessed fixtures if given the means to light vertical surfaces with another system. The partition-washers were used when available, to substantially elevate vertical luminance in the field of view. However, they were not associated with significant improvements in mood, satisfaction and discomfort, or improvements in task performance. Neither did their use offset the preferred output of ceiling-recessed, parabolic, ambient lighting. Therefore, we must conclude that providing additional partition lighting in this way is unlikely to be of value in practice.

Similarly, provision of supplemental task lighting (Design 3 in Figure A) did not significantly improve ratings of mood, satisfaction and discomfort, or offset the preferred output of ceiling-recessed, parabolic, ambient lighting. However, our results do suggest a benefit on the performance of some tasks (Figure C shows examples). Recommended practice documents for office lighting commonly suggest that a straightforward route to lighting energy savings is to lower ambient lighting levels and to compensate with task lighting. Our findings suggest that the benefits of task lighting might not lie in energy savings, but in task performance improvements. Therefore, we recommend future research into the energy and human factors effects of task lighting to better understand the true benefits.

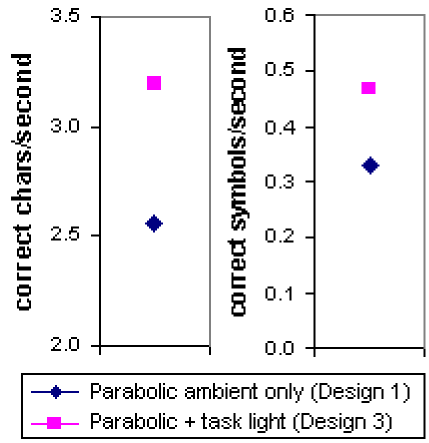


Figure C. Examples of the effect of lighting design on task performance. Shown are the statistically-significant main effects of providing task lighting on typing speed (left) and alertness/vigilance (right).

Finally, one of the lighting designs we studied was chosen to resemble a new, low-energy lighting design being installed in Canadian Federal Government buildings. It featured a workstation-specific dimmable direct/indirect fixture and a task light (Design 4 in Figure A), and has been proposed as a lighting design to maintain satisfaction while saving energy. Our results showed that in terms of mood, satisfaction, discomfort and task performance outcomes, this design was generally neither better nor worse than the other designs we studied. However, results from this project and earlier work indicate that some participants prefer light levels outside the range provided by this design. Modifying this design to offer a greater range of illuminances might prove beneficial.

Table of Contents

1. INTRODUCTION

Current recommended practice for VDT office lighting suggests that the luminance of vertical surfaces in the field of view is just as important in determining lighting quality in open-plan offices as desktop illuminance [IESNA, 2000]. However, typical direct ambient lighting systems are more efficient at lighting the desktop than vertical surfaces, which is understandable given that delivering horizontal illuminance has been the focus of the office lighting industry for many decades. Another one of the main goals of office lighting design has been to reduce reflected glare in computer screens. This is commonly done using ceiling-recessed fixtures with parabolic louvers; a side-effect of this luminaire design is that light distribution to vertical surfaces is compromised. This is unfortunate given the results of an experiment by Berrutto et al. [1997]. They constructed mock-up private offices where participants had control of five lighting circuits, including wall washers. Their results stressed the importance of the wall luminance in participants' lighting choices. One goal of the experiment described in this report was to examine if the luminance of partial-height partitions (the most common type of office enclosure in North America) is similarly important.

Previous work in mock-up open-plan offices has generated much useful information about preferred lighting conditions [Newsham & Veitch, 2001; Veitch & Newsham, 1998; Veitch & Newsham, 2000a; Veitch & Newsham, 2000b; Newsham et al., 2002a]. An understandable shortcoming in the experimental designs was the inability to physically separate the luminance of different surfaces. This is inevitable with typical ambient lighting systems: parameters such as desktop illuminance and partition luminance are highly intercorrelated. This causes a problem experimentally, because it is very difficult to determine which surfaces are most important for occupant satisfaction. The most energy-efficient use of light might rest on lighting the most important surfaces while not "wasting" light on unimportant surfaces. It is possible that lighting designed to illuminate open-office partitions efficiently will produce a luminous environment that is more satisfactory to the occupants than traditional designs, and at lower power draw. For the purposes of this experiment, we built a custom "partition washer" designed to preferentially light the office partitions.

It is often suggested that providing light local to the task area can compensate for substantial reductions in ambient lighting and lighting energy consumption [Tiller et al., 1995], while providing a satisfactory luminous environment [Veitch & Newsham, 1998; New Buildings Institute, 2001; Hedge, 1998]. For example, Yamakawa et al. [2000] conducted a study of task-ambient lighting use in a mock-up office space. In their study, participants were exposed to ambient lighting from ceiling-recessed parabolic fixtures at one of three fixed levels of 200, 300 or 400 lx. Participants then used a dimmer control to select a preferred level of output from a task light. On average, a 100 lx reduction in ambient lighting was compensated by only a 30 lx increase in task lighting. In our experiment we explored whether local partition or task lighting can displace ambient lighting to deliver net energy savings.

In addition, this experiment also investigated the benefits of providing individual lighting control. 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 et al., 1993]. 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; Veitch & Newsham, 2000a; Moore et al., 2002; Maniccia et al., 1999; Escuyer & Fontoynont, 2001].

Further, this experiment specifically tested the hypothesis that working under lighting conditions that match the occupant's personal preference (or close to it) will improve satisfaction and task performance (the positive affect hypothesis). Baron has demonstrated this effect with fragrances [Baron & Thomley, 1994] and, to a lesser extent, with lighting conditions (fluorescent lamp type and horizontal illuminance) [Baron et al., 1992]. Newsham & Veitch [2001] also obtained supporting results with regard to luminous conditions. Their data came from participants who occupied a mock-up office space for a day and completed various simulated office tasks and questionnaires. They examined data from participants who worked under a fixed, pseudo-random lighting condition during the day, and made their own preferred lighting choice at the end of the day. Participants whose daytime light levels were closest to their own preference had significantly better ratings of mood (pleasure), lighting satisfaction, and environmental satisfaction.

Newsham et al. [2002b] conducted a pilot study designed to address some of the issues outlined above. They demonstrated a significant improvement in satisfaction with lighting after dimming control over a single circuit was introduced in a mock-up office space. Further, their data indicated that participants desired an increased level of partition illuminance (delivered using a partition washer) beyond that provided by a conventionally-designed ceiling-recessed parabolic system alone. The experiment described in this report grew out of this pilot study.

This report should is a continuation of an earlier report “Lighting for VDT workstations 1: Effect of control on energy consumption and occupant mood, satisfaction and discomfort” [Newsham et al., 2003]. The earlier report and the current report both detail the results of an experiment carried out in a mock-up office laboratory at NRC. One-hundred-and-eighteen participants, recruited from a local temporary-employment agency, worked in the laboratory for one day each. They worked on simulated office tasks, and completed a variety of questionnaires regarding their mood, satisfaction, and discomfort. Up to two participants worked on each day, housed in identical workstations.

Each participant worked under one of four office lighting designs (see Figure 1a and 1b). Design 1 was a conventional, ceiling-recessed, parabolic ambient lighting system; Design 2 used the same ambient lighting system as Design 1, with the addition of a custom, partition washer; Design 3 used the same ambient lighting system as Design 1, with the addition of an angle-arm task light; Design 4 used a suspended direct/indirect fixture for ambient light, and the same angle-arm task light used in Design 3. All designs offered dimming control over the ambient lighting system; Design 2 offered additional dimming control over the partition washer. In addition, Designs 3 and 4 allowed movement of the task light’s arm. Details on the lighting designs are available in Newsham et al. [2003].

Participants worked under one of four fixed initial lighting conditions until mid-afternoon, after which participants were invited to choose their preferred light level using dimming controls on their computer desktop. The full details of the experimental design are given in Newsham et al. [2003].

The experiment was designed to address several research questions:
1. Does providing task/partition lighting reduce ambient lighting use?
2. What are occupants’ preferred luminous conditions?
3. What is the effect of getting lighting control on mood, satisfaction, and task performance?
4. What is the effect of working under non-preferred lighting conditions on mood, satisfaction, and task performance?
5. Is there an effect of lighting design, and is additional vertical luminance beneficial?

Newsham et al. [2003] analysed data relevant to questions 1, 2 (desktop illuminance and partition illuminance at a single representative point only), 3 (mood and satisfaction effects only), 4 (mood and satisfaction effects only), and 5 (mood and satisfaction effects only). Results showed that while people chose to use the task/partition lighting, such use did not reduce average preferred levels of the parabolic ambient lighting. There was strong evidence that having dimming control over lighting, and using it to create preferred conditions, led to improvements in mood, satisfaction, and physical comfort.

This report addresses questions 2 through 5 with reference to more detailed photometric data, and to task performance outcomes. The Discussion and Conclusions sections of this report will address the experimental findings as a whole, encompassing the analysis in Newsham et al. [2003], and the analysis in this report.

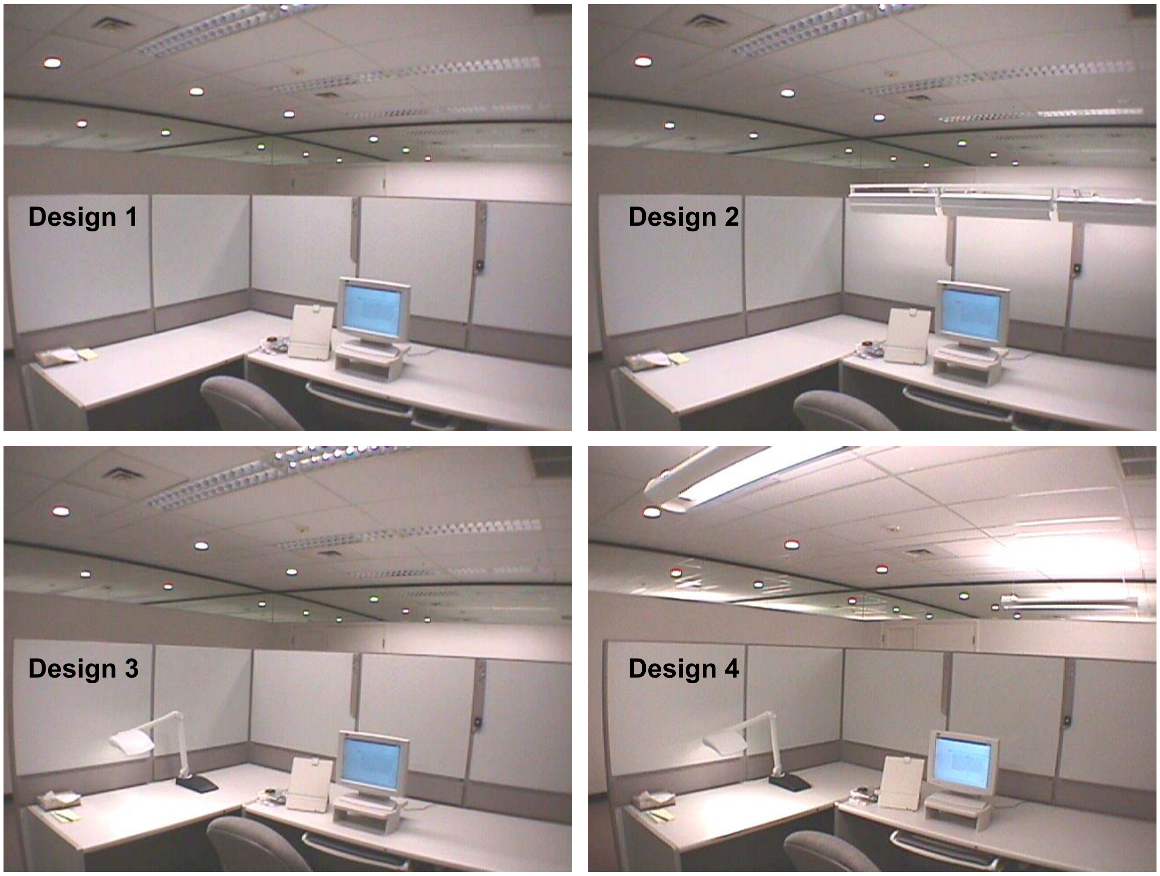
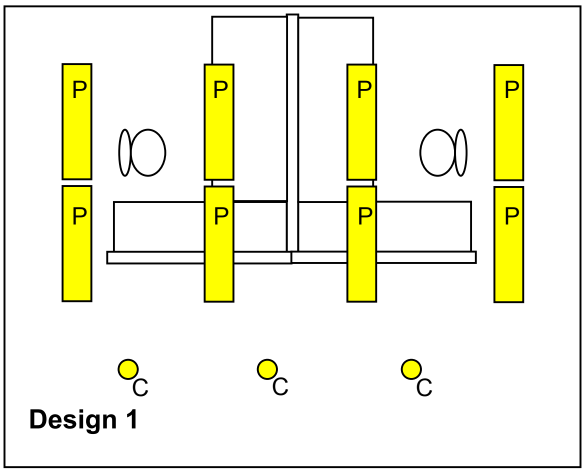
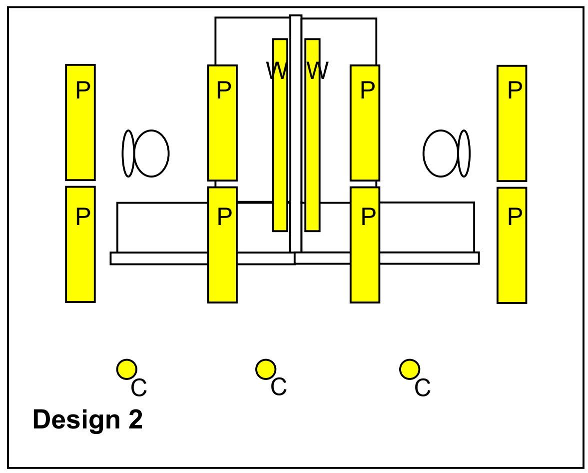
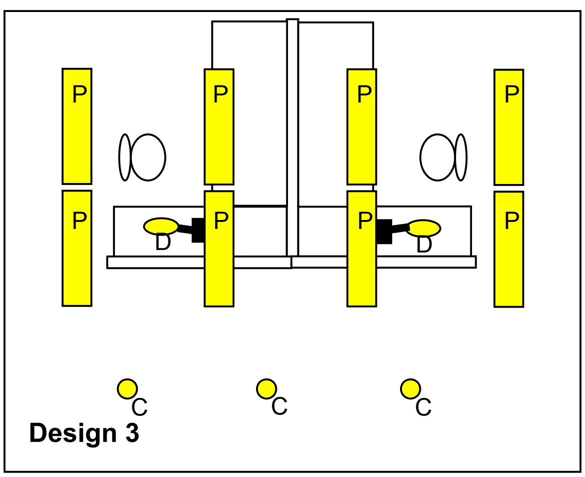


Figure 1a. Photograph of each lighting design in the experimental facility. Workstation A is shown, Workstation B was identical (in mirror-image), with the partition behind the computer screen shared between the two workstations.

Letter Code	Description
P	1' x 4' deep-cell (2x16 cells) semi-specular parabolic louvre fixtures, recessed in the ceiling. 2 x 32W T8 lamps (3500K); Electronic dimming ballast (5-110%).
I	10" x 4.5' Direct/indirect fixtures, suspended 18" from the ceiling. 2 x 32W T8 lamps (3500K); Electronic dimming ballast (5-110%).
W	Partition washer: 3 x 2', cantilevered from partition 1 x 17W T8 lamp each (3500K) + 50% neutral density filter Electronic dimming ballast (5-110%).
D	Angle-arm task light; 1 x 18Wquad CFL (4100K)
C	Pot light for corridor area. 1 x 50W PAR 20 Halogen floodlight.







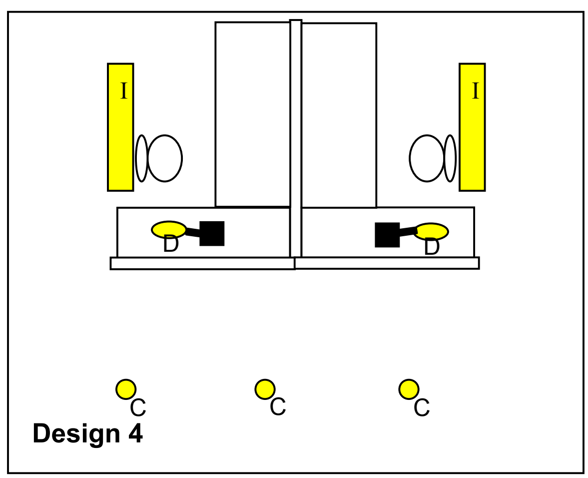


Figure 1b. Schematic diagram (plan view) of the luminaire layout for each lighting design. Luminaire descriptions are shown in above table.

Figure 2. The chin cup used for the vision test.

2. METHODS & PROCEDURES

A full explanation of methods and procedures was given in Newsham et al. [2003]. Descriptions of the daily schedule and the simulated office tasks, relevant to the analyses presented in this report, are repeated below.

Table 1 shows the model experimental schedule followed with each participant. Note that when participants returned from the afternoon coffee break on-screen instructions informed them that they now had control over the lighting assigned to their workstation. In Design 1 this meant dimming control over the recessed parabolics (one circuit). In Design 2 this meant dimming control over the recessed parabolics (one circuit), and the partition washer (one circuit). In Design 3 this meant dimming control over the recessed parabolics (one circuit), and the ability to move the arm of the task light. In Design 4 this meant dimming control over the suspended direct/indirect fixture (one circuit), and the ability to move the arm of the task light.

2.1 Simulated Office Tasks

The simulated office tasks completed by the participants were as follows:

Vision Test. We measured contrast sensitivity using custom software. A square target grating was presented on the computer screen (see Figure 3), and the participant's task was to indicate, as fast as they could, whether they saw a target or not by pressing a 'Yes' or 'No' key on the keyboard. The absolute luminances of the background and target grating depended on the prevailing illumination. The characteristics of the prevailing illumination, and the LCD backlighting, meant that there was also a luminance gradient across the screen. As an example, with lighting from ambient parabolics only at 50% output, the luminance just above the target grating was 27 cd/m^2, and just below the grating was 21 cd/m^2. The grating varied in luminance contrast from 0 to 16 grey levels above or below the grey level of the screen background (which was set to grey level 128 on the range 0 to 255). In the example above, a grey level difference of 16 corresponded to a luminance difference of ~ 6 cd/m^2. The target was varied by foreground:background contrast, orientation (lines horizontal or vertical), and size (width of the grating lines within the fixed-size target). Thirty-six combinations of these target parameters were presented in a randomised order each time the task was completed. We recorded both accuracy and speed of detection as outcomes. This was the only task where we controlled task-eye geometry. Participants positioned their head in a chin cup, which was 40" (1.02m) from the floor, and 20" (0.51m) from the computer screen, as shown in Figure 2.

Simple Cognitive/Clerical Performance. This was assessed using a typing task scored for speed and accuracy. In this task, participants retyped three ~300-word passages from printed originals. The three passages were presented in differing font sizes: 8, 12, and 16 point Times Roman, while the on-screen font size was always 12 point. The software required participants to type the text correctly; speed and number of errors were automatically recorded. Participants were asked to place the paper on a document holder (not adjustable), which was at a fixed location on the desk close to the computer screen.

Complex Cognitive Performance. There were three measures of this construct. All were based on short articles on popular topics broadcast in the popular media. The selected articles were 200-300 words long.

1. Article Categorisation. The participant saw a 40-60-word summary of a given article (the first 3 or 4 sentences), shown in 12-point type. Below the article was a list of 4 categories into which the article might be placed. In half of the summaries some words of text were highlighted; the highlighted text was designed to indicate a key phrase in the text to aid categorisation. The task was to read the summary and to place it in one of four categories, based on subject matter. Dependent measures were the time required to perform the categorisation, and accuracy of categorisation (correct responses were established by independent ratings from three researchers).

2. Summary Evaluations. Clicking 'Done' after the categorisation question caused a rating question to appear, in which the participant indicated on a 0-100 slider their interest in reading the whole article based on just the summary. Clicking "Done" after this question caused the screen to refresh. The entire article appeared in another box, along with the summary and an area in which there were three more rating questions. The participants were asked to indicate their agreement with the following statements: "The summary contains all the important facts expressed in the full article"; "The summary is grammatically correct"; "The summary is well written". Responses were on a 5-point scale from Strongly Disagree to Strongly Agree (0-4).

3. Summary Extraction. Participants read an article (~300 words) on paper. When they had finished, a list of all the sentences appearing in the article in sequential order appeared on screen. Participants were asked to indicate the 4 most important sentences in the article in conveying the meaning of the article (by checking a box beside the sentences they chose). This task is much easier to score than summaries generated from free composition. The dependent measure was the time taken.

Conflict Resolution. Participants read scenarios describing common workplace conflicts, then responded using multiple choice to indicate their preferred conflict resolution styles: Competition, Accommodation, Collaboration, Compromise, or Avoidance. It was based on the 2-dimensional model of conflict proposed by Thomas [Kilmann & Thomas, 1977; Thomas, 1976].

Vigilance/Alertness. There was always an envelope icon on the computer screen in a fixed location. Participants were instructed that when the icon changed colour and they heard a 'beep', they were to click on the icon as quickly as possible. The dependent variable was the time taken to respond to the event. These events occured at pre-determined randomized intervals (but not during any other timed task, to avoid software conflicts). One outcome from the NRC conveyor belt task (described below) also provided a measure of vigilance/alertness.

Motivation/Persistence. The NRC conveyor belt task, with a simple target moving at higher and higher speeds, was the measure of persistence. Symbols entered the screen from the left, travelling along a black line that represents a conveyor belt. Certain symbols were designated as targets. When targets crossed the screen into a box called the 'removal area', participants were instructed to remove them as quickly as possible by pressing the spacebar on the computer keyboard. Participants were instructed to stop responding when they could no longer keep up. The dependent measure of persistence was the maximum speed at which they stopped responding. This measure is analogous to the paper-based task developed by Feather [1962], in which participants try to complete impossible puzzles. We also measured the rate of correct target removal.

Work Structure. For the typing, conveyor belt, and summary extraction tasks, we also recorded the length of the time intervals taken by the participant between completing one part of the task and starting the next. These were analyzed to give an indication of whether or not lighting conditions altered the work strategies of participants, as had been observed in a prior experiment [Boyce & Eklund, 1996].

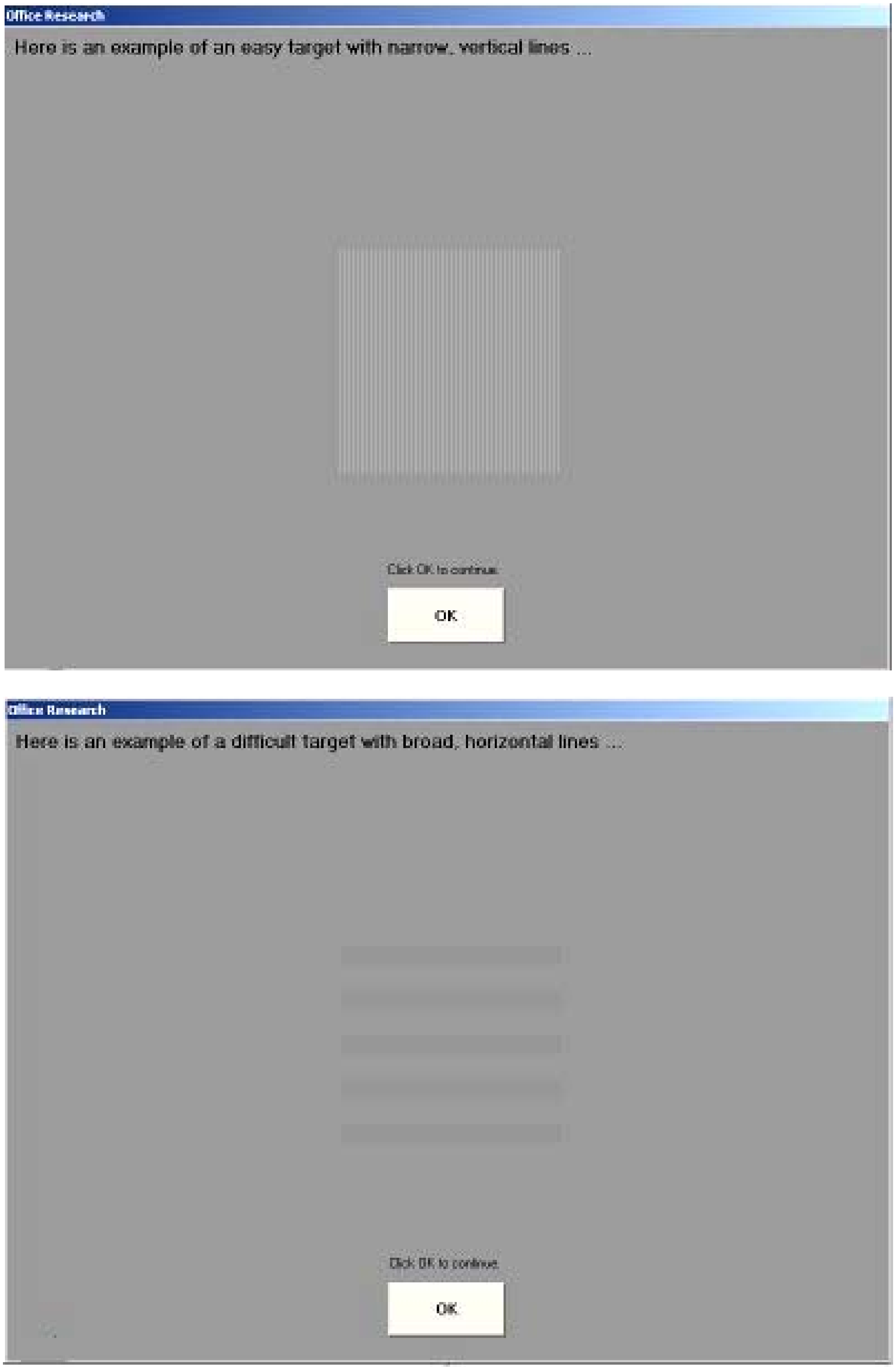


Figure 3. Example screenshots of on-screen vision test.

Table 1. Model experimental schedule for each participant.

Approx. Time	Duration (min)	Task
8:45 a.m.	15	Arrival, greeting, instructions, consent, assignment to workstations
9:00	5	Vision Test I
9:05	10	Response training
		Demographics
		Visual Comfort I
		Physical Comfort I
		Room Appraisal I
9:15	15	Training - Typing, Summarizing
		Task Competence: Self-set goals
9:30	20	Training - Categorization, Conveyor Belt
9:50	10	Lighting Preferences I
		Mood I
		Environmental Competence I
10:00	*15*	*Break*
10:15	15	Typing I
10:30	15	Summarizing I
10:45	20	Categorization I
11:05	10	Conveyor Belt I
11:15	30	Conflict Resolution
11:45	*60*	*Lunch*
12:45	15	Typing I
1:00	15	Summarizing I
1:15	20	Categorization I
1:35	10	Conveyor Belt I
1:45	20	Mood II
		Room Appraisal II
		Lighting Preferences II
		Visual Comfort II
		Physical Comfort II
		Workplace Satisfaction I
2:05	5	Vision Test II
2:10	*15*	*Break*
2:25	*10*	*Instructions on Using Lighting Controls*
2:35	15	Typing I
2:50	15	Summarizing I
3:05	20	Categorization I
3:25	10	Conveyor Belt I
3:35	20	Mood III
		Room Appraisal III
		Lighting Preferences III
		Visual Comfort III
		Physical Comfort III
		Environmental Competence II
		Workplace Satisfaction II
		Lighting Control Evaluation
3:55	5	Vision Test III
4:00	5	Workday Experiences
4:05	10	Debrief, Farewell

2.2 Photometric Measurements

During the experimental session we recorded illuminance at two fixed positions in each workstation using Minolta T-10M illuminance meters. The measurement points are shown in Figure 4; these positions were chosen as typical desktop and partition illuminance spot measurements. Readings were taken automatically every time a control action was taken by a participant, and were also triggered manually by the experimenter at the start of the day, and during breaks.

Newsham et al., [2003] provided data on the illuminance conditions chosen by the participants, for the two fixed points in each workstation. Following completion of all experimental sessions, the dimmer settings and illuminances recorded during the experimental sessions were used to recreate the lit environments experienced by the participants. The dimmers were set to the values used/chosen at a particular point during the experimental session, and the resulting illuminances at the two fixed points were checked against those recorded during the experimental session to ensure that the conditions had been faithfully reproduced. Then a larger set of luminance and illuminance measurements were taken, as shown in Figures 5 and 6. Luminance measurements were made with a tripod-mounted Topcon BM-3 luminance meter with a 2^{o} field of view, and illuminance measurements were made with Minolta T-1 illuminance meters.

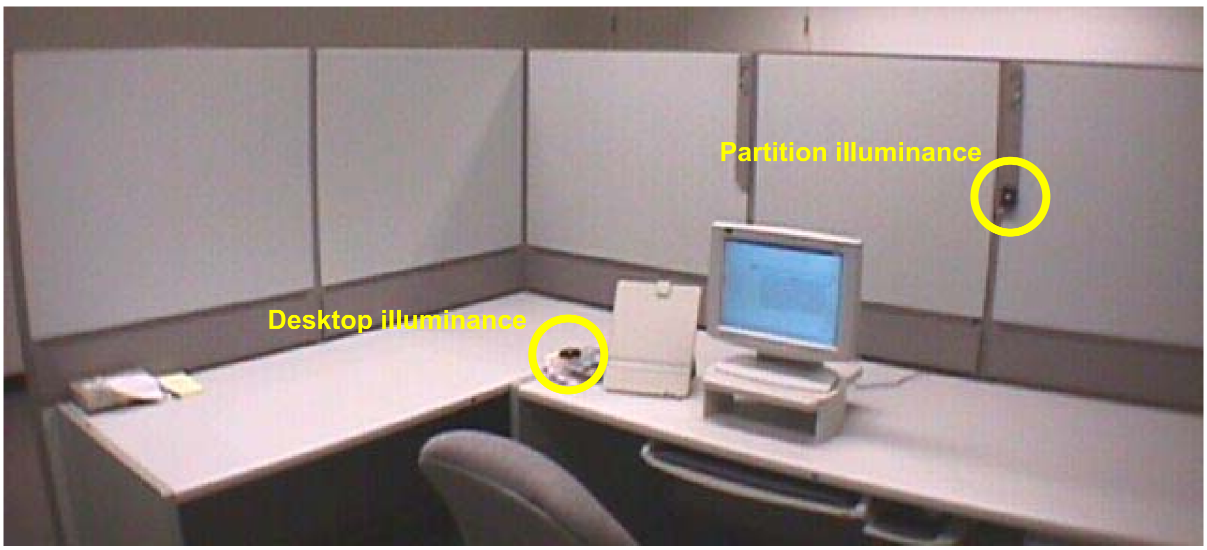


Figure 4. Fixed photometric measurement points in Workstation A; two more illuminance sensors were placed at identical points in Workstation B.

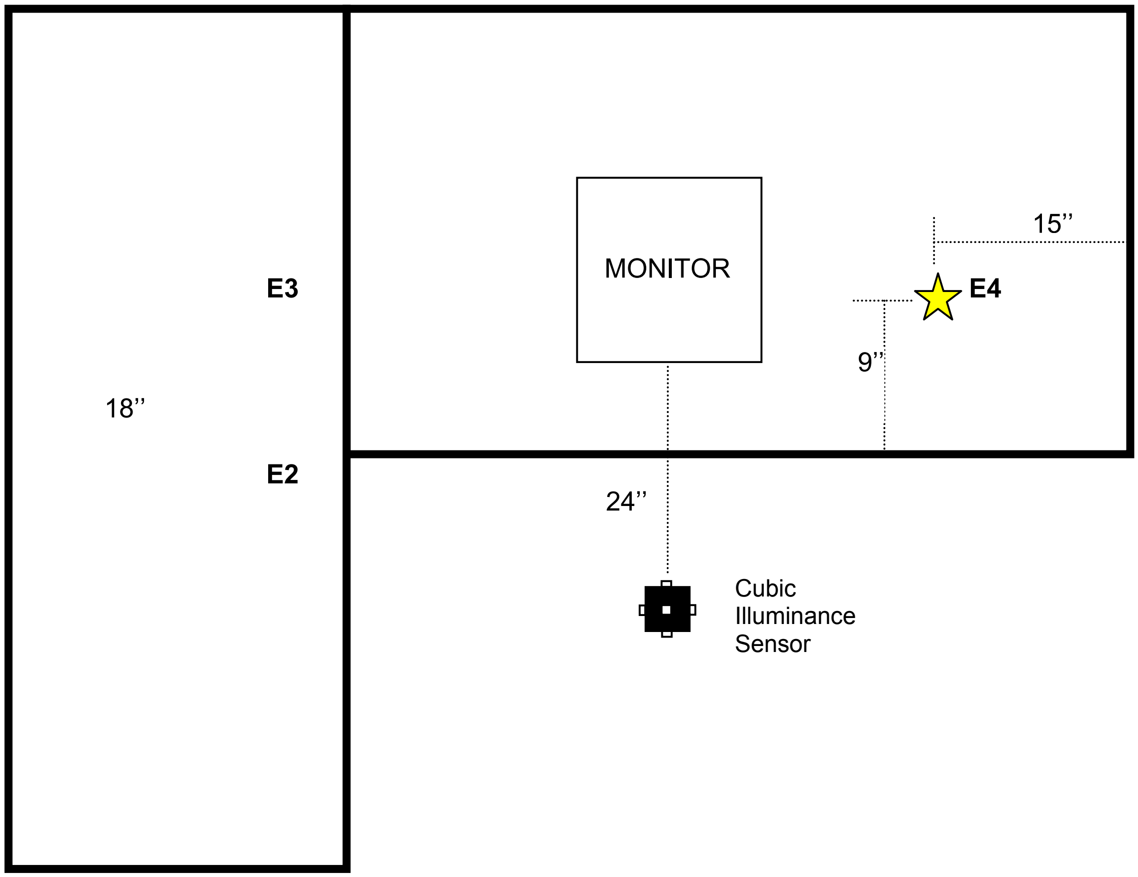
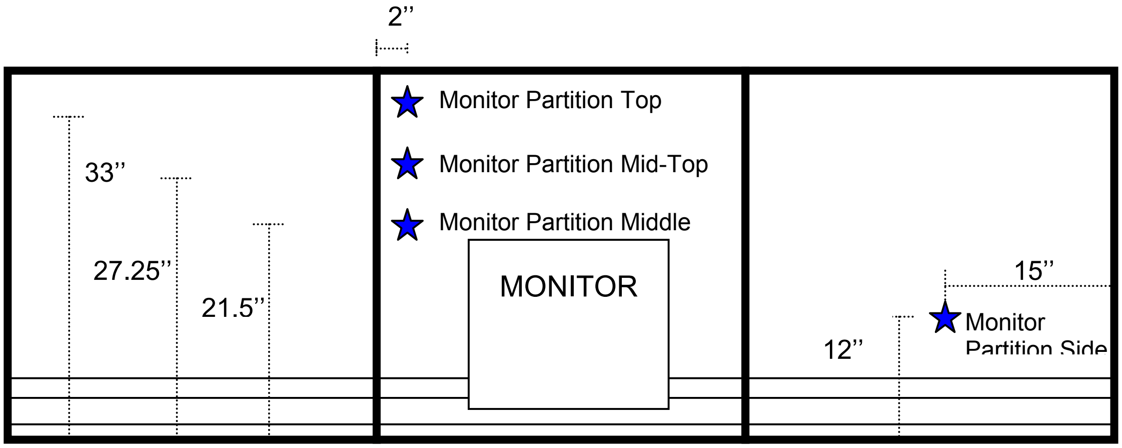
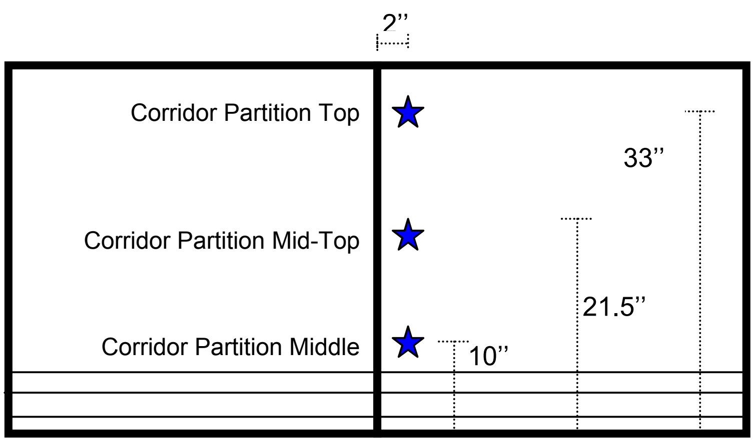


Figure 5. The location of the additional illuminance measurements made when the conditions were recreated. Locations for Workstation A are shown, Workstation B locations mirrored these.



For workstation A there was an additional luminance measurement point on the wall to he right of the computer screen (left in workstation B), 52" from the floor, and 55" from the partition behind the computer screen. The luminance measurement on the ceiling was made at a point directly above the seated participant.



With the workstation A participant facing their computer screen, this partition was to their left (right in workstation B), adjacent to the corridor. That part of the partition above the desktop is shown.

Figure 6. The location of the additional luminance measurements made when the conditions were recreated. Locations for Workstation A are shown, Workstation B locations mirrored these.

3. RESULTS & DISCUSSION

As described in the Introduction, the experiment was designed to address several research questions:

1. Does providing task/partition lighting reduce ambient lighting use?
2. What are occupants' preferred luminous conditions?
3. What is the effect of getting lighting control on mood, satisfaction, and task performance?
4. What is the effect of working under non-preferred lighting conditions on mood, satisfaction, and task performance?
5. Is there an effect of lighting design, and is additional vertical luminance beneficial?

As stated above, this report addresses questions 2 through 5 with reference to more detailed photometric data, and to task performance outcomes. Each of these questions is addressed with reference to the collected data in the sub-sections below.

3.1 What are occupants' preferred luminous conditions?

Several sets of post-session measurements were made for each participant, the exact number depending on the number of different conditions created by the participants during the session. For all participants, we made measurements at the following times:

1. The initial lighting conditions, pre-control, during the morning coffee break
2. The lighting conditions after first use of control (experimenting with the controls was ignored, only the choice that participants settled on was measured)

After that, any change of condition that prevailed for more than a few minutes, was recorded.

We assumed that a reasonable error related to this kind of measurement, accounting for instrumentation accuracy, lumen depreciation, and any other differences between the room between the original experimental session and the day on which the conditions were reproduced, was 10%. Therefore, any condition for which the difference between the original and reproduced measurements at the four fixed locations totalled more than 40% (4 x 10%) was dropped from the dataset. For Design 1, 7 out of 125 total measurements were dropped in this manner; for Design 2 none were dropped; for Design 3, 16 out of 99 were dropped; for Design 4, 10 out of 109 were dropped. The designs featuring the angle-arm task light (Design 3 and 4) tended to have a greater number of dropped cases. This is because of the ability the participants had to change the position of the task light arm. We recorded the position of the arm at the end of each experimental session, but had no way of recording if the task light was in other locations during the session afternoon. Differences in task light location could make a big difference to recorded luminous conditions.

Table 2 shows the illuminances measured at the four fixed locations for the four initial conditions for each lighting design, when the conditions were reproduced. For comparison, look at Table 2 in Newsham et al. [2003] – the values are very similar, suggesting that our ability to reproduce luminous conditions was acceptable. The mean percentage difference across all designs was 3.0% for workstation A desktop, 3.2% for workstation A partition, 2.6% for workstation B desktop, and 2.4% for workstation B partition.

Table 3 shows the illuminances measured at the four fixed locations for the four initial conditions for each lighting design, when conditions were reproduced; data for participant choices after first control, and after the final control action made in the space are shown. These data are summarized in Figure 7. All participants used the dimmers when control was first offered. On 15 experimental days (out of 62) participants made no further adjustments in the experimental session, in these cases the final control photometric measurements are the same as the first control measurements. Table 3 shows that, on average, participant choices did not change substantially from first to final control. Differences in means are rarely >100 lux though, interestingly, the general tendency is for mean illuminance to decline from first to final control. Final control does represent choices made after a longer exposure to the space and to the tasks, therefore, for the remainder of the descriptive photometric data, we will present conditions prevailing at the time of final control only. Table 3 also shows that, for the illuminances after final control, there is no systematic difference in means based on the initial conditions at the start of the day. This is a welcome finding, suggesting that individual preferences for office lighting are intrinsic, and not biased by initial conditions. Therefore, for the remainder of the descriptive photometric data, we will present conditions by lighting design over all initial conditions combined. We will maintain the presentation by lighting design because of the very different lighting equipment used in each of the designs.

Table 4 shows the luminances measured at various points in the workstations, after the final control action; data for select points are summarized in Figure 8. For Design 1, the dimmable recessed parabolics, the average chosen luminances on the vertical surfaces are in the 30-40 cd/m^2 range, consistent with other studies of office worker preferred luminances [Newsham et al., 2002; Veitch & Newsham, 2000a; Loe et al., 1994; Berrutto et al., 1997]. The addition of the task light in Design 3 increases luminances on the partitions by ~ 5 cd/m^2. The partition washer in Design 2 increases measured luminances considerably, particularly on the partition behind the computer screen. For that partition, chosen luminances are 3-4 times the preferred luminances observed in the other studies referenced above, remember, participants could have turned the partition washer off, which would have made Design 2 essentially the same as Design 1. This suggests that preferred luminances are somewhat dependent on the lighting equipment available. In Design 4, the total number of lumens available was considerably lower than in the other designs, and the chosen luminances on the partitions are consequently lower. However, unlike the other designs, Design 4 had the only ambient lighting fixture with an uplight component, leading to a considerably higher ceiling luminance than that prevailing in the other designs.

Table 5 shows the illuminances measured at various locations on the desktop, and on the six faces of the cubic illuminance sensor, placed approximately where a seated participant's head would have been; data for select illuminances are summarized in Figure 9. Again, data refer to conditions after the final control action. For Design 1, with recessed parabolic fixtures, the average chosen illuminances are in the 350-500 lux range, consistent with other studies of office worker preferred illuminances [Veitch & Newsham, 2000a; Newsham & Veitch, 2001]. Also consistent with previous work was the wide range of individual preferences, from virtually zero illuminance, up to 1000 lux or more. The addition of the task light in Design 3 increases illuminances compared to Design 1, particularly at the E1 location, close to the default position of the task light. The partition washer in Design 2 increases illuminances compared to Design 1, the biggest increases occurring at the locations closest to the partition where the washer was mounted. Design 4 generally had lower chosen illuminances than the other Designs. However, it did allow for a relatively high illuminance at the E1 location, below where the fixture was mounted.

Table 6 shows illuminance ratios, derived from the cubic illuminance measurements; these data are summarized in Figure 10. As expected, Designs 1, 2 and 3, with the parabolic ambient lighting, have a higher horizontal:vertical ratio than Design 4, with the direct/indirect fixture. Previous work in the same laboratory, indicated that designs with front:back and side:side ratios further from 1:1 would be less favoured[1]. However, Table 6 shows that those designs with the side:side ratio closest to 1:1 are also the designs with the front:back ratio furthest from 1:1. Newsham et al. [2003] showed almost no effect of design on satisfaction outcomes. It is possible that the side:side and front:back ratio effects tended to cancel out leading to the almost null effect of design on satisfaction. However, a future study deliberately manipulating these ratios in a consistent manner is necessary to study these effects.

Table 7 shows the number of control actions taken by lighting design. A control action was defined as use of the dimmers to create a condition that then remained in use for several minutes. Therefore,

[1] This was suggested in the presentation of: Newsham, G.R.; Marchand, R.G.; Svec, J.M.; Veitch, J.A. "The Effect of power constraints on occupant lighting choices and satisfaction: a pilot study," at the IESNA Annual Conference, Salt Lake City, 2002, but was not part of paper which was published in the conference proceedings (pp. 115-131).

a single control action could encompass several dimmer adjustments by one or both occupants with a minute, prior to settling on a condition. Previous work[2] suggested that a successful control system would be one requiring the fewest adjustments. Design 3 exhibited the lowest number of control actions per day, on average. However, we did not record the number of adjustments to the location of the task light during the experimental session. We did note whether at the end of the day the task light arm was in a substantially different position compared to the start of the day, and this is also shown in Table 7. Adding these changes to the control actions made with dimmer system brings Design 3 more in line with Designs 1 and 2 in terms of total lighting adjustments.

Table 8 shows how those control actions were distributed by task, over all lighting designs. Table 8 also shows whether that action took dimmers up, down, or a mixture of up and down. The 'mixture' condition could occur in two different ways. It could occur when there were two participants, and one increased their dimmer setting while the other decreased it. Or it could occur in Design 2 where a single participant increased the ceiling-recessed parabolics and decreased the partition washer, or vice versa. It is interesting to note that for the most visually demanding on-screen tasks (Vision, Persistence) there was a tendency to lower light levels, whereas for the other tasks the direction of change was more balanced across participants. We cannot be sure why people doing visually demanding on-screen tasks tended to lower light levels, perhaps it was to focus attention on the self-luminous task, or to reduce an ambient light veil and thus increase task contrast. However, the important message from the data in Table 8 is that people did sometimes choose to change light levels between tasks. Individuals differ in what those preferred changes are, and only individual dimming control can provide people with the ability to make such independent choices.

Table 2. Illuminance measured at the 4 fixed points on the day conditions were recreated. For initial dimmer settings (pre-control). Data are presented by lighting design, and initial condition, for both workstations combined.

Lighting Design	Initial Condition	desktop	partition
1	**A**	194	80
	B	412	178
	C	589	254
	D	827	354
2	**A**	203	297
	B	428	384
	C	598	467
	D	804	550
3	**A**	196	63
	B	395	149
	C	560	220
	D	776	313
4	**A**	127	60
	B	180	102
	C	241	148
	D	302	200

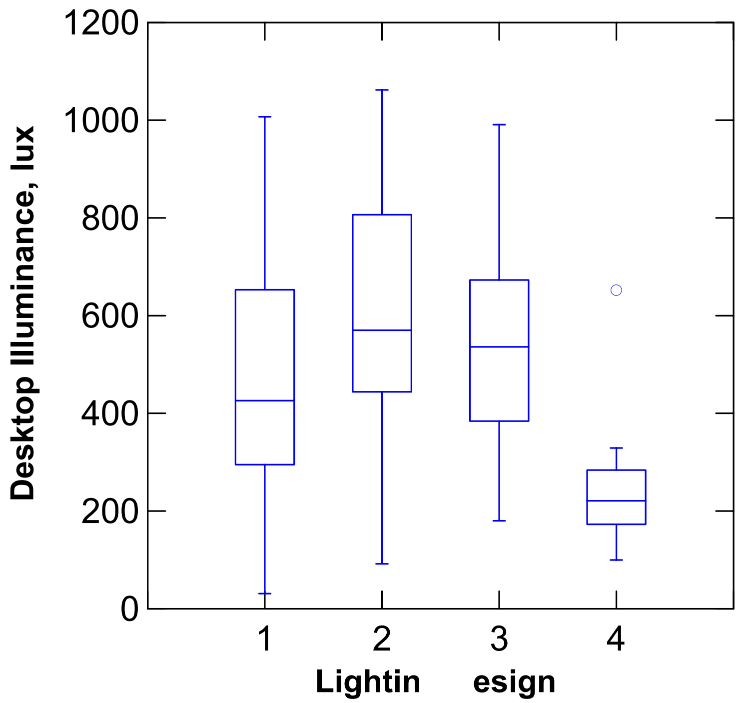
[2] Same comment as footnote 1.

Table 3. *Illuminance measured at the 4 fixed points on the day conditions were recreated. Data for participant choices after first control, and after the final control action made in the space are shown. Results are presented by lighting design, and initial condition.*

			After First Control		After Final Control	
Light. Design	**Initial Cndtn.**		**desk**	**partition**	**desk**	**partition**
1	**A**	**N**	7	7	7	7
		Min.	266	108	266	108
		Max.	739	316	739	309
		Med.	544	233	544	233
		Mean	508	217	483	205
		SD	186	80	193	82
	B	**N**	7	7	7	7
		Min.	293	120	31	11
		Max.	688	306	688	306
		Med.	614	255	614	255
		Mean	541	226	446	190
		SD	154	71	269	114
	C	**N**	8	8	8	8
		Min.	316	121	224	93
		Max.	963	436	1007	414
		Med.	487	204	416	177
		Mean	574	246	520	221
		SD	239	111	282	120
	D	**N**	8	8	7	7
		Min.	359	154	122	51
		Max.	941	394	948	437
		Med.	494	205	348	152
		Mean	537	229	436	189
		SD	203	83	352	161
2	**A**	**N**	8	8	8	8
		Min.	223	184	92	22
		Max.	936	941	891	875
		Med.	662	556	482	544
		Mean	627	590	471	501
		SD	262	246	243	283
	B	**N**	7	7	7	7
		Min.	444	203	357	216
		Max.	874	915	850	907
		Med.	794	867	598	680
		Mean	699	698	615	588
		SD	172	305	208	265
	C	**N**	8	8	8	8
		Min.	366	364	233	284
		Max.	1062	1093	1062	1093
		Med.	725	861	666	788
		Mean	706	764	648	723
		SD	254	274	297	300
	D	**N**	8	8	8	8
		Min.	570	501	233	141
		Max.	943	971	887	991
		Med.	819	658	759	635
		Mean	804	726	664	621
		SD	127	185	236	320

Table 3. *continued.*

Light. Design	Initial Cndtn.		After First Control desk	After First Control partition	After Final Control desk	After Final Control partition
3	A	N	7	7	7	7
		Min.	354	132	267	85
		Max.	1070	444	991	408
		Med.	725	288	641	253
		Mean	740	300	615	244
		SD	291	129	252	110
	B	N	6	6	5	5
		Min.	392	146	392	146
		Max.	624	255	559	218
		Med.	512	200	512	209
		Mean	509	200	499	195
		SD	82	37	64	30
	C	N	4	4	6	6
		Min.	298	105	206	63
		Max.	737	295	737	295
		Med.	378	131	362	129
		Mean	448	165	390	144
		SD	198	87	187	81
	D	N	7	7	7	7
		Min.	180	31	180	31
		Max.	999	427	949	403
		Med.	787	306	667	272
		Mean	654	257	633	248
		SD	297	145	266	128
4	A	N	6	6	6	6
		Min.	150	76	150	76
		Max.	329	171	329	171
		Med.	234	146	198	116
		Mean	232	134	219	123
		SD	64	38	68	38
	B	N	7	7	7	7
		Min.	117	51	157	82
		Max.	284	185	652	185
		Med.	239	143	267	143
		Mean	220	133	299	142
		SD	66	52	161	39
	C	N	5	5	6	6
		Min.	138	69	164	90
		Max.	292	191	296	193
		Med.	270	171	242	150
		Mean	249	157	242	151
		SD	64	51	50	39
	D	N	8	8	7	7
		Min.	149	78	100	52
		Max.	294	192	291	189
		Med.	259	165	211	122
		Mean	237	147	191	115
		SD	53	43	81	59



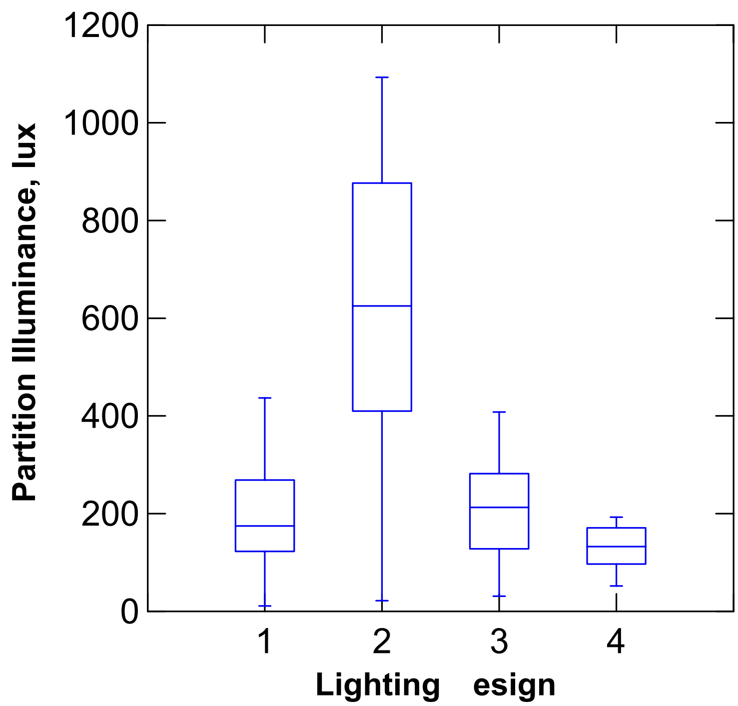


Figure 7. Summary chart of illuminance measured at the fixed points on the day conditions were recreated. Participant choices after the final control action are shown. Results are presented by lighting design, and include both workstations. The line in the middle of the box is the median value; the box shows the interquartile range. The 'whiskers' show the range of values falling within ±2 interquartile ranges of the mean, and circles indicate individual extreme values.

Table 4. *Luminance measured at various points in the workstations on the day conditions were recreated. Data for participant choices after the final control action made in the space are shown. Results are presented by lighting design, over all initial conditions and both workstations.*

Light. Design		Luminance (cd/m^2)								
		Side Wall	**Monitor Partition Side**	**Ceiling**	**Monitor Partition Top**	**Monitor Partition Mid-Top**	**Monitor Partition Middle**	**Corridor Partition Top**	**Corridor Partition Middle**	**Corridor Partition Bottom**
1	**N**	29	29	29	29	29	29	29	29	29
	Min.	7	7	6	3	7	5	5	6	8
	Max.	89	59	63	99	101	92	72	71	85
	Med.	39	25	29	42	41	36	31	30	35
	Mean	43	29	30	46	46	42	33	34	38
	SD	23	15	14	27	27	24	17	18	21
2	**N**	31	31	31	31	31	31	31	31	31
	Min.	8	6	12	10	8	7	8	9	11
	Max.	92	76	75	322	293	210	82	86	88
	Med.	55	46	43	175	185	121	45	43	46
	Mean	54	44	44	171	166	116	44	47	50
	SD	24	19	16	84	82	55	18	19	21
3	**N**	25	25	25	25	25	25	25	25	25
	Min.	8	4	14	17	11	9	12	15	24
	Max.	83	57	63	103	99	93	73	75	81
	Med.	45	29	35	52	52	48	36	39	47
	Mean	43	29	35	54	51	48	38	40	46
	SD	20	14	13	24	23	22	17	17	17
4	**N**	26	26	26	26	26	26	26	26	25
	Min.	15	7	41	10	14	6	17	15	18
	Max.	56	28	190	43	36	36	44	39	48
	Med.	39	19	128	28	27	25	31	32	32
	Mean	38	19	128	27	26	25	30	29	31
	SD	13	7	47	9	7	7	8	8	8

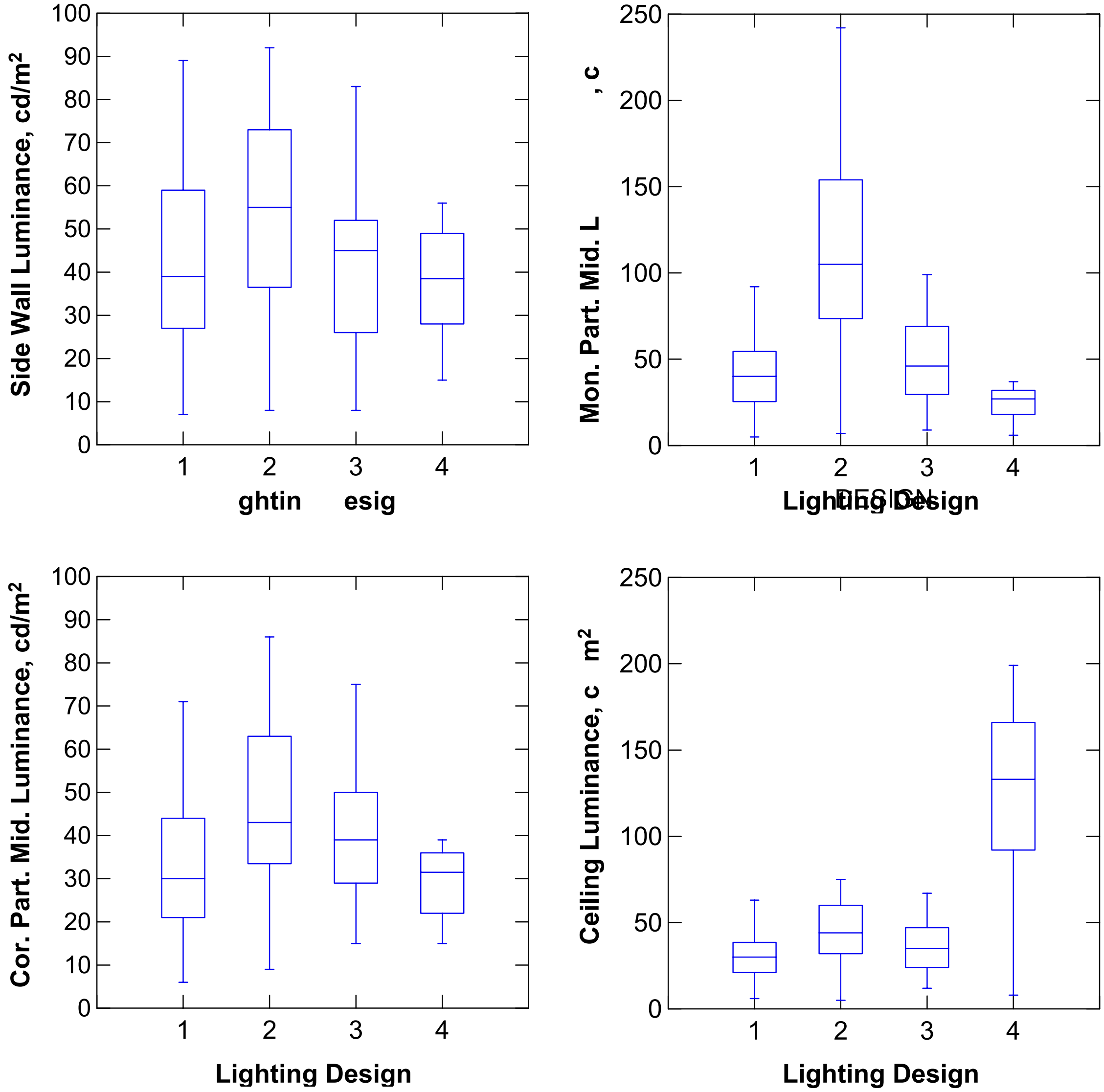


Figure 8. Summary chart of luminance measured at select points on the day conditions were recreated. Participant choices after the final control action are shown. Results are presented by lighting design, and include both workstations. The line in the middle of the box is the median value; the box shows the interquartile range. The 'whiskers' show the range of values falling within ±2 interquartile ranges of the mean.

Table 5. Illuminance measured at various points in the workstations on the day conditions were recreated. Data for participant choices after the final control action made in the space are shown. Results are presented by lighting design, over all initial conditions and both workstations.

		Illuminance (lux)									
		Desktop				Cubic					
Light. Design		E1	E2	E3	E4	Front	Back	Top	Bottom	Left	Right
1	**N**	29	29	29	29	29	29	29	29	29	29
	Min.	10	7	34	16	14	8	17	-3	7	11
	Max.	1090	1142	988	1174	291	418	1179	76	343	349
	Med.	375	452	341	352	110	170	490	29	124	110
	Mean	408	476	429	419	130	188	546	33	134	129
	SD	266	282	259	289	80	111	322	22	82	86
2	**N**	31	31	31	31	31	31	31	31	31	31
	Min.	32	106	24	28	4	14	48	-1	21	14
	Max.	1069	1174	1001	1093	326	2389	1188	76	351	332
	Med.	512	563	568	561	168	299	597	36	167	168
	Mean	488	600	552	538	161	389	658	41	164	167
	SD	254	265	249	276	88	528	303	21	81	84
3	**N**	25	25	25	25	25	25	25	25	25	25
	Min.	116	185	63	41	58	19	65	7	43	22
	Max.	1907	1283	1148	2134	285	387	1118	86	331	328
	Med.	1141	686	514	486	145	202	578	40	132	124
	Mean	968	658	541	828	156	192	553	41	147	137
	SD	619	289	276	677	66	97	280	21	77	77
4	**N**	26	26	26	26	26	26	26	26	26	26
	Min.	86	83	78	69	41	52	109	8	44	34
	Max.	1447	635	468	1804	93	221	445	32	114	122
	Med.	805	333	215	250	77	147	301	22	81	86
	Mean	719	327	255	674	72	148	301	22	81	84
	SD	538	153	140	620	16	53	108	8	22	26

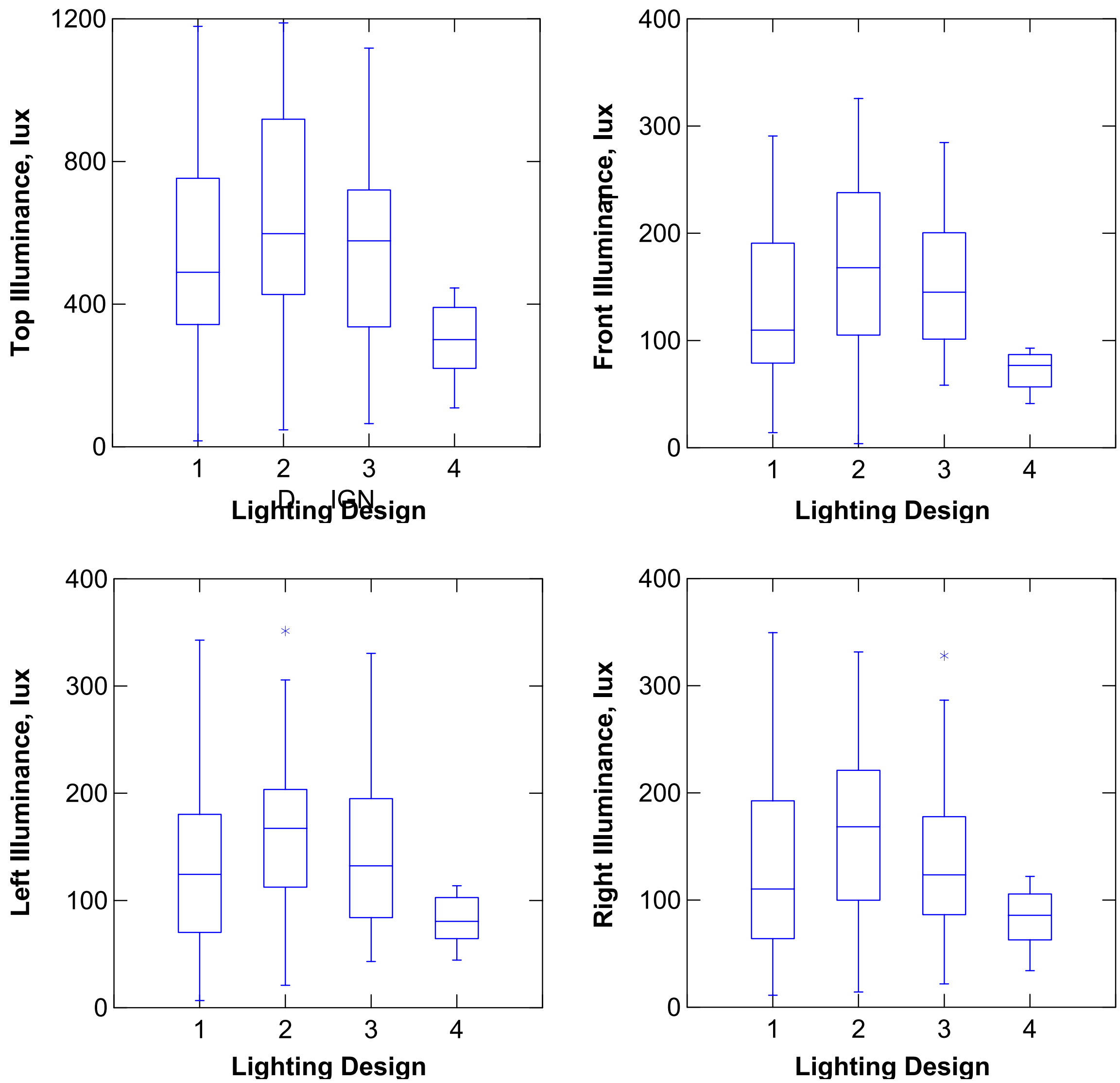


Figure 9. Summary chart of select cubic illuminances measured on the day conditions were recreated. Participant choices after the final control action are shown. Results are presented by lighting design, and include both workstations. The line in the middle of the box is the median value; the box shows the interquartile range. The 'whiskers' show the range of values falling within ±2 interquartile ranges of the mean, and stars indicate individual extreme values.

Table 6. Illuminance ratios derived from cubic illuminance measurements. Data for participant choices after the final control action made in the space are shown. Results are presented by lighting design, over all initial conditions and both workstations.

Light. Design		**Ratio**		
		Horiz:Vert	**Front:Back**	**Side:Side**
1	**N**	29	29	29
	Min.	1.49	0.06	1.62
	Max.	4.71	2.24	1.82
	Med.	3.72	0.75	1.70
	Mean	3.64	0.78	1.71
	SD	0.52	0.36	0.05
2	**N**	31	31	31
	Min.	0.95	0.05	1.38
	Max.	4.56	2.24	1.67
	Med.	3.57	0.78	1.55
	Mean	3.39	0.71	1.54
	SD	0.91	0.44	0.06
3	**N**	25	25	25
	Min.	1.67	0.69	1.62
	Max.	3.77	3.67	2.07
	Med.	3.51	0.79	1.79
	Mean	3.37	0.95	1.82
	SD	0.42	0.58	0.12
4	**N**	26	26	26
	Min.	2.36	0.35	1.00
	Max.	3.41	0.99	1.30
	Med.	3.15	0.47	1.06
	Mean	3.06	0.53	1.09
	SD	0.28	0.16	0.09

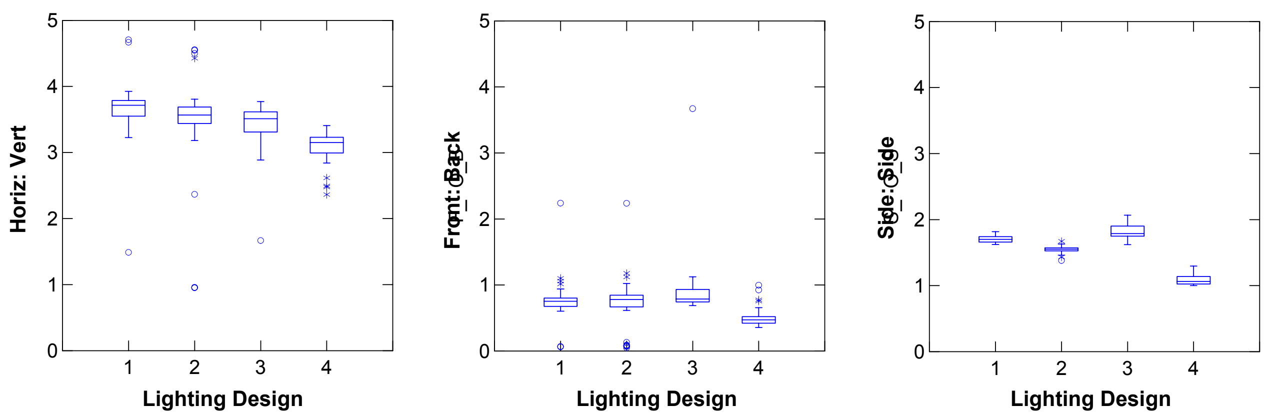


Figure 10. Summary chart of cubic illuminance ratios measured on the day conditions were recreated. Participant choices after the final control action are shown. Results are presented by lighting design, and include both workstations. The line in the middle of the box is the median value; the box shows the interquartile range. The 'whiskers' show the range of values falling within ±2 interquartile ranges of the mean, and stars and circles indicate individual extreme values.

Table 7. Number of dimming control actions made over all experimental days, for each lighting design. Number of participants who changed their task light position is also shown.

Lighting Design	Control Actions	Expmnt. Days	Actions per Day	Task Light adjustments
1	46	15	3.1	
2	49	16	3.1	
3	38	16	2.4	8
4	41	15	2.7	10

Table 8. Number of dimming control actions over all experimental days and lighting designs for each task or task category.

Task	Number of Control Actions	Direction of Control Action		
		Up	**Down**	**Mix**
Vision	13	4	9	0
Typing	17	7	7	3
Cognitive	34	11	18	5
Persistence	26	4	20	2
Questionnaires	16	7	7	2
Getting Printed Materials	2	2	0	0

3.2 What are the effects on task performance?

To answer this question we began by conducting a series of analyses of variance using the data from the various tasks. When there was only one outcome for a particular aspect of performance the tests were univariate (ANOVAs). When there was more than one outcome for a particular aspect of performance the tests were multivariate (MANOVAs). For the MANOVAs, outcomes were grouped according to the aspect of performance being investigated; though many were based on multiple outcomes from a single task type, some did involve outcomes from more than one task. Following our common practice (and in order to avoid Type I statistical errors) we examined univariate effects only if the overall MANOVA was significant. In some cases simple transformations were applied to outcome variables to improve the normality of data distribution, any such transformations are described below.

Each analysis looked at between-subject (BS) lighting design effects, and, where applicable, within-subject (WS) time-of-day and task characteristics effects, and their interactions. The initial condition for each lighting design was also varied, but we did not include it as a separate independent variable in these analyses. The primary reason to vary initial condition was for the analysis of the effect of non-preferred conditions (see Section 3.3). As shown above, final preference did not vary systematically with initial condition, and so we collapsed over initial condition and analysed 4 (lighting design) x 3 (time-of-day) ANOVAs and MANOVAs.

For lighting design effects we conducted four single degree-of-freedom contrasts:

1. Design 1 vs. Design 2 (effect of adding the partition washer to ambient parabolics)
2. Design 1 vs. Design 3 (effect of adding the desk lamp to ambient parabolics)
3. Design 1 vs. Design 4 (comparison of typical office lighting to new PWGSC concept)
4. Design 3 vs. Design 4 (effect of ambient lighting design when both designs have a desk lamp)

Note that we are testing more contrasts (4) than we have degrees of freedom (4 different designs means 4-1 d.f.); the fourth contrast above is not independent of the other three. This does increase the risk of familywise statistical error. Nevertheless, we felt the theoretical interest in the question justified this increased error risk.

With reference to Table 1, most performance outcomes were measured at three general times of day (am (T1), pm-before control was introduced (T2), and pm-after control was introduced (T3)). In such cases, for time-of-day effects, we conducted tests on two single degree-of-freedom contrasts: T1 vs. T2 and T2 vs. T3. T2 vs. T3 was also a pre-control vs. post-control contrast.

The results of the individual tests are detailed below. Tables 9 to 23 summarize the results of the analyses where significant effects were found (details of non-significant tests are not shown), and these effects are shown graphically in Figures 11 to 24.

Vision Test (Contrast Sensitivity)

We first assumed that sensitivity to contrast differences would be the same whether the contrast was positive or negative. Therefore performance at contrast +16 was combined with performance at contrast -16, and so on[3]. Thus, we had six contrast levels (0, 1, 2, 4, 8, 16), forming a within-subject variable in the analysis, in addition to time-of-day. We chose to collapse over grating size and orientation for this analysis. Response times and accuracy scores were combined to form a composite visual performance score: total correct/total time (correct responses per second). Therefore the ANOVA was a 4 Lighting Design (BS) x 3 Time (WS) x 6 Contrast (WS). Note that the effect of contrast was analyzed as a linear effect across all six contrast levels, assuming the contrast

[3] This simplified the analysis considerably, though it did introduce some error. For example, whereas the measured luminance difference between target and background for +16 was ~6.5 cd/m^2, it was only 5 cd/m^2 for –16. But both were easily distinguishable from +/-8.

levels are equally spaced. Although the differences in absolute contrasts associated with each contrast level were not equally spaced, we know that response of the human visual system is non-linear with respect to luminance. Our assumption of equal spacing may be valid in regard to visual response and, indeed, Figure 11 demonstrates a very linear response, at least between contrasts 1 and 8, when the contrasts are represented as being equally spaced. Although, when all contrasts are included, the shape of the mean performance curve does not appear very linear (Figure 11), the analysis shows a very high $\eta^2_{partial}$ (0.920) for the linear effect.[4]

The effect of target contrast was strong, and as expected (Figure 11). Where there was any contrast, performance in identifying that there was a target was very poor for the lowest contrast (1 grey level), increasing rapidly with increasing contrast. There appears to be no further improvement beyond contrast level 8. When there was no contrast, performance in correctly responding that there was no target was very good. Observing this expected trend gives us confidence in the validity of the task.

As shown in Figure 12, there were significant effects on the Time-of-day contrasts, with performance on the vision test over all contrasts and lighting designs increasing significantly from T1 to T2, and from T2 to T3.

There was a significant interaction between target contrast (linear trend) and time-of-day, from both T1 to T2 and T2 to T3, which modifies the simple time-of-day effect. Both the slope and intercept of the linear trend are higher at T2 compared to T1. For T3, the slope is higher than at T2, suggesting faster improvement with contrast, though the intercept is lower, suggesting poorer performance at low contrasts.

There were no main effects on the Lighting Design contrasts, but there was one significant interaction on Lighting Designs 1 vs. 3 from T1 to T2 (Figure 13). Although performance improves for both lighting designs from T1 to T2, the improvement (the gradient of the line in Figure 13) was significantly lower for Design 3.

[4] We did repeat the analyses for the very linear part of the curve (contrasts 1-8) only, but this did not improve interpretation of the outcomes.

Table 9. Tests of the effect (linear trend) of Contrast (grey level) on performance on the Vision Task, by Time-of-Day. M = mean, SD = standard deviation.

VISION (correct/sec)		**Contrast (Grey Level)**						**Linear Trend**		
		0	**1**	**2**	**4**	**8**	**16**	ANOVA	slope	intercept
Overall	*M (SD)*	0.848 (0.323)	0.222 (0.158)	0.762 (0.253)	1.320 (0.350)	1.498 (0.336)	1.355 (0.358)	$F(1,114) = 1309.08$; $\eta^2_{partial} = 0.920$; $p < 0.001$		
T1	*M (SD)*	0.671 (0.344)	0.187 (0.158)	0.545 (0.256)	1.125 (0.427)	1.212 (0.456)	1.124 (0.460)	T1 vs T2: $F(1,114) = 14.80$; $\eta^2_{partial} = 0.115$; $p < 0.01$	0.169	0.218
T2	*M (SD)*	0.932 (0.383)	0.258 (0.204)	0.833 (0.297)	1.356 (0.369)	1.664 (0.406)	1.370 (0.399)		0.198	0.376
T3	*M (SD)*	0.942 (0.388)	0.220 (0.191)	0.907 (0.319)	1.479 (0.407)	1.619 (0.364)	1.572 (0.401)	T2 vs T3: $F(1,114) = 23.75$; $\eta^2_{partial} = 0.172$; $p < 0.001$	0.226	0.331

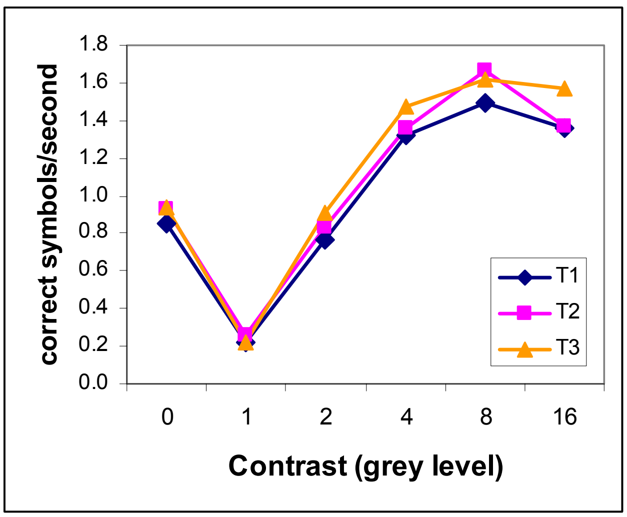


Figure 11. The effect of contrast (grey level) and Time-of-Day on performance on the Vision Task.

Table 10. Tests of the effect of Time-of-Day on performance on the Vision Task. M = mean, SD = standard deviation.

VISION (correct/sec)	**Time of Day**		
	T1	**T2**	**T3**
M (SD)	0.810 (0.292)	1.069 (0.268)	1.123 (0.253)
ANOVA	T1 vs T2: F(1,114) = 189.01; $\eta^2_{partial}$ = 0.623; p < 0.001	T2 vs T3: F(1,114) = 18.57; $\eta^2_{partial}$ = 0.140; p < 0.001	

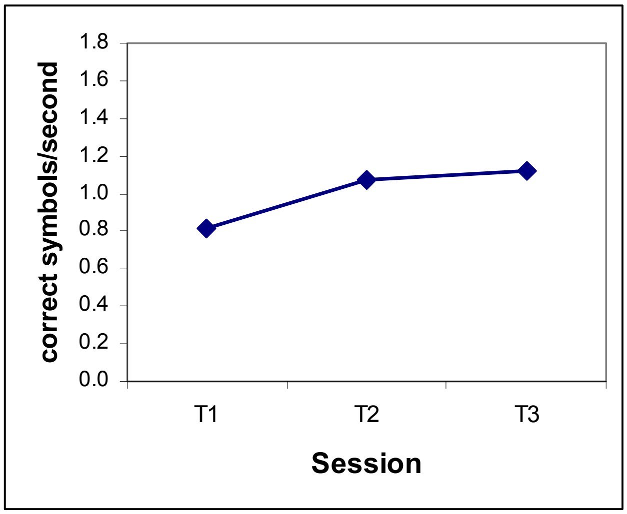


Figure 12. The effect of Time-of-Day on performance on the Vision Task.

Table 11. Tests of the interaction between Time-of-Day and Lighting Design on performance on the Vision Task. M = mean, SD = standard deviation.

VISION (correct/sec)		**Lighting Design**				ANOVA
		1	**2**	**3**	**4**	
T1	*M (SD)*	0.783 (0.267)		0.820 (0.340)		$F(1,114) = 5.45$; $\eta^2_{partial} = 0.046$; $p < 0.05$
T2	*M (SD)*	1.101 (0.258)		1.014 (0.290)		

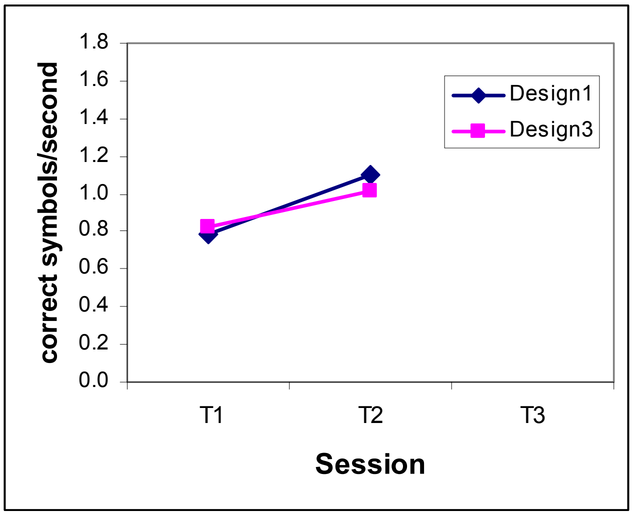


Figure 13. The interaction effect of Time-of-Day and Lighting Design on performance on the Vision Task.

Simple Cognitive/Clerical Performance (Typing)

The single dependent variable for this task was correct characters typed per second, which was recorded for each font size and each time of day. Therefore the ANOVA was a 4 Lighting Design (BS) x 3 Time (WS) x 3 Font Size (WS).

As shown in Figure 14, there were significant effects on the Time-of-Day contrasts, with average performance on the typing task over all fonts and lighting designs increasing significantly from T1 to T2, and from T2 to T3.

There was also a significant effect on one of the Lighting Design contrasts, the contrast between Design 1 and Design 3 (Figure 15). The typing speed under Design 3 was significantly higher than under Design 1. The difference in means is large, at 24%.

There was a significant linear trend in the main effect of Font Size (Figure 16) in the expected direction: typing speed increases with Font Size. It is clear from Figure 16 that the average trend shows little improvement beyond 12-point font. Nevertheless, the quadratic trend was a slightly less successful fit to the data[5]. There were no significant interactions between Font Size (linear) and Lighting Design or Time, or both. A post-hoc test confirmed that the difference in typing speed between Font 8 and Font 12 was significant ($F(1,101) = 84.26$; $\eta^2_{partial} = 0.455$; $p < 0.001$), whereas the difference in typing speed between Font 12 and Font 16 was not significant. The lack of improvement at the largest font size was unexpected. One explanation might be that although the text to be typed was presented on paper in different font sizes, the text as typed on screen was always in 12-point font. As a result, it might have been easier to scan the printed and on-screen text to find errors (for example) when the two texts were in the same font size.

[5] $F(1,101) = 46.82$; $\eta^2_{partial} = 0.358$; $p < 0.001$

Table 12. Tests of the effect of Time-of-Day on performance on the Typing Task. M = mean, SD = standard deviation.

TYPING (char/sec)	**Time of Day**		
	T1	**T2**	**T3**
M (SD)	2.66 (0.97)	2.86 (0.99)	2.92 (1.01)
ANOVA	T1–T2: $F(1,101) = 36.79$; $\eta^2_{partial} = 0.349$; $p < 0.001$	T2–T3: $F(1,101) = 4.23$; $\eta^2_{partial} = 0.040$; $p < 0.05$	

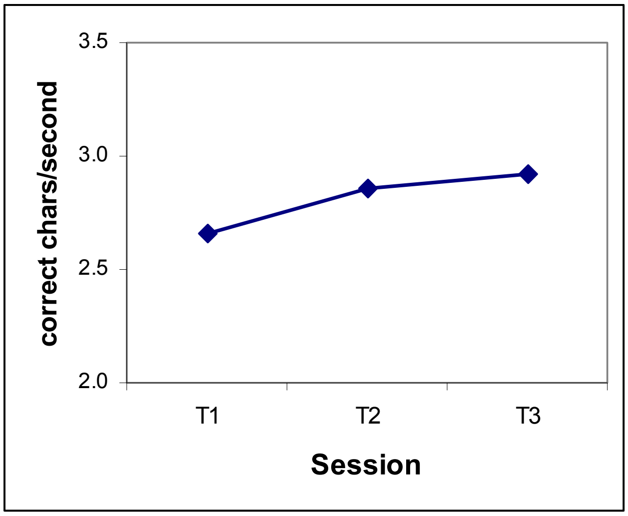


Figure 14. The effect of Time-of-Day on performance on the Typing Task.

Table 13. Tests of the effect of Lighting Design on performance on the Typing Task. M = mean, SD = standard deviation.

TYPING (char/sec)	**Lighting Design**			
	1	**2**	**3**	**4**
M (SD)	2.57 (0.88)		3.19 (1.38)	
ANOVA	Design 1 vs. 3: F(1,101) = 5.30; $\eta^2_{partial}$ = 0.050; p < 0.05			

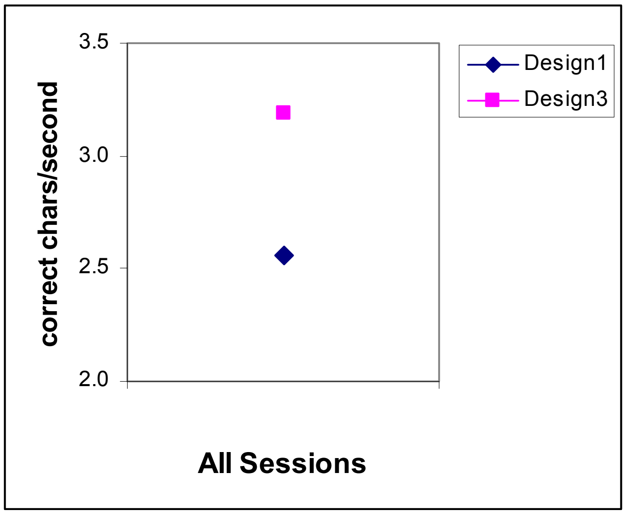


Figure 15. The effect of Lighting Design on performance on the Typing Task.

Table 14. Tests of the effect of Font Size on performance on the Typing Task. M = mean, SD = standard deviation.

TYPING (char/sec)	**Font Size (Points)** **8**	**12**	**16**	**Linear Trend** ANOVA
M (SD)	2.66 (0.99)	2.91 (1.00)	2.87 (0.98)	$F(1,101) = 56.48$; $\eta^2_{partial} = 0.359$; $p < 0.001$

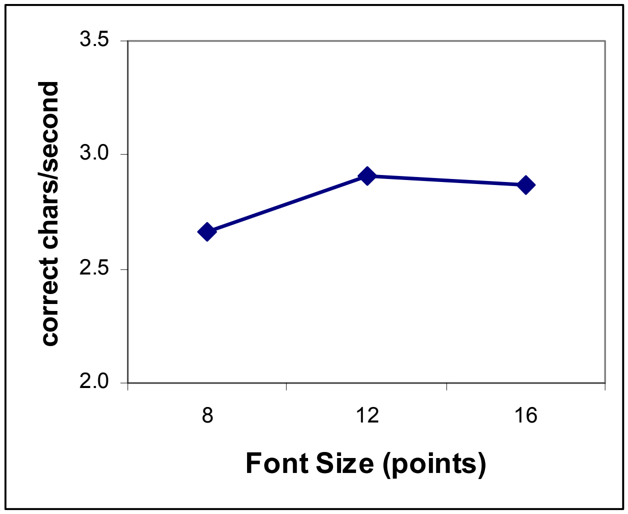


Figure 16. The main effect of Font Size on performance on the Typing Task.

Complex Cognitive Performance

We formed two MANOVAs from the performance outcomes from these tasks. Both MANOVAs were 4 Lighting Design (BS) x 3 Time (WS) analyses. The first MANOVA focussed on speed and accuracy outcomes. There were a maximum of 10 trials of the Categorization and Summary tasks in each (non-practice) session, and different participants completed different numbers of trials depending on how fast they were. To avoid having missing data, we analyzed outcomes from the first six trials in each session only, a number which everyone completed. Session scores were calculated as the mean score of the six trials within that session. There was one accuracy score, the accuracy of categorization, between 0 and 6 correct responses per session. This score was squared to improve normality (CATCORSQ in Figure 17). There were three measures of speed. The first, CATTIM, was the time taken to make the category decision. The second, CATTR, was the time taken to complete the entire categorization trial, including category decision and evaluation of the summary that was categorized. The third, SUMTIM was the time spent on the screen that introduced each summary extraction trial and invited them to read the source article plus the time to complete the extraction trial. The reason for combining these times was that we believed that, despite instructions to the contrary, participants were not reading the source article until they got to the extraction screen. For speed measures we interpret lower times to complete tasks as indicating better performance.

As shown in Figure 17, there were significant effects on the Time-of-Day contrasts, the MANOVA was significant from T1 to T2, and from T2 to T3. Looking at the univariate effects, accuracy improved significantly from T1 to T2, and from T2 to T3. Speed showed significant improvements over time as well: CATTR and SUMTIM both decreased from T1 to T2, and again from T2 to T3; CATTIM showed a significant decrease from T2 to T3 only.

There were no main effects of Lighting Design, but there were several significant Lighting Design x Time-of-Day interactions (Figure 18). For CATTIM, the contrast of Lighting Designs 1 and 2 from T1 to T2 was significant; although faster at T1, participants under Design 2 tended to get slower with time, whereas Design 1 participants got faster with time, and were faster at T2. For CATTR there were three significant interactions. From T1 to T2, Design 1 participants started off faster compared to Design 2 participants, and their rate of improvement from T1 to T2 was greater. From T2 to T3 this trend was reversed: Design 2 participants improved at a greater rate, though, at T3, the mean time was still lower for Design 1 participants. Similarly, from T2 to T3, Design 3 participants improved their performance at a greater rate that Design 1 participants, though they still took longer to complete the task, on average, than Design 1 participants. For SUMTIM there were two significant interactions. From T1 to T2, Design 1 participants started off faster compared to Design 2 participants, and their rate of improvement from T1 to T2 was greater. From T2 to T3, Design 3 participants improved their performance at a greater rate that Design 1 participants, the mean performance for Design 3 participants was slower that Design 1 participants at T2, and about equal at T3.

The second MANOVA focussed on cognitive outcomes, evaluations of the short summaries used in the Categorization Task. Again, we analyzed outcomes from the first six trials in each session only, and session scores were calculated as the mean score of the six trials within that session. INTEREST was the participant's level of interest in reading the whole article based on just the short summary, on a scale of 0-100. The other outcomes, FACTUAL, GRAMMATIC and WELL WRITTEN were ratings of the summary, and were scored on a scale of 0-4. For all these scales we interpret higher scores as indicating better performance.

As shown in Figure 19, there were significant effects on Time-of-Day contrasts, the MANOVA was significant from T1 to T2, and from T2 to T3. Only GRAMMATIC, the rating of whether the short summary was grammatically correct, showed no significant univariate effect. Other univariate effects showed the same pattern. INTEREST, FACTUAL and WELL WRITTEN all declined from T1 to T2, then showed a significant increase from T2 to T3. This might indicate a 'post-lunch' dip, or might be a function of the quality of the articles used at T2.

There was also a significant effect on the Lighting Design contrasts, the contrast between Design 1 and Design 2 (Figure 20). INTEREST under Design 2 was significantly higher than under Design 1. The difference in means was large, at 16%.

Table 15. Tests of the effect of Time-of-Day on the speed and accuracy outcomes of the Complex Cognitive Tasks. M = mean, SD = standard deviation.

COGNITIVE	**Time of Day** T1	T2	T3
CATCORSQ *M (SD)*	18.0 (6.9)	23.0 (7.5)	32.1 (5.7)
univariate effect	T1–T2: F(1,114) = 24.28; $\eta^2_{partial} = 0.176$; $p < 0.001$	T2–T3: F(1,114) = 126.48; $\eta^2_{partial} = 0.526$; $p < 0.001$	
CATTIM(sec) *M (SD)*	20.8 (7.6)	20.2 (8.7)	16.2 (7.5)
univariate effect		T2–T3: F(1,114) = 68.32; $\eta^2_{partial} = 0.375$; $p < 0.001$	
CATTR(sec) *M (SD)*	96.8 (37.1)	87.2 (35.1)	77.3 (32.0)
univariate effect	T1–T2: F(1,114) = 41.57; $\eta^2_{partial} = 0.267$; $p < 0.001$	T2–T3: F(1,114) = 45.02; $\eta^2_{partial} = 0.283$; $p < 0.001$	
SUMTIM(sec) *M (SD)*	130.9 (39.8)	122.1 (44.3)	105.1 (41.4)
univariate effect	T1–T2: F(1,114) = 23.01; $\eta^2_{partial} = 0.168$; $p < 0.001$	T2–T3: F(1,114) = 86.84; $\eta^2_{partial} = 0.432$; $p < 0.001$	
MANOVA	T1–T2: Wilks' $\Lambda = 0.549$; F(4,111) = 22.79; $\eta^2_{partial(ave)} = 0.156$; $p < 0.001$	T2–T3: Wilks' $\Lambda = 0.282$; F(4,111) = 70.64; $\eta^2_{partial(ave)} = 0.404$; $p < 0.001$	

Figure 17. Effect of Time-of-Day on speed and accuracy performance on Complex Cognitive Tasks.

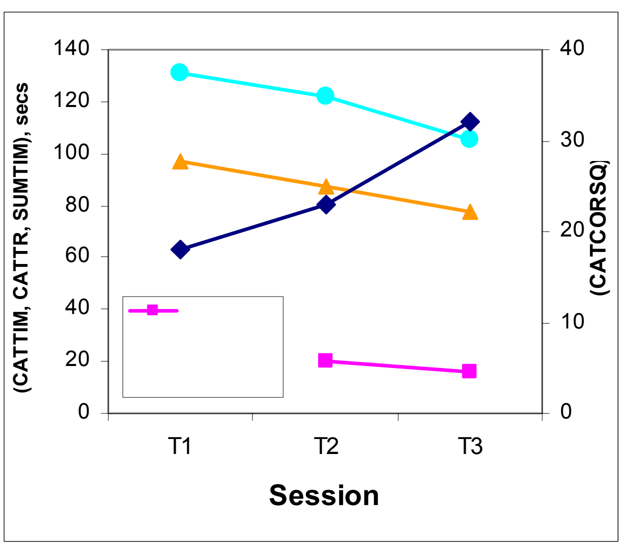


Table 16. Tests of the interaction of Time-of-Day and Lighting Design on the speed and accuracy outcomes of the Complex Cognitive Tasks. M = mean, SD = standard deviation.

COGNITIVE		**Lighting Design**					
		1	**vs 2**	univariate effects	**1**	**vs 3**	univariate effects
CATCORSQ *M (SD)*				No significant			
CATTIM(sec) *M (SD)*							
	T1	21.3 (7.8)	19.7 (7.1)	F(1,114) = 4.49; $\eta^2_{partial}$ = 0.038; $p < 0.05$			
	T2	19.2 (7.8)	20.6 (9.5)				
CATTR(sec) *M (SD)*							
	T1	91.4 (33.3)	104.8 (41.3)	F(1,114) = 6.00; $\eta^2_{partial}$ = 0.050; $p < 0.05$			
	T2	76.6 (27.9)	100.1 (43.4)	F(1,114) = 7.94; $\eta^2_{partial}$ = 0.065; $p < 0.01$	76.6 (27.9)	92.9 (34.6)	F(1,114) = 5.20; $\eta^2_{partial}$ = 0.044; $p < 0.05$
	T3	73.9 (36.1)	85.9 (35.4)		73.9 (36.1)	80.6 (31.0)	
SUMTIM(sec)*M (SD)*							
	T1	132.4 (36.0)	138.3 (45.3)	F(1,114) = 10.36; $\eta^2_{partial}$ = 0.083; $p < 0.01$			
	T2	113.7 (28.4)	136.1 (58.6)		113.7 (28.4)	126.6 (49.7)	F(1,114) = 5.67; $\eta^2_{partial}$ = 0.047; $p < 0.05$
	T3				104.5 (35.4)	104.8 (37.1)	
MANOVA				D1vsD2 on T1vsT2 Wilks' Λ = 0.880; F(4,111) = 3.77; $\eta^2_{partial(ave)}$ = 0.044; $p < 0.01$			
				D1vsD2 on T2vsT3 Wilks' Λ = 0.909; F(4,111) = 2.78; $\eta^2_{partial(ave)}$ = 0.024; $p < 0.05$			D1vsD3 on T1vsT2 Wilks' Λ = 0.910; F(4,111) = 2.75; $\eta^2_{partial(ave)}$ = 0.030; $p < 0.05$

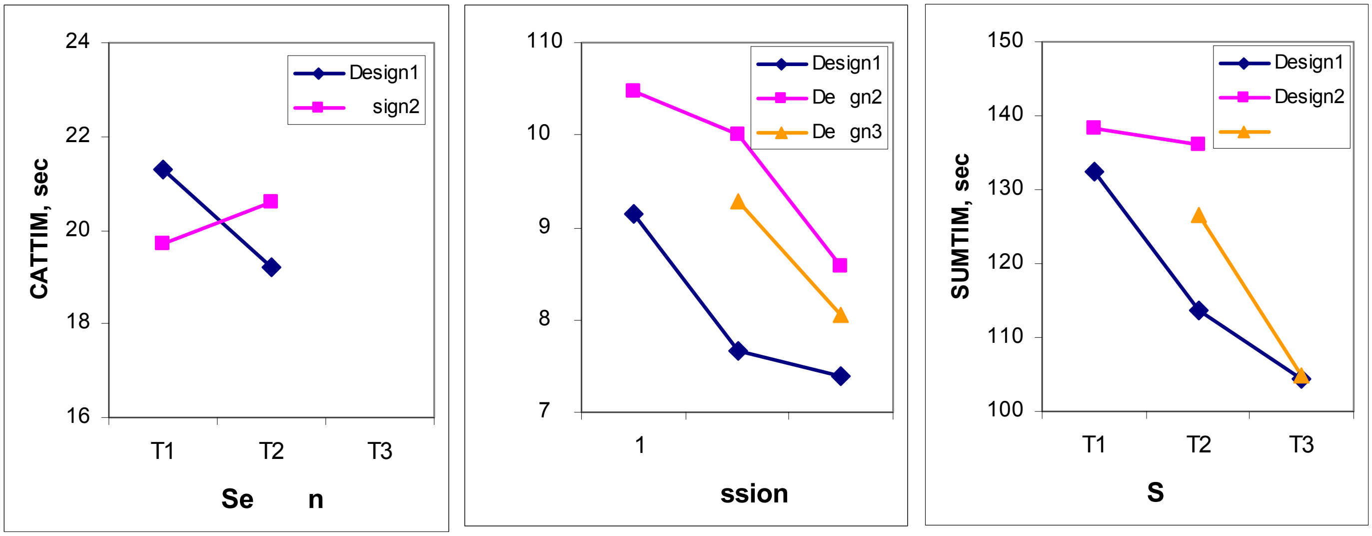


Figure 18. The interaction effects of Time-of-Day and Lighting Design on speed and accuracy performance on the Complex Cognitive Tasks.

Table 17. Tests of the effect of Time-of-Day on the evaluation outcomes of the Complex Cognitive Tasks. M = mean, SD = standard deviation.

COGNITIVE		**Time of Day**		
		T1	**T2**	**T3**
INTEREST	*M (SD)*	60.5 (17.6)	48.7 (15.7)	54.6 (14.2)
univariate effect		T1–T2: F(1,114) = 44.75; $\eta^2_{partial}$ = 0.282; $p < 0.001$	T2–T3: F(1,114) = 17.81; $\eta^2_{partial}$ = 0.135; $p < 0.001$	
FACTUAL	*M (SD)*	2.46 (0.66)	2.21 (0.60)	2.49 (0.58)
univariate effect		T1–T2: F(1,114) = 18.46; $\eta^2_{partial}$ = 0.139; $p < 0.001$	T2–T3: F(1,114) = 30.06; $\eta^2_{partial}$ = 0.209; $p < 0.001$	
GRAMMATIC.	*M (SD)*			
WELL WRITN.	*M (SD)*	2.40 (0.58)	2.19 (0.55)	2.43 (0.54)
univariate effect		T1–T2: F(1,114) = 13.03; $\eta^2_{partial}$ = 0.103; $p < 0.001$	T2–T3: F(1,114) = 24.15; $\eta^2_{partial}$ = 0.175; $p < 0.001$	
MANOVA		T1–T2: Wilks' Λ = 0.651; F(4,111) = 14.89; $\eta^2_{partial(ave)}$ = 0.136; $p < 0.001$	T2–T3: Wilks' Λ = 0.700; F(4,111) = 11.90; $\eta^2_{partial(ave)}$ = 0.134; $p < 0.001$	

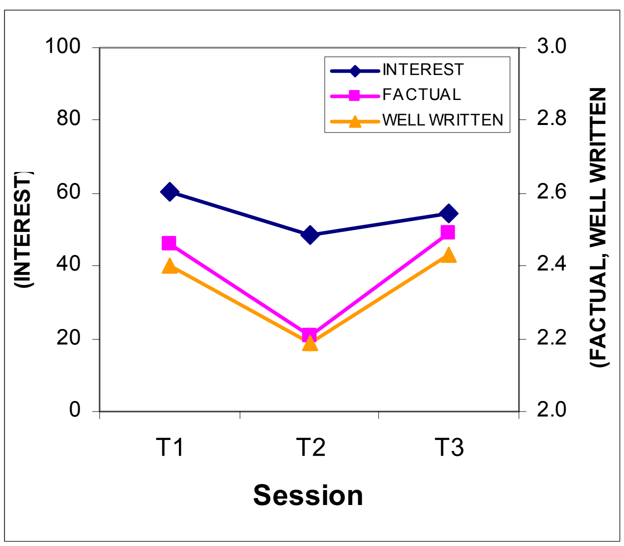


Figure 19. The effect of Time-of-Day on evaluations in the Complex Cognitive Tasks.

Table 18. Tests of the effect of Lighting Design on the evaluation outcomes of the Complex Cognitive Tasks. M = mean, SD = standard deviation.

COGNITIVE		**Lighting Design**			
		1	**2**	**3**	**4**
INTEREST	*M (SD)*	50.7 (15.7)	58.9 (9.1)		
univariate effect		$F(1,114) = 6.82$; $\eta^2_{partial} = 0.056$; $p < 0.05$			
FACTUAL	*M (SD)*				
GRAMMATIC.	*M (SD)*				
WELL WRITN.	*M (SD)*				
MANOVA		Wilks' $\Lambda = 0.910$; $F(4,111) = 2.73$; $\eta^2_{partial(ave)} = 0.025$; $p < 0.05$			

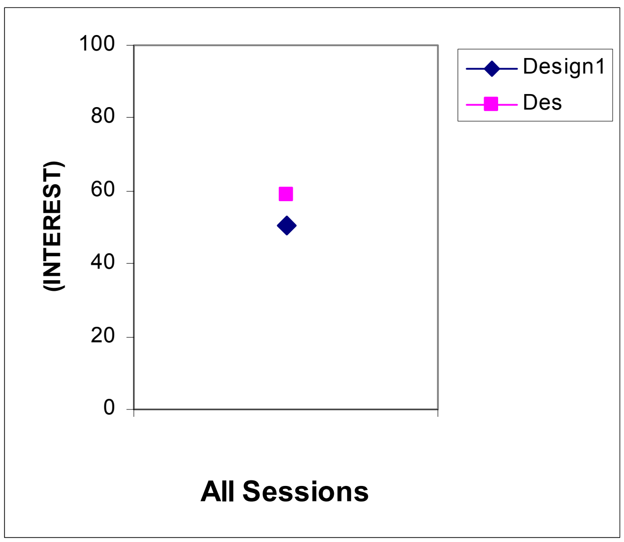


Figure 20. The effect of Lighting Design on evaluations in the Complex Cognitive Tasks.

Conflict Resolution

The conflict resolution task provided two types of scores, five ratings and five rankings. The ratings were the average (over five scenarios) likelihood that an individual would resolve conflicts using competition, collaboration, compromise, avoidance, or accommodation strategies, on a scale from –3 through +3, where higher scores indicated greater likelihood of using that strategy. The rankings were the average rank assigned to each of the five strategies over the various scenarios. Table 19 summarizes the characteristics of these two sets of variables. For some of the scales, internal consistency reliability is acceptable, but for others it is unacceptably low. Overall, this task requires further development and refinement as a measure of conflict resolution tendencies.

This task was administered at one time only. The analysis was involved two MANOVAs with Lighting Design (BS) as the only independent variable. The first MANOVA involved five dependent variables, the five strategy ratings. The second MANOVA also involved five dependent variables, the five strategy rankings. Neither MANOVA was statistically significant.

Table 19. Conflict resolution scale characteristics (n=116). M = mean, s.d. = standard deviation.

	Cronbach's alpha	M	(s.d.)
Ratings			
Competition	.54	0.42	0.91
Accommodation	.34	0.28	0.75
Avoidance	.40	-1.15	0.73
Collaboration	.57	1.15	0.82
Compromise	.54	1.68	0.65
Rankings			
Competition	.52	3.34	0.73
Accommodation	.20	3.20	0.55
Avoidance	.41	4.24	0.53
Collaboration	.52	2.31	0.65
Compromise	.40	1.90	0.53

Note. Each scale is the average score for that concept rated on 5 conflict scenarios. Ratings indicate the absolute likelihood that the individual will use that strategy to resolve conflict, and are on a scale from –3 through +3. Rankings indicate the relative likelihood of using that strategy in relation to the others, and are on a scale from 1 through 5.

Vigilance/Alertness

There were two measures of vigilance. One was derived from the conveyor belt task: it was the average hit rate ((hits-false positives)/targets) at the third highest speed (~1.1 symbols/sec) in each trial. We chose this speed for analysis because the data showed that at this speed the task was challenging and participants were still responding as expected, but not so difficult that they had given up or were just responding randomly. Performance was averaged over the four trials in a single session to give a session average score. The other measure was the speed of response to an envelope prompt (response/sec), similar to the beep and symbol flash of an e-mail arriving. The session average score was the mean of two possible responses in each session. These two dependent measures were used in one 4 Lighting Design (BS) x 3 Time-of-Day (WS) MANOVA.

As shown in Figure 21, there was a significant effect on the Time-of-Day contrasts, with performance on the conveyor belt task over all lighting designs increasing significantly from T1 to T2; there was no further significant effect from T2 to T3.

There was also a significant effect on the Lighting Design contrasts, on the contrast between Design 1 and Design 3 for the conveyor belt task (Figure 22). Performance under Design 3 was significantly higher than under Design 1. The difference in means was large, at 42%.

Table 20. Tests of the effect of Time-of-Day on Vigilance/Alertness.
M = mean, SD = standard deviation.

VIGILANCE		**Time of Day**		
		T1	**T2**	**T3**
HITS (sym/s)	*M (SD)*	0.333 (0.252)	0.391 (0.277)	
univariate effect		T1–T2: $F(1,93) = 8.46$; $\eta^2_{partial} = 0.083$; $p < 0.01$		
ENVELOPE (/s)	*M (SD)*			
MANOVA		T1–T2: Wilks' $\Lambda = 0.914$; $F(2,92) = 4.31$; $\eta^2_{partial(ave)} = 0.042$; $p < 0.05$		

Figure 21. The effect of Time-of-Day on Vigilance/Alertness.

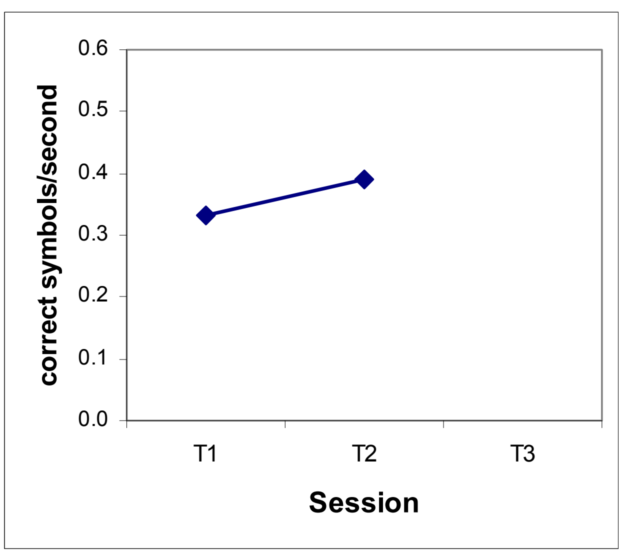


Table 21. Tests of the effect of Lighting Design on Vigilance/Alertness.
M = mean, SD = standard deviation.

VIGILANCE		**Lighting Design**			
		1	**2**	**3**	**4**
HITS (sym/s)	*M (SD)*	0.329 (0.240)		0.468 (0.250)	
univariate effect		F(1,93) = 7.55; $\eta^2_{partial}$ = 0.075; p < 0.01			
ENVELOPE (/s)	*M (SD)*				
MANOVA		Wilks' Λ = 0.902; F(2,92) = 4.99; $\eta^2_{partial(ave)}$ = 0.045; p < 0.01			

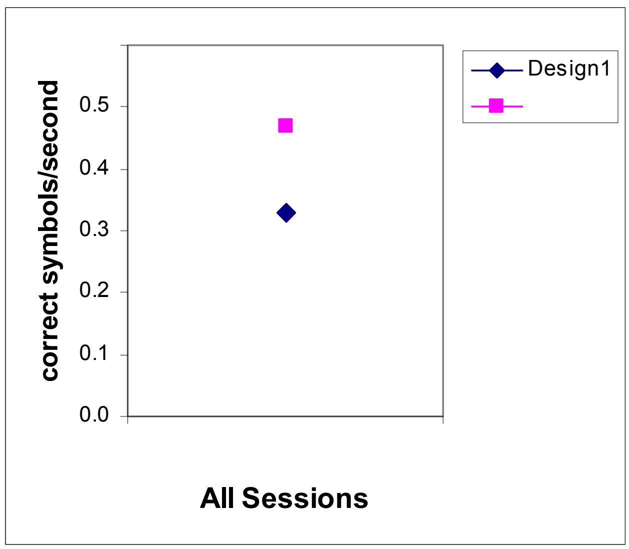


Figure 22. The effect of Lighting Design on Vigilance/Alertness.

Motivation/Persistence

Persistence at a very difficult, almost impossible, task was the indicator of motivation. This variable was measured using the conveyor belt task, which had moving targets at increasing speeds from 1 through 8 (equivalent to the appearance of ~0.7 to 2.6 symbols/sec). The participant was instructed to give up if the task got too difficult, and the measure for analysis was the speed (1 to 8) at which the participant gave up; if they did not give up they were assigned a score of 9. There were four trials in each session, and the analyzed score was the average 'speed at give-up' for the session. When we examined the distribution of this variable we saw that it was not normally distributed, so we transformed the variable by squaring it. This enlarged the scale, so that the maximum possible score was 81. This was the only outcome variable in this analysis, which was, therefore, a 4 Lighting Design (BS) x 3 Time-of-Day (WS) ANOVA.

There was one significant interaction on the contrast of Lighting Designs 1 and 3 from T1 to T2 (Figure 23). Although persistence for both Designs was about the same at T1, participants under Design 1 tended to get less persistent with time, whereas Design 3 participants got more persistent.

Table 22. Tests of the interaction between Time-of-Day and Lighting Design on Persistence. M = mean, SD = standard deviation.

PERSISTENCE		**Lighting Design**				ANOVA
		1	**2**	**3**	**4**	
T1	*M (SD)*	44.3 (22.6)		43.1 (23.7)		$F(1,114) = 4.31$; $\eta^2_{partial} = 0.036$; $p < 0.05$
T2	*M (SD)*	40.8 (20.2)		46.8 (24.6)		

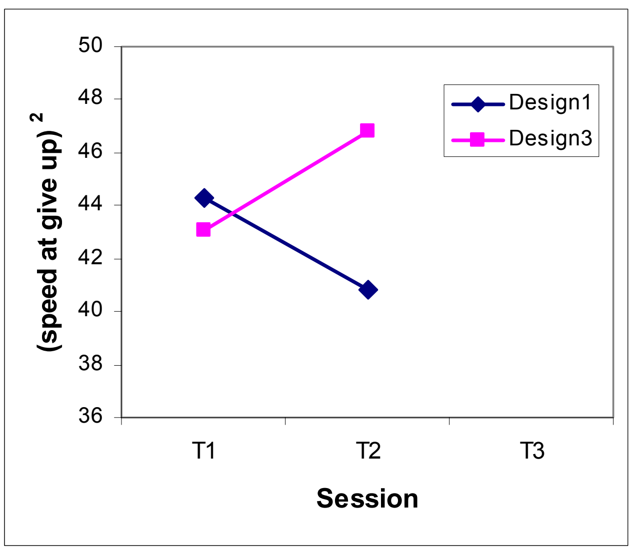


Figure 23. The interaction effects of Time-of-Day and Lighting Design on Persistence.

Work Structure

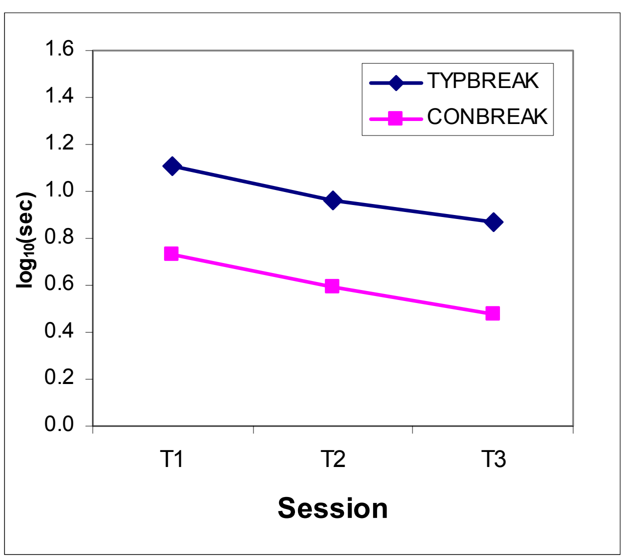
Most of the tasks occurred in sets of several trials; for two tasks we have data on the length of time between trials. This is the period of time during which the introductory screen for the new trial appeared on the computer. For the typing and conveyor belt tasks this time amounted to a rest break, as there was no work to be done, and participants were free to wait as long as they wanted before continuing. In both cases the measurement was in seconds, and average scores were calculated for each session (across three trials in each session for typing, four for conveyor). Outliers with breaks longer than 50 seconds were removed. To improve the normality of the data, a $\log_{10}$ transformation was applied. The rest breaks for typing and conveyor belt tasks were the two outcomes in a 4 Lighting Design (BS) x 3 Time-of-Day (WS) MANOVA.

As shown in Figure 24, there were significant effects on the Time-of-Day contrasts, the MANOVA was significant from T1 to T2, and from T2 to T3. Both typing breaks and conveyor belt breaks decreased in length significantly from T1 to T2, and again from T2 to T3.

Table 23. Tests of the effect of Time-of-Day on the Rest Breaks taken between tasks. M = mean, SD = standard deviation.

WORK STRUCTURE		**Time of Day**				
		T1		**T2**		**T3**
TYPBREAK	*M (SD)*	1.11 (0.22)		0.96 (0.28)		0.87 (0.26)
univariate effect			$F(1,110) = 27.62$; $\eta^2_{partial} = 0.201$; $p < 0.001$		$F(1,110) = 9.05$; $\eta^2_{partial} = 0.076$; $p < 0.01$	
CONBREAK	*M (SD)*	0.73 (0.27)		0.59 (0.28)		0.48 (0.26)
univariate effect			$F(1,110) = 23.36$; $\eta^2_{partial} = 0.175$; $p < 0.001$		$F(1,110) = 18.24$; $\eta^2_{partial} = 0.142$; $p < 0.001$	
MANOVA			Wilks' $\Lambda = 0.673$; $F(2,109) = 26.45$; $\eta^2_{partial(ave)} = 0.188$; $p < 0.001$		Wilks' $\Lambda = 0.767$; $F(2,109) = 16.55$; $\eta^2_{partial(ave)} = 0.109$; $p < 0.001$	

Figure 24. The effect of Time-of-Day on Rest Breaks.



3.3 What is the effect of getting lighting control on task performance?

At first sight, the answer to this question lies simply in a comparison between task performance after control was introduced (T3) and performance pre-control (T2). For many tasks and measures there are significant improvements in performance post-control. However, we have evidence from other studies [Veitch & Newsham, 1998; Veitch & Newsham, 2000b; Boyce, Veitch et al., 2003] that there are practice effects associated with these tasks over relatively short exposure times, such performance in this experiment would be expected to improve over time even in the absence of control. Therefore, the pertinent question is: did the introduction of dimming control improve performance beyond the inherent improvement due to practice? Two further ways of analysing the data helped us address this question.

In our previous report on the questionnaire data [Newsham et al., 2003], we performed an analysis looking at the magnitude of light level change between pre- and post-control conditions vs. the magnitude of questionnaire outcome changes. That analysis was based on the following hypothesis:

> *Participants who made the biggest changes in light levels post-control were the participants who were furthest from their own preferred luminous conditions pre-control; and, these same participants will experience the biggest improvements in ratings as a result*.

The data analysis in [Newsham et al., 2003] supported this hypothesis, for outcomes related to mood, room appearance, lighting and environmental satisfaction, and physical discomfort. Participants who made the biggest changes to lighting conditions post-control tended to register the biggest improvements in outcomes, and, those who made little change in light levels registered little or no improvements in outcomes. This suggests that it is not simply having control that is important, but rather the usefulness of the control in enabling the occupant to create preferred conditions.

We therefore decided to use the same analysis technique with the task performance data, to see if those that made the biggest changes to light level also registered the biggest improvements in performance. If so, this would indicate that control had an effect separate from the practice effect.

All details of the analysis were as in Newsham et al. [2003], given the success of the previous analysis we saw no reason to modify it. The light level measure was simply the illuminance measured at a fixed, representative, desktop location, E_{desk}. As a measure of change in this variable we chose the difference between the value of E_{desk} at the end of the day (representing the net result of several adjustments during the post-control period after the maximum exposure to conditions and tasks), and the fixed value prevailing during the entire pre-control period, this difference is denoted as ΔE_{desk}. We assumed that positive and negative values of ΔE_{desk} of the same magnitude would predict similar effects on performance, and so we opted to use the absolute value of the change in E_{desk}, or $|\Delta E_{desk}|$. Finally, to achieve better normality in the distribution of our measure of the change in luminous environment, we took the square root, so our final predictor variable was $|\Delta E_{desk}|^{0.5}$. For each of the performance measures we took the change between T3 and T2 as our dependent variables; in the text below we will use a Δ prefix to indicate these change scores.

The next stage was to perform regressions of Δ(ratings) vs. $|\Delta E_{desk}|^{0.5}$ for each outcome of interest. As in Newsham et al. [2003], we excluded data from Lighting Design 4 from our analyses because participants' ability to manipulate lighting conditions in Design 4 differed substantially in magnitude compared to the other designs. Design 4 also used a different ambient lighting system than the other three designs. In addition, regression analyses benefit from a large degree of variation in the predictor variable, with values well-distributed across that range; desktop illuminance conditions produced by Design 4 did not fit this description.

Table 24 details the results of the regression analyses, results are shown in graphical form in Figure 25. Three dependent variables show significant regressions in these analyses, two of the effects support our hypothesis, but the other does not; all of the effect sizes are small to medium in size (r^2_{adj}

< 0.07). For typing, at 8-point font, bigger changes in light level did foster bigger improvements in typing speed. However, the opposite was true for 16-point font model text, where bigger changes in light level were associated with bigger deteriorations in typing speed. One could argue that, on balance, dimming control is good for typing performance, because improvements to more difficult tasks should carry greater weight than decrements to visually easier tasks. This might be true in some situations, but not all. The other significant effect is on a cognitive performance measure, CATTIM, the time taken to categorize a short article. Bigger changes in light level were associated with bigger reductions in categorization time, which we interpret as an improvement in performance.

Given the small number of significant effects, the effect size, and the fact that one of the three effects opposed the hypothesis, support for our hypothesis is weak at best.

Table 24. Summary of the regression analysis for change in performance vs. change in luminous conditions. Only significant relationships are shown. In every case, the predictor variable is $|\Delta E_{desk}|^{0.5}$, the square-root of the absolute change in desktop illuminance between the start and end of the day. The outcome variables are the change in ratings from T3 compared to T2.

Outcome	Predictor	Intercept	Slope	F	r^2
TYPING					
Δ CPS (8-pt)	$\lvert\Delta E_{desk}\rvert^{0.5}$	- 0.378	0.014	(1,86) 4.24	0.047
Δ CPS (16-pt)	$\lvert\Delta E_{desk}\rvert^{0.5}$	0.217	- 0.021	(1,84) 7.29	0.080
COGNITIVE					
Δ CATTIM (sec)	$\lvert\Delta E_{desk}\rvert^{0.5}$	- 1.036	- 0.201	(1,87) 4.85	0.053

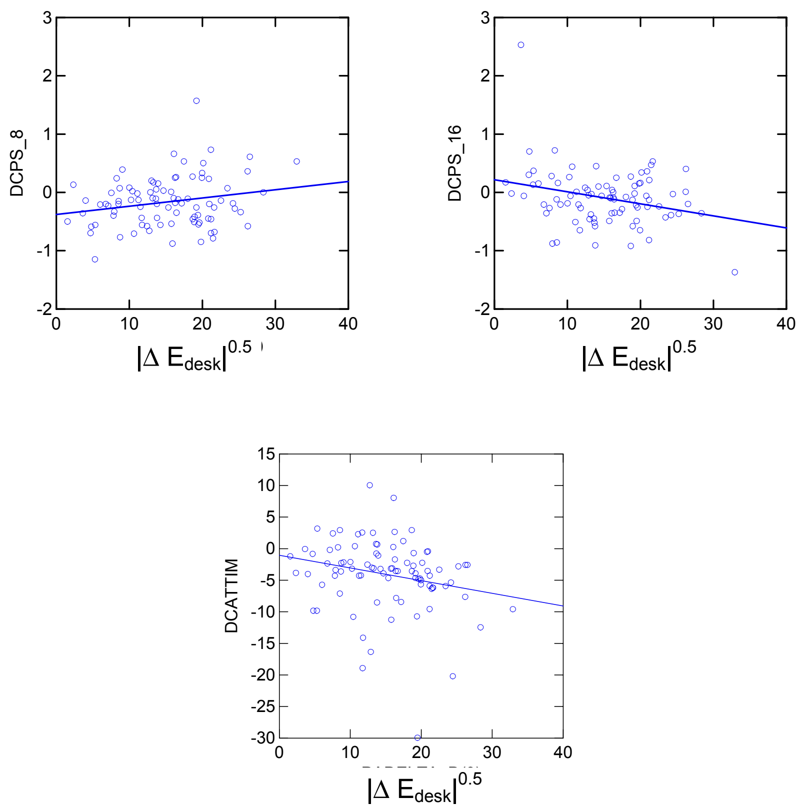


Figure 25. Graphical representations of the regression analyses comparing changes in desktop illuminance to changes in task performance.

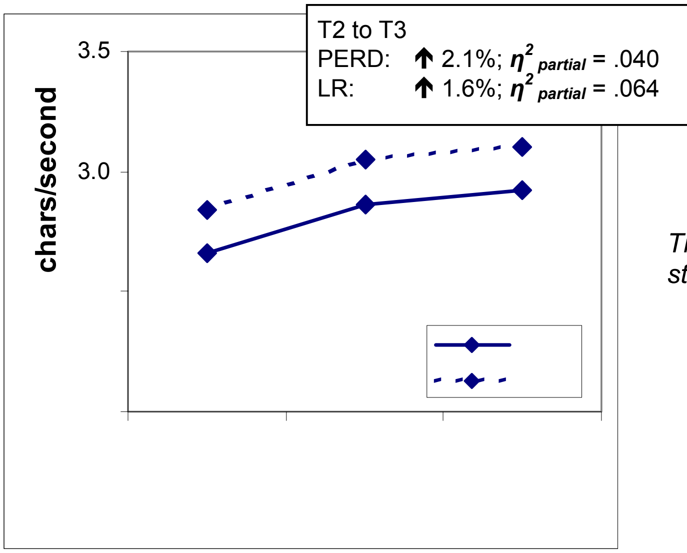
The second way we analyzed the data to examine the question of improvements to task performance beyond practice effects was in comparison to data from another, very similar, experiment. This experiment [Boyce, Veitch et al., 2003] used an almost identical one-day schedule of identical tasks, they also employed temporary office workers as participants in typical partitioned office accommodation. We compared our data to those from one part of Boyce, Veitch et al.'s study in which participants did not have dimming control, and experienced one of two typical office lighting designs for the experimental day. One hundred and seven participants provided data in this part of the Boyce, Veitch et al. study.

Although the Boyce, Veitch et al. experiment was very similar to ours, it was not identical. Ours took place in a mock-up office laboratory, theirs took place in mock-up office on one floor of a real office building. Our space was windowless, theirs had view windows, although they were designed to provide very little illumination. In our experiment there were a maximum of two participants per day, in Boyce, Veitch et al. the maximum was nine participants per day. The schedule was split into four sessions like ours, with the first session designed as a practice session. However, the start times for each session were not identical, due to differing morning start times, and different coffee and lunch break durations. Boyce, Veitch et al. used several additional tasks that we did not use, such as a colour vision task and a group discussion task. Not every common task was administered the same number of times in each experiment. For example, Boyce, Veitch et al. administered the on-screen Vision test only twice during the day. Finally, though the tasks were identical, the derived outcome variables did differ for a small number of tasks. However, despite these differences there were many outcomes for which a direct comparison could be made between (the equivalent of) T2 and T3 performance in both studies.

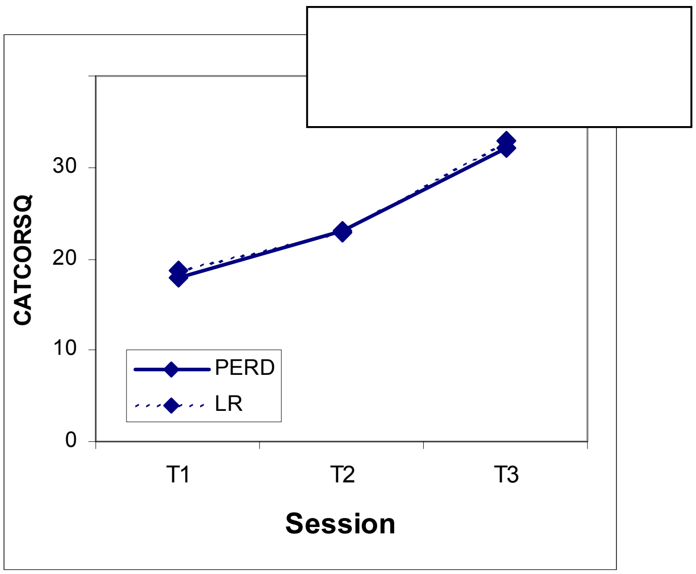
Figures 26 to 36 show the time evolution of the performance of all equivalent outcomes in both studies, collapsed over lighting design and any task-specific variables. Each Figure also shows a comparison of the T2 vs. T3 contrast for both studies. The size of the effect (if significant) is summarized in two ways, the difference in the mean performance between T2 and T3, and the variance in performance explained by the Time-of-Day effect ($\eta^2_{partial}$). If introducing control provides a boost to task performance over the simple practice effect we would expect to see proportion of variance explained, and changes in mean score, to be higher in our experiment than in Boyce, Veitch et al.

Two outcomes (INTEREST and CONBREAK) in this experiment showed significant improvement from T2 to T3, whereas in Boyce, Veitch et al. there was no improvement. Conversely, on two outcomes (GRAMMAR and ENVSPD) Boyce, Veitch et al. showed significant improvement from T2 to T3, whereas in this experiment there was no improvement. For outcomes where both experiments showed significant improvement from T2 to T3, the mean improvement was greater for Boyce, Veitch et al. on four outcomes, greater for this experiment on two outcomes, and equal on one outcome. The variance explained was greater for Boyce, Veitch et al. on five outcomes, and greater for this experiment on two outcomes. Nonetheless, over all outcomes the data from the two experiments are remarkably similar, and differences, where they occur, are small.

Overall then, there is little evidence that providing individual dimming control improved performance over and above the known practice effect, for the short-term tasks we used in our experiment.



Time-of-Day on Typing Speed for this study (labelled "PERD") and that of Boyce,



ccuracy that of

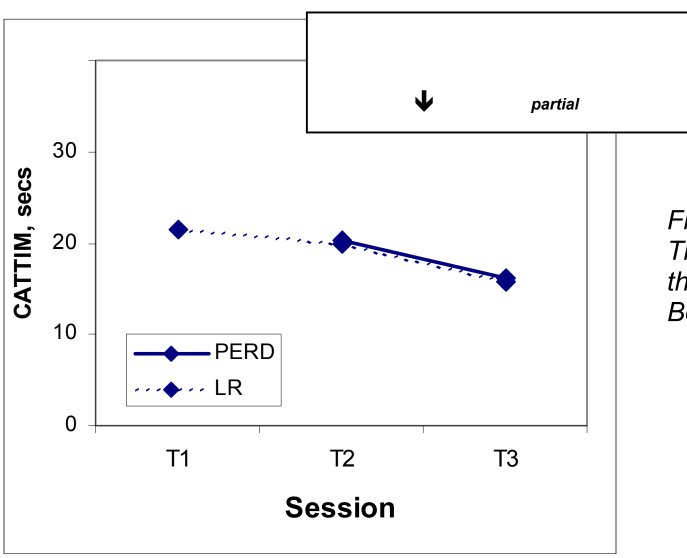


Figure 28. Comparison of the effect of Time-of-Day on Categorisation Time for this study (labelled "PERD") and that of Boyce, Veitch et al. [2003] (labelled "LR").

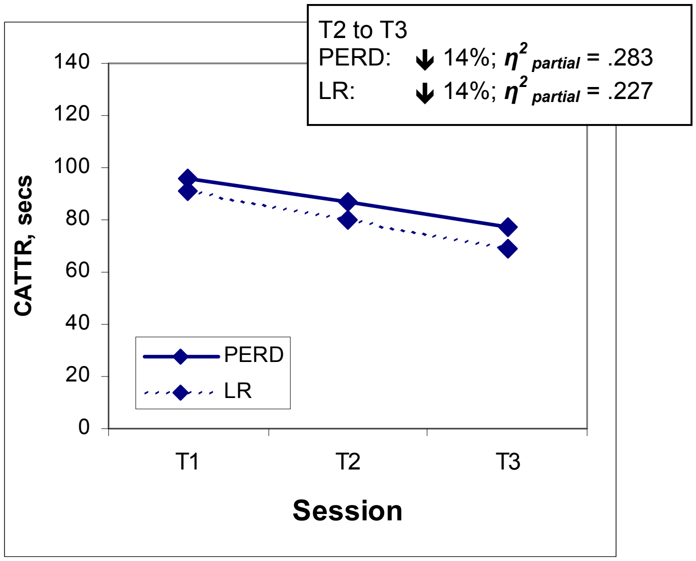


Figure 29. Comparison of the effect of Time-of-Day on Total Categorisation Time for this study (labelled "PERD") and that of Boyce, Veitch et al. [2003] (labelled "LR").

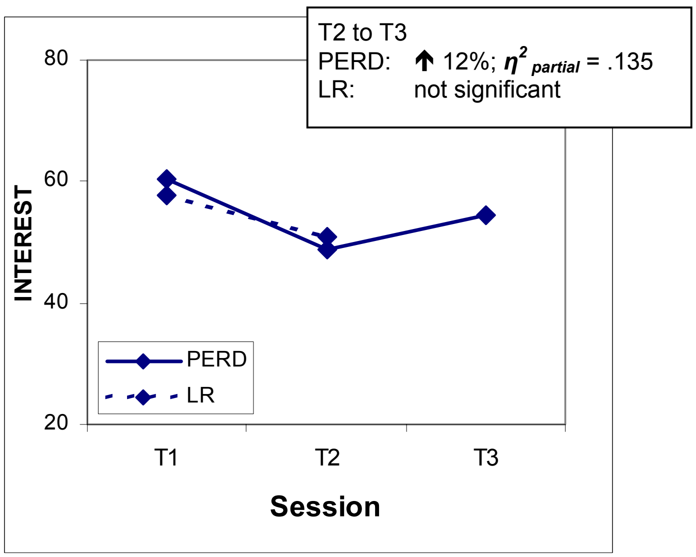


Figure 30. Comparison of the effect of Time-of-Day on Categorisation Interest Evaluation for this study (labelled "PERD") and that of Boyce, Veitch et al. [2003] (labelled "LR").

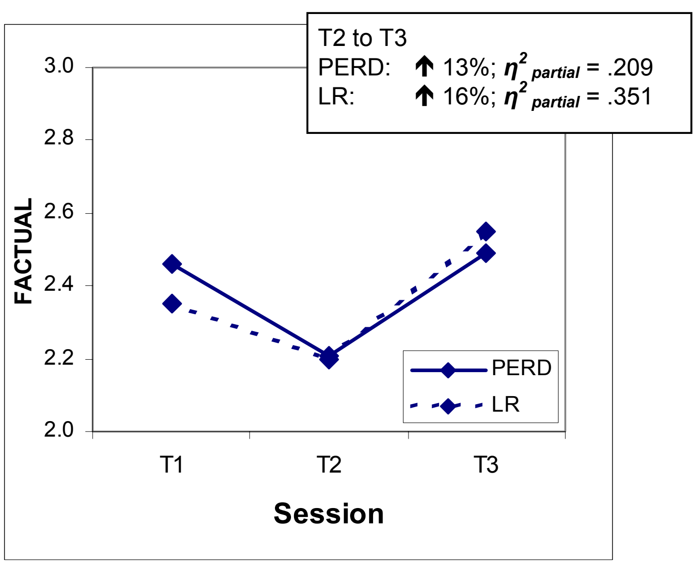


Figure 31. Comparison of the effect of Time-of-Day on Categorisation Factual Evaluation for this study (labelled "PERD") and that of Boyce, Veitch et al. [2003] (labelled "LR").

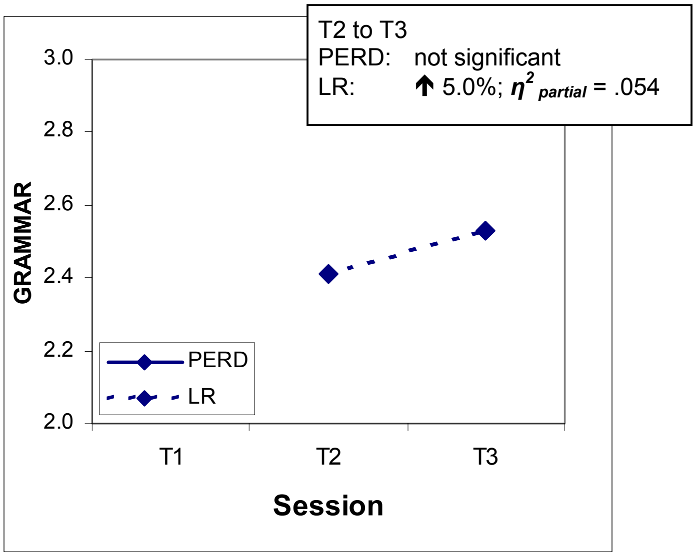


Figure 32. Comparison of the effect of Time-of-Day on Categorisation Grammar Evaluation for this study (labelled "PERD") and that of Boyce, Veitch et al. [2003] (labelled "LR").

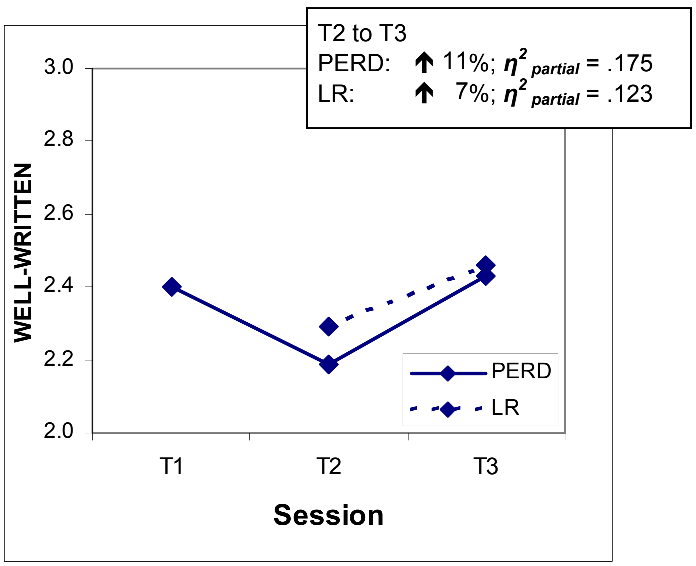


Figure 33. Comparison of the effect of Time-of-Day on Categorisation Well-Written Evaluation for this study (labelled "PERD") and that of Boyce, Veitch et al. [2003] (labelled "LR").

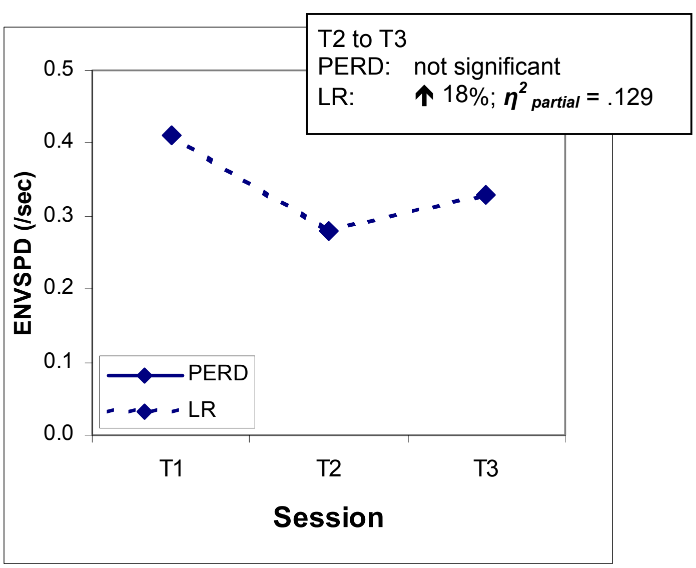


Figure 34. Comparison of the effect of Time-of-Day on Vigilance for this study (labelled "PERD") and that of Boyce, Veitch et al. [2003] (labelled "LR").

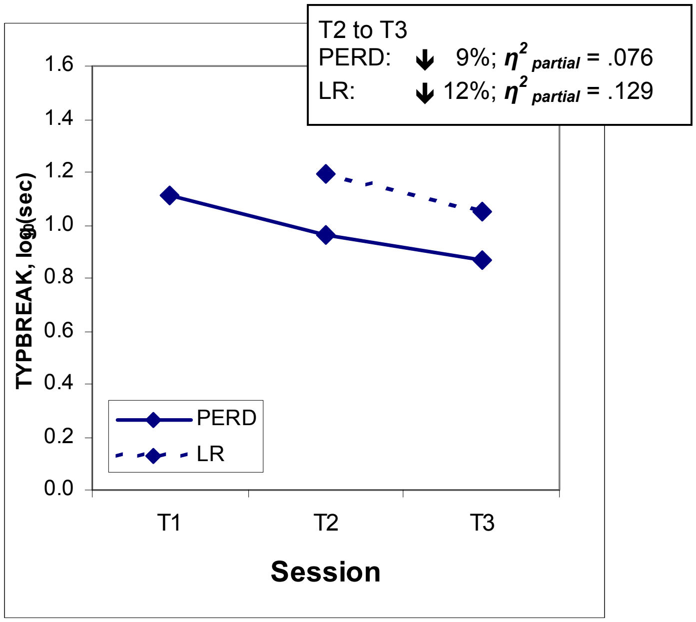


Figure 35. Comparison of the effect of Time-of-Day on Rest Breaks between Typing Tasks for this study (labelled "PERD") and that of Boyce, Veitch et al. [2003] (labelled "LR").

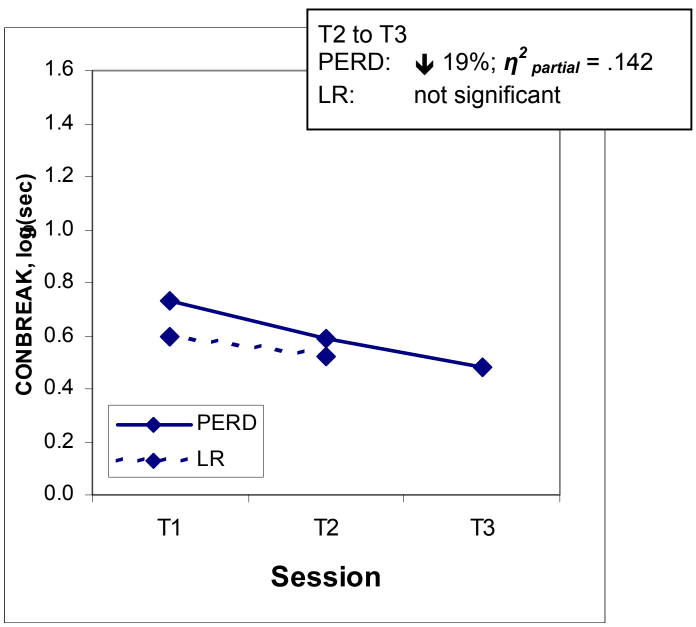


Figure 36. Comparison of the effect of Time-of-Day on Rest Breaks between Conveyor Belt Tasks for this study (labelled "PERD") and that of Boyce, Veitch et al. [2003] (labelled "LR").

3.4 Is there an effect of lighting design?

Several of the task performance analyses showed significant between-subjects effects due to lighting design. All of these effects were on the contrast between Design 1 and Design 2, or Design 1 and Design 3. Some were main effects, and some were interactions with time.

We will focus first on the Design 1 vs. Design 2 comparison; remember, Design 1 was a conventional, ceiling-recessed, parabolic system, Design 2 used the same ambient system as Design 1, but with the addition of a custom partition-mounted partition washer fixture. There was only one main effect of lighting system for this comparison, on INTEREST, the interest in reading a full article based on a short summary, registered on a 0-100 point scale by the participant. We interpret a higher score as better performance. Scores for Design 2 were significantly higher than for Design 1, the mean score was 8.2 points, or 16%, higher (58.9 vs. 50.7). All other effects were interactions with time, and occurred for the speed measures on the cognitive task, where we interpret shorter times to complete the tasks as better performance. For CATTIM, Design 2 participants got slower from T1 to T2, whereas Design 1 participants got faster, and there was a crossover from Design 2 participants being faster than Design 1 participants, to Design 1 participants being faster. On CATTR, both Design 1 and Design 2 participants got faster over time. For T1 to T2, the rate of improvement was better for Design 1, whereas for T2 to T3 the rate of improvement was better for Design 2, but the mean time to complete the task was always higher for Design 2. On SUMTIM, both Design 1 and Design 2 participants got faster from T1 to T2, but the rate of improvement was better for Design 1, and the mean time for Design 1 was lower than for Design 2 at both times. Overall, the results are mixed, with neither design consistently favoured. This suggests that the hypothesis that additional vertical luminance will improve performance is not supported for the tasks and lighting systems we used.

Now we will consider the Design 1 vs. Design 3 comparison; again, Design 1 was a conventional, ceiling-recessed, parabolic system, whereas Design 3 used the same ambient system as Design 1, but with the addition of an angle -arm task light. There were two main effects of lighting system for this comparison. On typing speed, correct characters per second typed for Design 3 were significantly higher than for Design 1, the mean score was 0.62 characters per second or 24% faster (3.19 vs 2.57). On Vigilance, we measured the number of target symbols successfully removed per second at a challenging rate of symbol appearance. Scores for Design 3 participants were significantly higher compared to Design 1 (0.391 vs 0.333), with a 17% difference in mean scores. All other effects were interactions with time. On the Vision task, the number of symbols correctly identified per second improved from T1 to T2 for both lighting designs. The rate of improvement was better for Design 1 than Design 3, but the difference was small. On CATTR, both Design 1 and Design 3 participants got faster from T2 to T3. The rate of improvement was better for Design 3, but the mean time to complete the task is higher for Design 3 at both times. On SUMTIM, both Design 1 and Design 3 participants got faster from T2 to T3. The rate of improvement was better for Design 3, and although Design 3 participants were slower at T2, the difference in performance had disappeared by T3. For Vigilance, Design 1 participants got slower from T1 to T2, whereas Design 3 participants got faster. Mean performance for both designs was similar at T1, but at T2 the score for Design 3 participants was substantially higher. The results are mixed, but, on balance, tend to favour Design 3 over Design 1, in other words, the addition of a task light is associated with task performance improvements.

The most obvious explanation for an improvement in typing speed with a task light is that participants were provided with more light on the paper-based target text, leading to an improvement in visibility. The mechanism for improvements on other tasks is not so obvious. The addition of the task light might have provided a more pleasing luminous environment. However, Newsham et al. [2003] did not find improvements in satisfaction outcomes due to lighting design. The ability of participants to move the task light at T3 to a more favoured position should further boost Design 3 compared to Design 1, but evidence for this is weak. Therefore, although adding a task light does seem to improve some aspects of task performance, the reason is far from clear.

4. FURTHER DISCUSSION

In this Discussion we will synthesize the results from both Newsham et al. [2003] and from this report, in order to give a comprehensive answer to the various questions of interest.

4.1 What are occupants' preferred luminous conditions?

The results of this experiment generally confirm the results of other similar studies of office worker lighting preferences [Newsham et al., 2002; Veitch & Newsham, 2000a; Newsham & Veitch, 2001; Loe et al., 1994; Berrutto et al., 1997], and current recommended practices [for example, IESNA 2000; ANSI/IESNA, 1993; CIBSE 1994; CIBSE 1993]. With conventional lighting systems, average preferred desktop illuminances were in the 400-500 lux range, and average preferred partition luminances were in the 30-40 cd/m^2 range. Nevertheless, it is worth noting that these preferences did vary according to the lighting equipment available. For example, when a partition washer was available, participants chose partition luminances that were, on average, over 100 cd/m^2 directly behind the computer screen, despite the fact that they could have chosen much lower levels.

4.2 What is the effect of lighting control on mood, satisfaction, and task performance?

After introducing individual lighting control part-way through an experimental day, there were significant improvements ratings of mood, satisfaction and discomfort [Newsham et al., 2003]. This beneficial effect is particularly convincing given that in other laboratory studies related to lighting in spaces without windows [Veitch & Newsham, 1998; Veitch & Newsham, 2000a], using the same Mood scores we have used here[6], we have observed that, in the absence of interventions designed to boost mood, mood scores will become more negative over the course of an experimental day. It was also shown that participants who made the biggest changes in lighting conditions experienced the biggest improvements, and that those who made little change in lighting conditions tended to experience no improvement in outcome measures. This suggests that it is not simply having control that leads to benefits, but using the control to create preferred conditions.

In this report we showed that multiple measures of task performance also improved after the introduction of control. However, improvements in these measures over time due to practice are well-known, and the improvements we registered post-control were no greater than those expected due to practice alone. Participants who made the biggest changes in lighting conditions experienced the biggest improvements in typing of 8-point font target text and in the time taken to complete a summary categorization task, but also experienced the largest decrements in typing of 16-point font text. Therefore, there was little evidence that introducing control improved task performance in this experiment.

In terms of the practical implications of these results, the key question for both the satisfaction and task performance outcomes is whether our experimental finding would persist in the long-term in a real office setting. In other words, were the benefits we observed on mood, satisfaction and discomfort due to a short-term novelty effect in a laboratory, or would occupants with dimming control over lighting in a real office feel better than those without such control, and continue to feel better? If the effect does persist, then it is also possible that benefits to task performance, which we did not see in the short-term laboratory study, would emerge over the longer-term. Remember also that in a real setting the tasks that people would perform will inevitably be different than the representative tasks we used in the experiment, and that these tasks may be more or less sensitive to lighting conditions. In a real setting there are also many other measures related to an organisation's performance that we did not or could not address in a laboratory study, such as absenteeism, organizational commitment, or teamwork. There are still other measures that are more appropriately measured at the level of a business unit than at the level of an individual. These considerations argue for a field study of the

[6] Note, in these other lighting studies, mood was measured at two times of day only, which does limit the strength of comparison to this study.

effects of having individual dimming control over lighting to address these longer-term, real-world effects. We suggest that such a field study be a priority for the lighting controls industry.

4.3 Is there an effect of lighting design, and is additional vertical luminance beneficial?

One of the main goals of this research was to look at the effect of providing additional vertical luminance. In this experiment this additional luminance was provided using a custom, partition washer (Lighting Design 2). We hypothesized that for people working on computer-based tasks, the luminance on vertical surfaces would take on greater importance, and that participants would lower ambient light levels (from a ceiling-recessed parabolic system) if they had another method of achieving their preferred vertical luminance. However, the experiment offered little support for this hypothesis. The results showed that participants did use the partition-washer system to elevate luminances in the field of view. Nonetheless, ambient light levels were not reduced compared to the choices of participants with the ambient system only (Lighting Design 1), and there were no significant improvements in mood, satisfaction, or discomfort [Newsham et al., 2003]. In this report we showed there were some significant differences between Designs 1 and 2 in task performance. However, these differences were not consistent in direction.

The results relating to task lighting were more interesting. In Lighting Design 3 participants had an angle-arm task light as well as the conventional, parabolic, ambient lighting system of Design 1. The hypothesis, derived from recommended practice for office lighting [e.g., New Buildings Institute, 2001] was that the addition of the task light would lead to reductions in chosen ambient light levels, while at least maintaining satisfaction and task performance. Surprisingly, we found that Design 3 participants did not lower their ambient light levels compared to Design 1 participants, on average; neither were there any significant differences in mood, satisfaction, or discomfort [Newsham et al., 2003]. However, in this report we demonstrated that, on balance, there were improvements in task performance with the addition of the task light. Boyce, Veitch et al. [2003] compared a direct/indirect parabolic system only vs. the same ambient system supplemented with a luminous shade desk light with three possible levels of output[7]. They used many of the same outcome measures we used in our experiment, but no clear evidence of benefits to satisfaction or task performance through the addition of the desk lamp. But remember, both the ambient system and the desk lamp were very different fixture types compared to the ones in our analyses.

Recommended practice documents for office lighting commonly suggest that a straightforward route to lighting energy savings is to lower ambient lighting levels and to compensate with task lighting. Given the popularity of such recommendations, we recommend further research into the energy and human factors effects of task lights in offices. Our findings suggest that saving energy with task lighting might not be as straightforward as previously thought, but that there might be task performance improvements.

5. CONCLUSIONS

Again, these final conclusions synthesize the findings in this report and those from Newsham et al. [2003]. Remember, as always with the results of research projects, these conclusions and recommendations should be considered in the context of the research's experimental design.

- Introducing individual lighting control improved ratings of mood, satisfaction and discomfort, but did not improve task performance. Our results were obtained from a relatively short exposure in a mock-up office laboratory. We recommend a longer-term study in a real office setting to examine if the mood, satisfaction and discomfort benefits persists, and if benefits to task performance, or other outcomes important to organisations, emerge. In consideration of other studies demonstrating energy and satisfaction benefits of individual lighting controls [Boyce et al., 2000; Jennings et al., 2000; Veitch & Newsham, 2000b; Moore et al., 2002; Maniccia et al., 1999; Escuyer & Fontoynont, 2001], we do, at the time, recommend the use

[7] They also tried a ceiling-recessed parabolic system as the ambient lighting source, but their analysis did not specifically contrast parabolic vs. direct/indirect + desk lamp.

of individual dimming control, a new field study will help to provide more information that might make a more convincing economic case for adoption.

- In concert with earlier work [Veitch & Newsham, 200b; Newsham & Veitch, 2001], our results suggest that it is not simply the availability of control that brings benefits to the user, but exercising control to achieve preferred conditions. We also saw that many people varied their lighting choices according to the task they were doing. For practice this implies that control systems should be easily accessible, easy to understand, and able to effect substantial changes in conditions.
- Partition washers designed to provide additional vertical illumination were used when offered, but did not significantly improve ratings of mood, satisfaction and discomfort, or offset the preferred output of ceiling-recessed ambient lighting. Neither did they improve task performance. Therefore, if partition washers are to yield benefits, it is likely via an implementation different from the one we employed.
- Provision of supplemental task lighting did not significantly improve ratings of mood, satisfaction and discomfort, or offset the preferred output of ceiling-recessed ambient lighting. However, our results do suggest a benefit on the performance of some tasks. Recommended practice documents for office lighting commonly suggest that a straightforward route to lighting energy savings is to lower ambient lighting levels and to compensate with task lighting. Our findings suggest that the benefits of task lighting might not lie in energy savings, but in task performance improvements. Therefore, we recommend future research into the energy and human factors effects of task lighting to better understand their true benefits, and how to use task lighting appropriately.

6. ACKNOWLEDGEMENTS

This work was sponsored by the National Research Council Canada (NRC), the Project on Energy Research & Development, and Public Works & Government Services Canada (PWGSC). The work was conducted under the PERD Lighting and Daylighting Project "Energy-efficient lighting and daylighting design in the modern workplace: defining occupant preference and increasing occupant performance", as part of the NRC/PWGSC Agreement "Lighting for VDT workstations: preferences and energy-efficient solutions" (NRC Project Number B3208). The authors are grateful for the technical help provided by Roger Marchand (NRC) and Jana Svec (NRC). Thanks are also due for the support of Morad Atif (NRC), Ivan Pasini (PWGSC) and Karen Pero (PWGSC).

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