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## IRC-RR-306

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# Lighting and Office Renovation Effects on Employee and Organizational Well-Being

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## Executive Summary

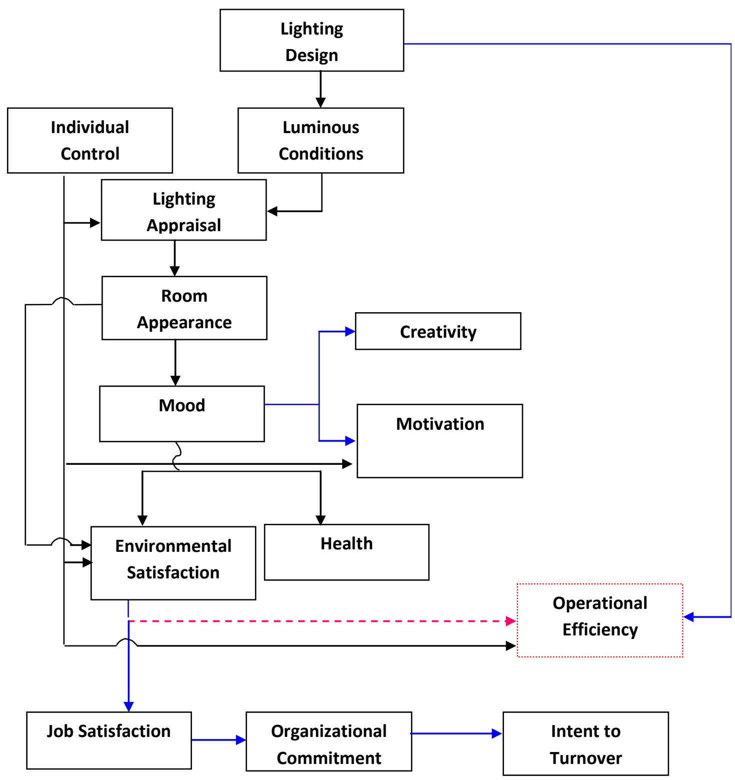
Building on the Light Right Albany experiments, this investigation was designed to achieve two objectives:

1. To replicate the results of the Light Right Albany experiments in a functioning work setting.
2. To extend the model developed from the Albany data to organizational effectiveness outcomes.

### Research Design

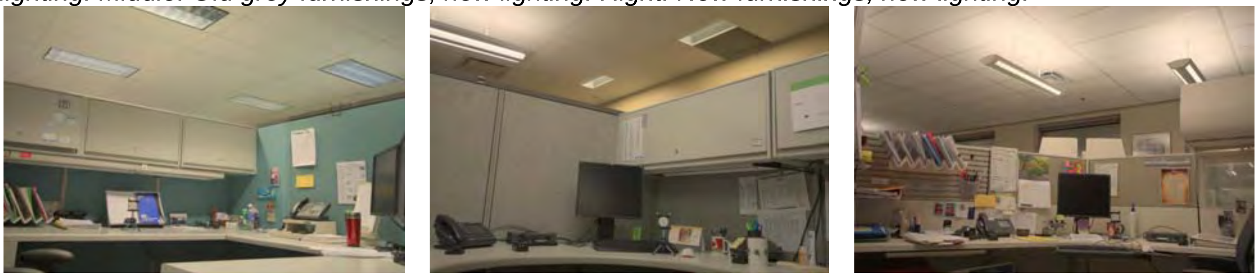
The project was designed around a linked mechanisms map (Figure ES1). As in the Albany experiments, each concept in the linked mechanisms map had at least one associated measurement.

***Figure ES1.*** *Proposed conceptual model. The black lines indicate relationships observed in the Albany experiments. The blue lines are relationships derived from other research. The red dashed line is based on anecdotal evidence.*




The experimental design was a naturally-occurring field experiment. The host organization has undertaken a major renovation of three office buildings, involving both furnishings and lighting. Individual floors in all buildings will be renovated in phases over several years. During the study period (May 2008-September 2009), both old (pre-renovation) and new (post-renovation) conditions existed in the buildings. The old lighting consisted of recessed parabolic-louvered luminaires (similar to the Base Case condition in the Albany experiment 1), and the new lighting consisted of workstation-specific individually-controllable suspended direct/indirect luminaires (similar to the Dimming Control condition in the Albany experiment 1). Figure ES2 shows the three conditions.

***Figure ES2.*** *Workstation views of furnishings and lighting conditions. Left: Old teal furnishings and old lighting. Middle: Old grey furnishings, new lighting. Right: New furnishings, new lighting.*



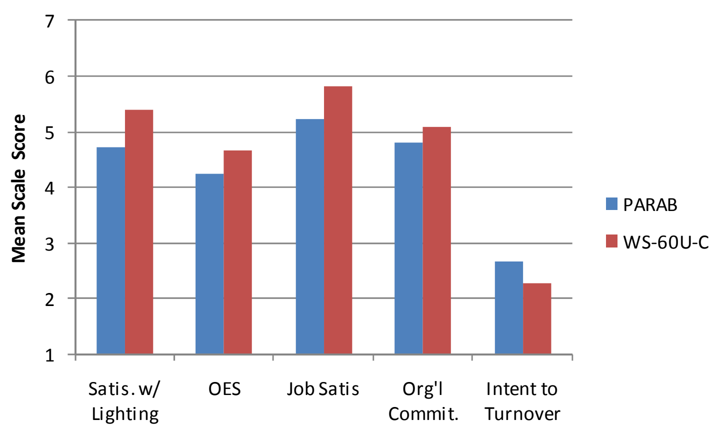
All occupants of the three buildings were asked to complete an online questionnaire on three occasions during the study, in May-June 2008 ($T_0$), June 2009 ($T_1$), and September 2009 ($T_2$). Each time, the questionnaire included questions and tasks to assess the individual-level concepts in the linked mechanisms map. Each measurement wave included a site visit by the research team, during which the physical conditions in selected locations were measured. Some of the participants moved to newly-renovated offices between the first and second measurement waves; others had already moved to new or newly-renovated spaces before the first wave; and others did not experience any office design or lighting changes during the study period.

Between-groups and repeated-measures statistical analyses were performed on planned comparisons between groups differing in lighting conditions, or in the availability of individual (personal) control over lighting, or in office furniture and layout, to determine the effects of the new lighting, the effects of the new furnishings, and the incremental benefit of adding individual control over lighting. Additional analyses tested the relationships between the concepts in the linked mechanisms map.

## Results

**Workstation-specific lighting with individual control is the higher-quality lighting solution.** Workstation-specific lighting with individual (personal) control was preferred over parabolic-louvered luminaires regardless of the surface reflectances of the furnishings. The workstation-specific luminaires with individual control were rated as providing lighting that was better than in other similar workplaces; the parabolic-louvered luminaires were seen as being the same as in other similar workplaces. In the most sensitive statistical tests, small effects were found for several outcomes. Pleasure, room attractiveness and illumination, lighting satisfaction, overall environmental satisfaction, job satisfaction and organizational commitment were all higher for the people in offices with workstation-specific luminaires. The frequency and intensity of physical symptoms and the intent to turnover were all lower for the people in offices with workstation-specific luminaires.

***Figure ES3.*** *Group means for the overall comparison between responses from people in workstations lit with parabolic-louvered luminaires, compared to those with workstation-specific direct-indirect luminaires with individual control, all with low-reflectance, old furniture. All differences are statistically significant.*



Several previous laboratory and field investigations have found that people prefer to control the local lighting in the workstation, and this investigation found no effects that were contrary to the expected direction. Figure ES3 shows some of the results in graphical format.

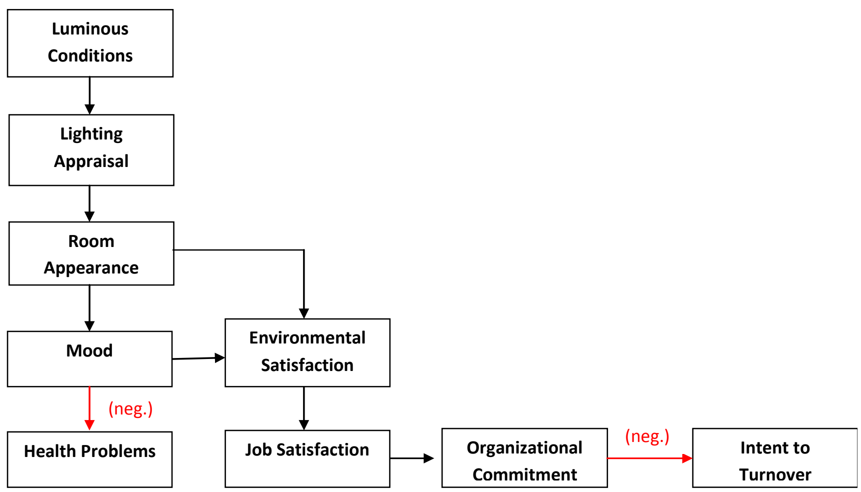
**Room surface reflectances influence lighting quality.** Workstation-specific luminaires with individual control were more likely to be rated as being better than in other similar offices when the surface reflectances were high. The workstation was also judged to be more attractive and to be more highly illuminated, and to deliver a better workplace image.

**Luminous conditions matter to organizational productivity.** We tested the overall linked mechanisms map using structural equation modelling. The best-fitting model was based on the Albany experiments' linked mechanisms map. As shown in Figure ES4, luminous conditions (rated on a scale from parabolic/low reflectance to workstation-specific-control/low reflectance to workstation-specific-control/high reflectance) predicted lighting appraisals, and these in turn indirectly related to reduced health problems and to reduced intent to turnover.

**Discussion**

This field investigation achieved both objectives. The basic findings from the Albany experiments were replicated, in that we obtained clear evidence that the workstation-specific direct-indirect luminaires with individual control deliver a high-quality work environment for occupants. Moreover, we replicated the appraisal path from the Albany linked mechanisms map and extended it to include organizationally-relevant outcomes. The best-fitting model links these luminous conditions to higher ratings of room appearance; more favourable mood; fewer health problems; higher environmental satisfaction; higher job satisfaction; higher organizational commitment; and, lower intent to turnover. If good-quality lighting only resulted in more attractive spaces, the chain of relationships would stop at room appearance. Lighting conditions in offices affect organizational productivity through effects on employees.

***Figure ES4.*** *Conceptual form of final structural equation model.*




Other NRC research in the same host organization has demonstrated that the workstation-specific direct-indirect luminaires with individual control, daylight harvesting, and occupancy sensors, can save 69% of the electricity used compared to a conventional grid of parabolic-louvered luminaires. The evidence that these luminaires also deliver a higher-quality work environment, and furthermore that this environment is associated with fewer health problems and better employee retention, makes this lighting solution an excellent choice for individuals, their employers, and the environment.

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## 1.0 Introduction

A century of lighting research has returned a good understanding of the effects of interior lighting on visual processes (Boyce, 2004). This, together with advances in technology, has largely eliminated problems of seeing from office work. Tasks themselves have changed and recommended practice documents for lighting, based on consensus built on vision research, have ensured that for most office workers the quantity of illumination is more than adequate for the tasks they must perform. However, the means to improve the quality of the lit environment beyond merely adequate seeing — to provide lighting that enhances the health, wealth, and happiness of the occupant — remain unclear (Boyce, 2004).

Recent laboratory research, including the Light Right Albany experiments, has begun to provide guidance on this question. The two Albany experiments tested the responses of, in total, 288 participants to six different lighting installations (Boyce et al., 2006a; Boyce et al., 2006b; Boyce, Veitch, Newsham, Myer, & Hunter, 2003). Of occupants whose lighting was typical of current practice, a 2 x 4 parabolic recessed troffer, approximately 70% rated the lighting as comfortable. This percentage rose to ~80% for a suspended direct/indirect system, and to ~90% for a suspended direct/indirect system with individual lighting control. This apparent preference for the combination of direct and indirect lighting is consistent with other work (Houser, Tiller, Bernecker, & Mistrick, 2002; Veitch & Newsham, 2000). The combination of direct and indirect lighting, rather than fully direct lighting, appears to be one way to improve office lighting quality.

Another result from Albany showed that individual control over lighting had a statistically significant effect on motivation over the working day; those without control showed a decline in motivation, whereas those with control maintained the same level throughout the day (Boyce, et al., 2003). An experiment conducted at the National Research Council of Canada at the same time as the Albany experiments used a different experimental paradigm to examine the benefits of individual control. In that experiment, 118 participants were given control over their office lighting for the last quarter of the working day (after the afternoon coffee break). There were statistically significant improvements in mood, environmental satisfaction, and visual comfort after the introduction of control; these effects appeared to be associated with the ability to obtain one's preferred lighting condition (Newsham, Veitch, Arsenault, & Duval, 2004). Obtaining one's preferred lighting conditions was associated with better mood, lighting quality ratings, and environmental satisfaction in an earlier NRC-IRC experiment (Newsham & Veitch, 2001). Because individual preferences vary widely, individual control is the only practical means to ensure that people have a fair chance of obtaining their own preferences.

These laboratory experiments can provide solid evidence that various lighting enhancements can have measurable, observable effects on occupants over the short term; however, they cannot demonstrate what happens when people work under such lighting over a longer period, as in an office occupied daily for weeks or years. Moreover, they cannot provide the evidence that employers want concerning the effects of lighting enhancements on organizational performance. This paper reports results of a field investigation that was designed to fill the knowledge gap with such evidence. This investigation had two objectives:

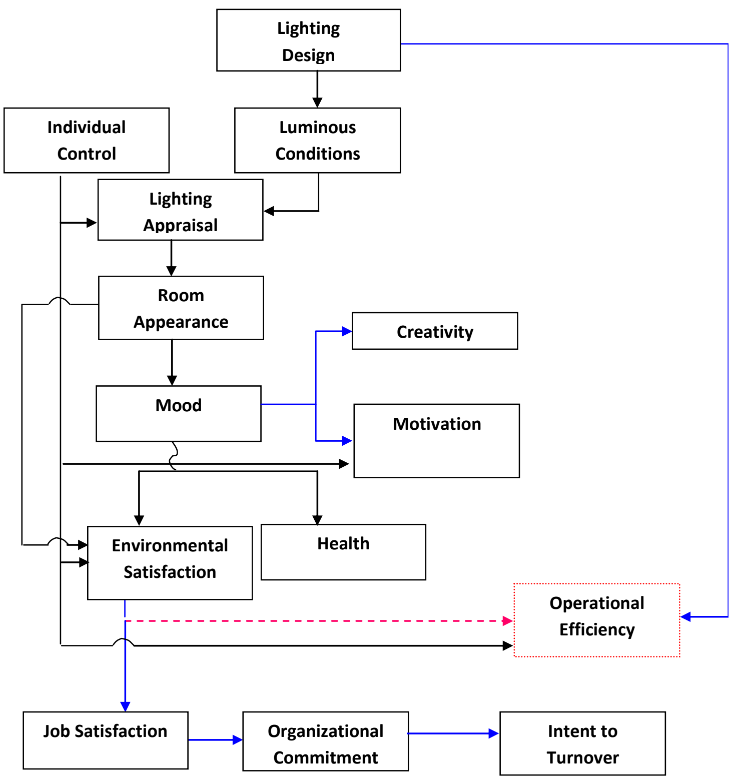
1. To replicate the results of the Light Right Albany experiments in a functioning work setting.
2. To extend the model developed from the Albany data to organizational effectiveness outcomes.

The project was designed around a linked mechanisms map. The proposed linked mechanisms map for this investigation is shown in Figure 1. As in the Albany experiments, each concept in the linked mechanisms map has at least one associated measurement. In Figure 1, black lines indicate relationships that were observed in tests of the linked mechanisms map using the data from the two experiments in Albany (Boyce, et al., 2003; Veitch, Newsham, Boyce, & Jones, 2008). The blue lines in Figure 1 are relationships supported by other research.

For instance, the connection from mood to creativity and motivation has as its basis the positive affect theory of Alice Isen as adapted for organizations and the physical environment (Baron, 1990; Baron & Thomley, 1994; Isen & Baron, 1991).

We proposed to link the existing linked mechanisms map to a body of research from organizational psychology, shown here schematically at the bottom of Figure 1. The connection from environmental satisfaction to job satisfaction is a robust relationship observed in several investigations, including NRC-IRC's Cost-effective Open-Plan Environments field study (Carlopio, 1996; Veitch, Charles, Farley, & Newsham, 2007). Carlopio (1996) and Donald and Siu (2001) observed a further connection from workplace satisfaction to job satisfaction to organizational commitment. A strong connection from job satisfaction to turnover intent and organizational rates of turnover is well-established (Harter, Schmidt, & Hayes, 2002; Koys, 2001; Lambert, Hogan, & Barton, 2001). Harter et al. (2002) also found that organizations with higher job satisfaction show improved customer satisfaction and profitability.

***Figure 1.*** *Proposed conceptual model.*
*The black lines indicate relationships observed in the Albany experiments. The blue lines are relationships derived from other research The red dashed line is based on anecdotal evidence.*




The experimental design is a naturally-occurring field experiment. The host organization is undertaking a major renovation of three office buildings in south-west British Columbia. The renovations involve both furnishings and updated lighting. Both the old and new lighting are the equipment types that were the focus of previous research. The old lighting consists of recessed parabolic-louvered luminaires (similar to the Base Case in the Albany experiment 1), and the new lighting consists of workstation-specific individually-controllable suspended direct/indirect luminaires (similar to Dimming Control in the Albany experiment 1).

All occupants of the three buildings (N ~ 2400) were asked to complete an online questionnaire on three occasions during the study ($T_0$: May-June 2008, $T_1$: June 2009, and $T_2$: September 2009). Each wave included questions and tasks relevant to all the individual-level concepts in the linked mechanisms map (white boxes in Figure 1), as well as demographic and work characteristics questions that were used to establish group equivalencies. Some of the participants moved to newly-renovated or newly-built offices between measurement waves; others had already moved to newly-renovated spaces; and others did not experience any office design or lighting changes during the study period.

# 2.0 Method

## 2.1 Research Design

The investigation was a naturally-occurring field quasi-experiment taking place in three buildings in southwest British Columbia that are occupied by one organization, a large Canadian corporation. The phrase “naturally-occurring” means that the host organization had complete control over all aspects of the buildings, their furnishings, their lighting, and their operation. The organization is undergoing a phased renovation of certain floors within its three buildings, involving changes to both lighting and furnishings. The old lighting consists of recessed parabolic-louvered luminaires (abbreviated PARAB) and the new lighting consists of workstation-specific individually-controllable suspended direct/indirect luminaires (abbreviated WS-81U-C to note the percentage of indirect light at full output of all “on” lamps), or the same luminaire with the indirect lamp turned off (abbreviated WS-76U-C). Four floors of one building have a similar, but not identical, luminaire, also with the indirect lamp turned off (abbreviated WS-60U-C). (The –C suffix denotes the availability of individual control.)

The phasing-in of the lighting retrofit provided comparison groups to permit the separation of effects associated with light distribution, individual control over lighting, and office furnishings. Table 1 shows the groups formed by the combinations of lighting and furnishings. In addition, some of the floors with WS-76U and WS-81U lighting lacked individual control at either $T_0$ or $T_1$, enabling comparisons of the effect of individual control between groups with the same luminaire and furnishings.

The renovation of Buildings 1 and 2 continued past the end of the investigation. Over time, all employees in Buildings 1 and 2 will move into renovated spaces with new panels and WS-81U-C lighting. (That is, those in the cell at the top left of Table 1 will over time move to the conditions described in the cell at bottom right.)

***Table 1**. Lighting and furnishings combinations in the three buildings, with valid sample sizes (N) for measurement waves $T_0$, $T_1$, $T_2$ shown beneath.*

| | PARAB | WS-60U-C | WS-76U-C | WS-81U-C |
|---|---|---|---|---|
| Old panels – teal | Bldg 1, 2<br>474, 451, 373 | | | |
| Old panels – grey | Bldg 3<br>4, 10, 12 | Bldg 3<br>69, 80, 62 | | |
| New panels | Bldg 1<br>20, 12, 8 | | Bldg 3<br>35, 50, 45 | Bldg 1, 2<br>61, 77, 43 |

## 2.2 Participants

Occupants in the three buildings were invited by e-mail to participate by completing an online questionnaire. There were three measurement waves. Table 2 summarizes the participation at each wave. Taken overall, 3841 unique individuals were invited to participate and 1750 participated at least once, for a response rate of 45% taken over the entire investigation. Within each wave the response rate of 30-40% is normal for this type of organizational survey (Rose, Sidle, & Griffith, 2007).

***Table 2.** Invitations issued and frequency of responses to the three measurement waves.*

| | Invited | Responded | Completed | New | Response Rate |
|---|---|---|---|---|---|
| $T_0$ | 2749 | 1022 | 837 | 2749 | 37% |
| $T_1$ | 3035 | 1022 | 932 | 889 | 34% |
| $T_2$ | 2856 | 791 | 708 | 203 | 28% |
| Total | | 1750 | | 3841 | 45% at least once |

To test for bias in the sample, we obtained sex and age distribution data from the host organization’s Human Resources department. Tables 3 and 4 summarize the combined respondents for the three waves in terms of age and sex (for those who answered these two questions), and compare the distribution of these variables to the population of employees in the three buildings. Looking at the whole sample, there was a slight tendency for more women than expected to respond, and the sample is slightly younger than expected.

The data analyses for this study considered only respondents in open-plan offices. Therefore, we also examined the age and sex distributions for respondents in open-plan offices. We could only compare these to the total population, as sex and age data were not available by office type. The tendency for there to be a higher proportion of women and younger people among the respondents was slightly more pronounced among the open-plan office respondents than in the overall sample, but as the expected distributions of age and sex for open-plan respondents are not known, we cannot judge whether or not the final sample shows any bias compared to the population of employees in the open-plan areas. In any case, the differences from the expected values are small.

***Table 3.*** *Sex distribution of participants and population.*

| | Valid N | Male % | Female % | $X^2(1)$ |
|---|---|---|---|---|
| Population | | 54.6 | 45.4 | |
| Full Sample | 1540 | 51.9 | 48.1 | 4.62* |
| Open-plan only | 1267 | 50.6 | 49.4 | 8.24** |

Note. *$p$<.05. **$p$<.01.

***Table 4.*** *Age distribution of participants and population.*

| | Valid N | 18-29 % | 30-39 % | 40-49 % | 50-59 % | >=60 % | $X^2(4)$ |
|---|---|---|---|---|---|---|---|
| Population | | 14.5 | 27.6 | 30.2 | 22.7 | 4.9 | |
| Full Sample | 1552 | 17.3 | 28.5 | 30.1 | 18.9 | 5.2 | 18.84*** |
| Open-plan only | 1280 | 18.8 | 28.8 | 30.4 | 17.1 | 5.0 | 34.17*** |

*Note.* ***$p$<.001.

We also recorded the education level and job category of participants at each measurement wave. There was no population data to which to compare this information. Table 5 shows the demographic characteristics of the respondents from the full sample and from the open-plan offices, whose data were used in the subsequent analyses.

***Table 5.*** *Education and job type distributions of participants.*

| | Valid N | Admin % | Technical % | Prof. % | Manager % | |
|---|---|---|---|---|---|---|
| Full Sample | 1547 | 17.2 | 17.8 | 48.6 | 16.4 | |
| Open-plan only | 1277 | 18.6 | 17.7 | 48.3 | 15.4 | |
| | **Valid N** | **High school %** | **Coll /Tech Cert %** | **U < Bach %** | **Bachelor %** | **Grad/Prof %** |
| Full Sample | 1545 | 4.0 | 18.6 | 9.0 | 34.0 | 34.3 |
| Open-plan only | 1274 | 3.8 | 18.6 | 9.7 | 34.9 | 33.1 |

## 2.3 Building Characteristics

***2.3.1 Building details.*** The three buildings are located in three different neighbourhoods in a large metropolitan area. In addition, the organization has other office space elsewhere in the region; one reason for the renovation is to increase occupancy in the buildings in order to reduce the need for the additional space.

All three buildings have large windows in all compass orientations. There are open-plan areas around the perimeters of the buildings, with services and shared spaces in the core. The windows in all buildings have venetian blinds, and on a few floors also have low-transmission transparent roller blinds. The windows do not open. One of the buildings has under-floor ventilation (Building 2); two have traditional ceiling ventilation (Buildings 1 and 3).

Buildings 1 and 2 were constructed in the late 1980s/early 1990s and have very similar original layout and furnishings (see below for furnishings details). These buildings are the target of the phased renovation in which new furnishings and lighting are being installed.

Building 3 was constructed in the mid-1990s as an 11-storey building, and three floors were added in 2007. Five floors have been occupied by the host organization since its construction, and to these have been added the newly constructed floors.

All employees use computers in their jobs; Over 96% of these were reported to be flat-panel LCD monitors. Some were on laptop computers, but most were stand-alone monitors. Some employees use two monitors, usually side-by-side.

***2.3.2 Furnishings.*** Buildings 1 and 2 were originally designed to the same standard in the late 1980s, and consequently share very similar furnishings and layouts (see Figure 2.A) in the unrenovated areas. The design and layout use modular systems furniture typical of North American offices. Most employees are in open-plan areas, but those with enclosed offices are on the periphery on the unrenovated floors. The cubicle sizes and panel heights vary from one area to another. The original floors in Building 3 are furnished with rectilinear cubicles similar to the layout of the unrenovated spaces in Buildings 1 and 2, although with a different colour scheme (see below).

The new layout, which is in place on renovated floors in Buildings 1 and 2 and on the newly built floors in Building 3, reduces the formal partitions between cubicles in favour of promoting team areas, and has changed the orientation of workstations to provide more shared window access. Panel heights are lower to promote daylight penetration. Enclosed offices are in the core of the building rather than on the periphery. Workstation sizes are smaller than in the original areas to increase the occupancy; however, each floor also has dedicated lounge or meeting areas as well as common services such as printers, photocopies, and fax machines.

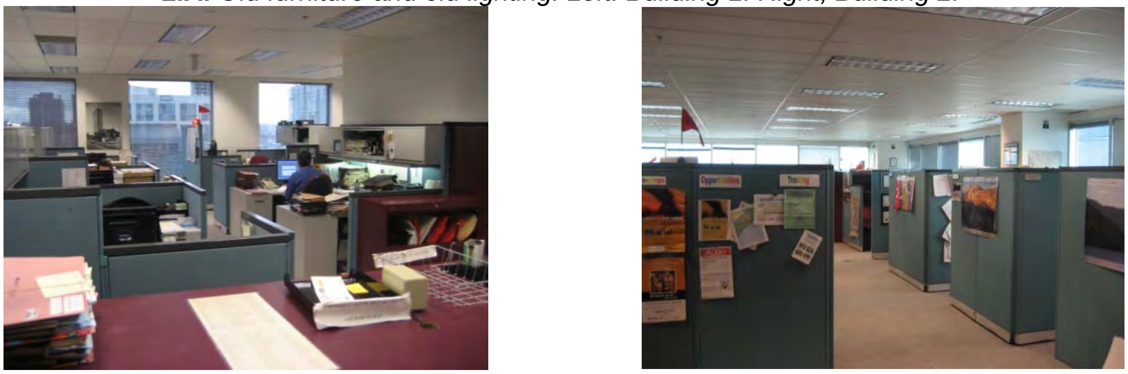
Table 6 summarizes the reflectances of key surfaces for the three furnishing conditions. The photographs below do not do justice to the visual change between the old and new furnishings. The predominant finish in the new spaces is a warm off-white colour, used on the panel trim, the cabinets and shelves, and on hard panel surfaces. The fabric panels in the new spaces are smaller than in the unrenovated areas, and the shelves and bins predominate. In addition, the renovated and new floors have several intense accent colours for columns and boundary walls, and on chairs and upholstery.

***Table 6.*** *Measured average reflectances of key surfaces.*

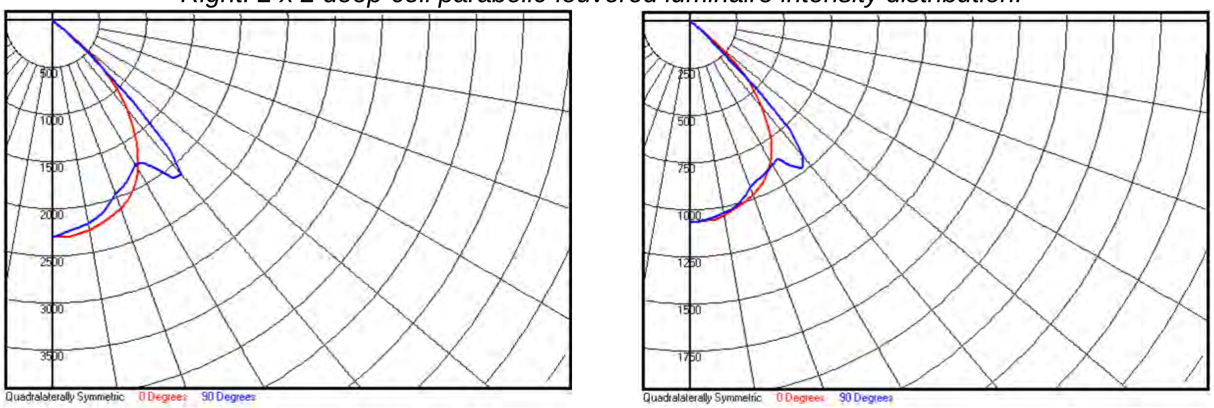
| | Principal Colours | Fabric panel | Shelves & Bins | Panel Trim | Hard Panels | Carpet | Desk | Ceiling Tile |
|---|---|---|---|---|---|---|---|---|
| Old - Bldg 1&2 | teal / grey | .27 | .43 | .15 | .10 | .16 | .49 | .72 |
| Old - Bldg 3 | grey / grey | .35 | .37 | .10 | .36 | .12 | .47 | .76 |
| Reno & New | off-white / gold | .36 | .63 | .63 | .44 | .17 | .62 | .78 |

***2.3.3 Lighting equipment and luminous conditions.*** On unrenovated floors in Buildings 1 and 2, and on one floor of Building 3, the lighting consists of 2’ x 4’ (90%) and 2’ x 2’ (10%) recessed deep-cell (4”) parabolic-louvered luminaires (PARAB), each with 2 T8 lamps at 85 CRI and 3500 CCT and non-dimming electronic ballasts. Figure 2.B shows the intensity distribution from these luminaires. Note that there is no indirect component for these luminaires: The luminaires deliver 100% downlight. Figure 2.C. shows workstation-level views of two workstations with this lighting.

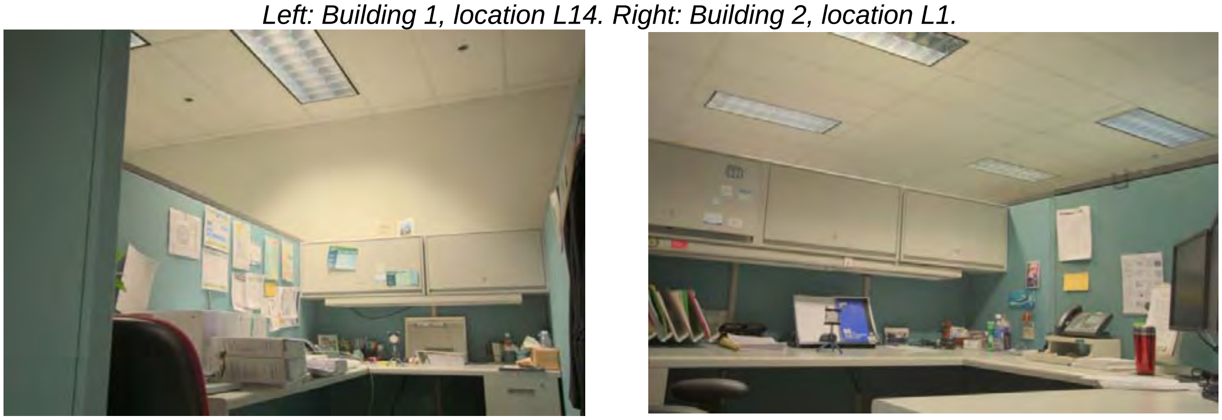
***Figure 2.*** *Illustration of old furnishings and lighting.*
***2.A.*** *Old furniture and old lighting. Left: Building 1. Right, Building 2.*



***2.B.*** *Left: 2 x 4 deep-cell parabolic-louvered luminaire intensity distribution.*
*Right: 2 x 2 deep-cell parabolic-louvered luminaire intensity distribution.*

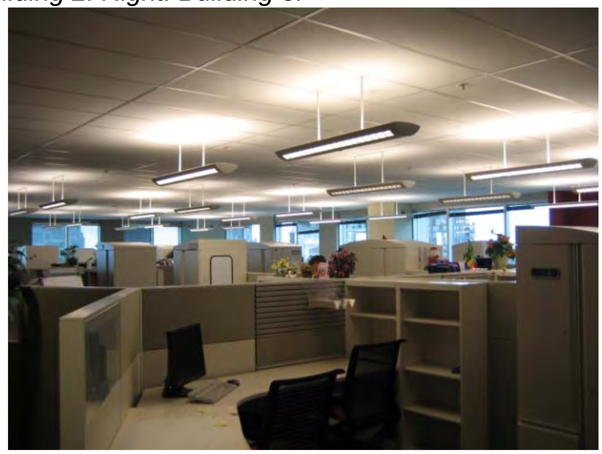



***2.C.*** *High-dynamic-range (HDR) image of sample workstation views, old lighting.*
*Left: Building 1, location L14. Right: Building 2, location L1.*

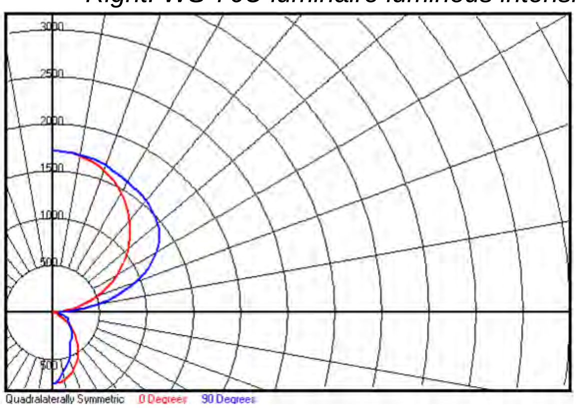


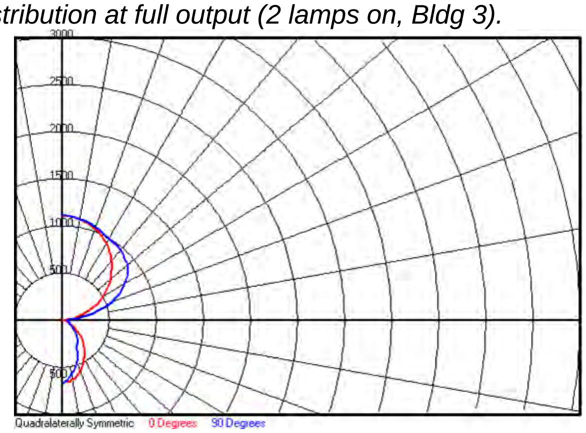
The new lighting in buildings 1 and 2 consists of workstation-specific, suspended direct-indirect luminaires with three lamps, all 32 W T8 lamps at 85 CRI and 3500 CCT. One of the three lamps provides the indirect component; it is run on a non-dimming electronic ballast at full power throughout the workday. The other two lamps provide the direct component, and are run on a dimming electronic ballast. Figure 3.B. shows the luminous intensity distribution from this luminaire. At full output, 81% of the light is directed up and 19% down. We have labelled this luminaire WS-81U. The newly-constructed floors at Building 3 have the same luminaire, but only the two dimmable lamps are used. This changes the distribution somewhat; at full output 76% of the light is directed up, and we have labelled this luminaire WS-76U (right panel, figure 3B).

***Figure 3.*** *Illustration of new furnishings and lighting.*
***3.A.*** *New conditions. Left: Building 2. Right: Building 3.*



***3.B.*** *Left: WS-81U luminaire luminous intensity distribution at full output (3 lamps on, Bldgs 1 and 2). Right: WS-76U luminaire luminous intensity distribution at full output (2 lamps on, Bldg 3).*

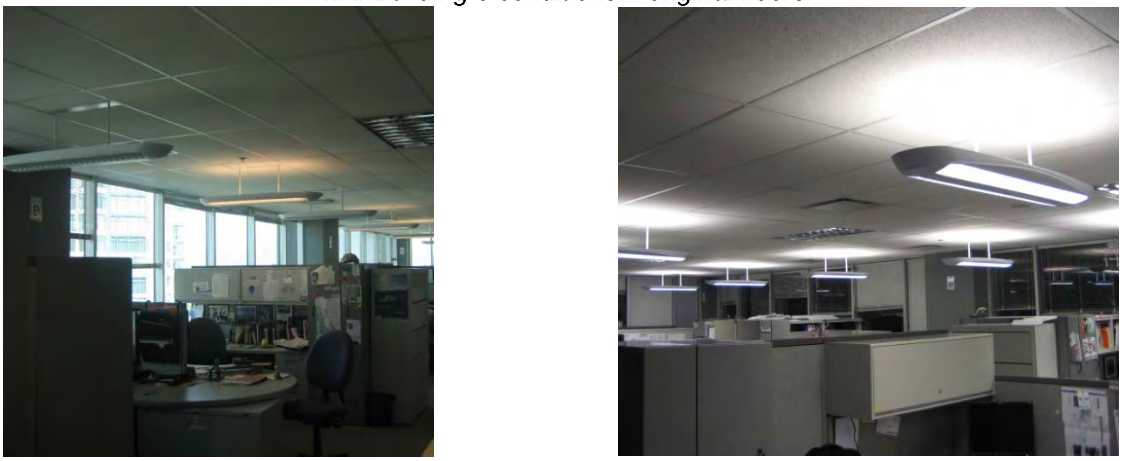


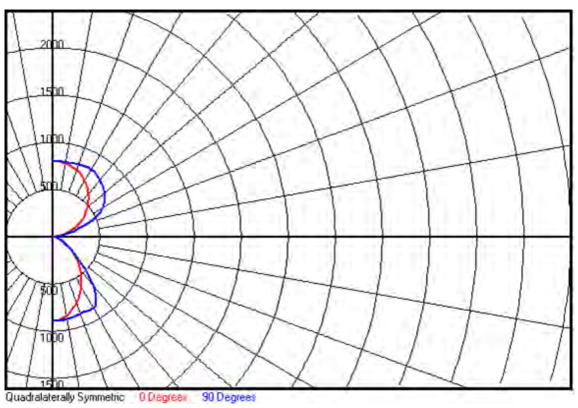

***3.C.*** *HDR image of selected new lighting, dimmers at 100%, Building 1, location L3.*

Occupants of four of the older floors in Building 3 have an earlier generation of the luminaire used on the renovated and newly-built floors (see Figure 4). The lamps are 32W T8, 3500 K, 85 CRI. The lighting is operated with downlights only; the uplights have been set to 0% output since mid-2006 as part of an aggressive energy conservation program. Figure 4.B. shows the luminous intensity distribution of the luminaire as operated. Sixty percent of the output is directed up, and we have labelled this luminaire WS-60U.

***Figure 4.*** *Illustration of old furnishings and new lighting in Building 3, original floors.*
***4.A.*** *Building 3 conditions – original floors.*



***4.B.*** *WS-60 luminous intensity distribution (Building 3, old floors, 2 down lamps on).*




***4.C.****High-dynamic range image of Building 3, WS—60U; old furnishings, location L6.*

For all the workstation-specific luminaires, the level of the direct component may be modified by output from an occupancy sensor, a light sensor, or individual control through the desktop computer. The occupancy sensor is integral to the luminaire, and detects motion in the workspace. If no presence is detected, the sensor prompts the downlight to gradually dim down to zero output and switch off. When presence is detected, the downlight automatically returns to the previously set level. The light sensor is also integral to the luminaire. It monitors the surrounding light levels and dims the downlight when sufficient light from other sources is present to maintain the preset light level; its principal function is to provide daylight harvesting. The individual (personal) control consists of a computer program resident on the occupant's computer, with a graphic interface that allows the individual to set the dimmer level for the downlight component to any level between 0 and 100%.

***2.3.4 Summary of buildings and floors by measurement wave.*** Table 7 summarizes the status of the study floors in the three buildings at each measurement wave. Some floors were not surveyed, either because their occupants were not employees of the host organization or because their layout and furnishings were different from the standard (e.g., the floor for senior management was differently laid out and furnished). Floors 1E, 2K, and 2Q were renovated as part of a pilot project and were occupied in spring 2007 (approximately 1 year prior to $T_0$). Floors 3F, 3G, and 3H were newly constructed and occupied in spring 2008 (1-3 months prior to $T_0$). Individual control over lighting was not enabled on these floors until after the $T_0$ measurement wave. Floor 1H was renovated in late 2008-early 2009 and occupied in March 2009. Individual control over lighting was withheld from this floor until after measurement wave $T_1$. Floor 1I was unoccupied during $T_1$ and $T_2$. because it was being renovated. Floors 1C, 1G, and 1K were slated to begin construction in December 2009; their occupants would have been aware at $T_2$ that they were to vacate their offices within a few months.

***Table 7.*** *Summary of lighting and furnishings on study floors.*

| Bldg | Floor | $T_0$ | | $T_1$ | | $T_2$ | |
|---|---|---|---|---|---|---|---|
| | | Lighting | Furniture | Lighting | Furniture | Lighting | Furniture |
| 1 | A | PARAB | New | PARAB | New | PARAB | New |
| 1 | B | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 1 | C | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 1 | D | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 1 | E | WS-81U-C | New | WS-81U-C | New | WS-81U-C | New |
| 1 | F | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 1 | G | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 1 | H | PARAB | Old, teal | WS-81U | New | WS-81U-C | New |
| 1 | I | PARAB | Old, teal | | | | |
| 1 | J | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 1 | K | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2 | C | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2 | D | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2 | E | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2 | F | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2 | H | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2 | I | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2 | J | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2 | K | WS-81U-C | New | WS-81U-C | New | WS-81U-C | New |
| 2 | L | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2 | M | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2 | N | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2 | O | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2 | P | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2 | Q | WS-81U-C | New | WS-81U-C | New | WS-81U-C | New |
| 2x | A | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2x | B | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2x | C | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2y | A | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2y | B | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 2y | C | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 3 | A | PARAB | Old, teal | PARAB | Old, teal | PARAB | Old, teal |
| 3 | B | WS-60U-C | Old, grey | WS-60U-C | Old, grey | WS-60U-C | Old, grey |
| 3 | C | WS-60U-C | Old, grey | WS-60U-C | Old, grey | WS-60U-C | Old, grey |
| 3 | D | WS-60U-C | Old, grey | WS-60U-C | Old, grey | WS-60U-C | Old, grey |
| 3 | E | WS-60U-C | Old, grey | WS-60U-C | Old, grey | WS-60U-C | Old, grey |
| 3 | F | WS-76U | New | WS-76U-C | New | WS-76U-C | New |
| 3 | G | WS-76U | New | WS-76U-C | New | WS-76U-C | New |
| 3 | H | WS-76U | New | WS-76U-C | New | WS-76U-C | New |

*Note*. Buildings 2x and 2y are three-story podium buildings connected to Building 2.

## 2.4 Questionnaire

The dependent variables encompassed all of the measurements of concepts in the linked mechanisms map (Figure 1). Among the criteria for selection of these variables was their demonstrated validity and reliability and their suitability for use in a computer interface by employees during a regular working day. The total time and effort burden on the research participants was a further consideration in selecting dependent variables for this investigation and tools with which to measure them.

***2.4.1 Performance measures.*** *Motivation*. Motivation may be expressed as the degree to which one will persist in the anagram task developed by Aspinwall and Richter (1999), in which participants are given a series of 5-letter anagrams, some solvable (e.g., "uijce = juice") and some unsolvable (e.g., "oneci" does not make an English word). The measure of persistence is the number of times the participant attempts to complete the impossible task during the allotted time, or the duration of time spent working on the unsolvable task. Participants spent 5 minutes on this task, or worked through the six items presented, of which two were unsolvable and four were solvable. We also obtained a cognitive performance measure by examining the success rate and time taken to solve the solvable anagrams.

*Creativity.* We used a divergent thinking task that has been used previously in lighting research (Veitch & Gifford, 1996), where it was sensitive to the degree of control participants had over the lighting at their workstation. In this task, participants are presented with a picture of an everyday object and asked to suggest as many novel uses for that object as possible. This task was presented only at $T_0$ because we observed that a large number of respondents quit the questionnaire at or immediately after this task, and we had many complaints about its suitability. The outcome measures included objective ratings of fluency (number of novel uses) and speed, and ratings of the perceived creativity of the uses. The ratings were performed by independent raters unaware of the hypotheses and of the office conditions of the respondents.

***2.4.2 Perceptions and feelings.*** *Lighting appraisal.* The principal lighting appraisal tool is the Office Lighting Survey (Eklund & Boyce, 1996), which was used in the Light Right Albany experiments (Boyce, et al., 2003). The responses from the Office Lighting Survey were compared with normative data collected by Eklund and Boyce in similar buildings in the Northeastern United States.

We added four questions concerning perceptions of daylight and windows. The first three are modelled on the Office Lighting Survey (Eklund & Boyce, 1996), and the fourth is a semantic differential rating of the attractiveness of the view through the window.

*Room appearance.* Participants were asked to evaluate the appearance of the space using a set of semantic differential rating scales selected from the 27 items used by Veitch and Newsham (1998). They were chosen because these items showed consistent correlations across the several studies in which the 27-item set was chosen (Boyce, et al., 2003; Newsham, et al., 2004; Veitch & Newsham, 1998). They produced average ratings for room attractiveness and room illumination.

*Environmental features ratings.* Participants rated their satisfaction with 23 specific aspects of their work environment using the NRC Environmental Features Ratings. This is a modified version of the 18-item questionnaire developed for the Cost-effective Open-Plan Environments project (Veitch, et al., 2007), itself based on the Ratings of Environmental Features developed by Stokols and Scharf (1990). For this project we added five questions about the furnishings and office layout to assess specific aspects that are expected to change in the renovation. The original 18 items formed a stable 3-factor structure that was used to create subscale scores for satisfaction with lighting, with ventilation & temperature, and with privacy & acoustics.

*Mood.* Mood was assessed using the Affect Grid, which is a simple measure of pleasure and arousal, in which the individual places a mark in one square of a 9 x 9 matrix on which one axis indicates pleasure and the other arousal (Russell, Weiss, & Mendelsohn, 1989).

*Environmental satisfaction.* We used the two-item measure of overall environmental satisfaction developed as part of NRC-IRC 's Cost-effective Open-Plan Environments (COPE) project, which has been shown to relate to conditions in the physical environment (Veitch, Charles, Newsham, Marquardt, & Geerts, 2003). We made a small change to the wording of the first question to return it to the original wording (Wilson & Hedge, 1987).

In addition, we asked three questions to assess employee opinions concerning the match between the physical environment in which they work and their understanding of corporate values, creating a separate scale that we call *workplace image*. They are based on questions used by workplace design consultants, which they have found to have practical utility (Laing, 2005).

*Job satisfaction.* We used a single-item measure of overall job satisfaction. The wording is based on the question used by Dolbier, Webster, McCalister, Mallon, and Steinhardt (2005). Single-item scales of job satisfaction have been shown to have acceptable reliability and to be suitable for use when longer scales are impractical (Dolbier, et al., 2005; Wanous, Reichers, & Hudy, 1997), although multi-item scales have higher reliability. In this instance, the overall length of the questionnaire makes a single-item scale preferable.

*Organizational commitment.* Participants answered the six-item scale of affective organizational commitment developed by Meyer, Allen, and Smith (1993). This scale uses the Allen and Meyer three-component conceptualization of organizational commitment (Allen & Meyer, 1990), which has been extensively tested and validated (Allen & Meyer, 1996), and is widely used. For instance, Saks and Ashforth (2002) used the 8-item version to study recent university graduates' job experiences, finding that the perceived fit between person and job or person and organization predicted organizational attitudes (affective commitment and intention to quit).

*Intent to turnover.* The survey included a three-item scale of turnover intention was developed by Colarelli (1984), and is a common measure of this concept. For instance, it was the intention to quit scale used by Saks and Ashforth (2002).

*Health.* Visual discomfort was measured using a short version of the scale developed by Wibom and Carlsson (1987), and with which they demonstrated that luminance ratios of greater than 10:1 between paper and a VDT screen tend to reduce visual comfort over several hours. The list of physical discomfort measures was adapted from the literature (Hedge, Erickson, & Rubin, 1992) and placed in the same format as the visual discomfort symptoms. Veitch and Newsham (1998) and Newsham et al. (2004) have found these discomfort measures to be sensitive to changes in lighting conditions.

*Absenteeism.* We relied on self-reported absenteeism because organizational data were not available, asking individuals to report the number of days during the previous month on which they were absent because of personal illness and the total number of days of paid time off that they have taken during that same period.

***2.4.3 Statistical controls.*** We included several demographic and work experience variables to provide statistical control by allowing a determination of the degree to which the occupants in the experimental groups are similar. Participants were asked to record their age, sex, education, job category, years of work experience (both overall and tenure with the host organization), the state of their vision (corrected or not), and to provide ratings of job demands and organizational climate. The job demand and organizational climate questions were taken from the organizational psychology literature (Lowe, Schellenberg, & Shannon, 2003). They were chosen for their brevity and because they have shown adequate internal consistency reliability and convergent and discriminant validity.

*Open comments.* The survey concluded with two open-ended questions. Participants were asked to indicate their beliefs about the purpose of the survey, and invited to report any comments, positive or negative, about their workplaces. These questions were used to explore possible source of bias in the data.

## 2.5 Procedure

***2.5.1 Online questionnaire.*** Approximately one week prior to each measurement wave, potential participants in the three buildings received messages from Corporate Communications announcing the study, and an article appeared in the organization's online newsletter (received by all employees, not only those in the study buildings). A week later, each of the potential participants received a personally-addressed e-mail invitation with a unique access code and a link to the questionnaire on NRC's secure server. Participation was encouraged by offering to make a $5 contribution to the organization's employee charitable foundation for each respondent. Respondents received a thank-you e-mail following their participation. Reminder messages were sent to those individuals who had not responded after one and two weeks, and the questionnaire was closed after three weeks. A short announcement in the online employee newsletter approximately one month later thanked all employees and announced the total contribution that would be made to the charitable foundation as a result of their participation in this wave of the study. Individuals who asked not to be contacted again following $T_0$ and $T_1$, were placed on a "do not call" list, and excluded from subsequent NRC e-mails concerning the study.

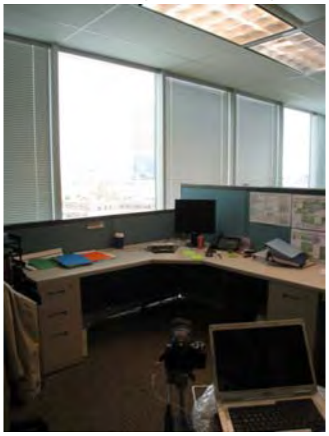
Clicking on the link in the e-mail message took the participant to the questionnaire on the secure NRC web site. The first page viewed was a consent form; it included a link to a pop-up window to view detailed NRC's privacy policy applicable to the study. Participants who agreed to the terms of the consent form entered their unique access codes and clicked "start survey" to proceed from the consent form to the first page of questions. The access codes permitted the matching of data from the different measurement waves.

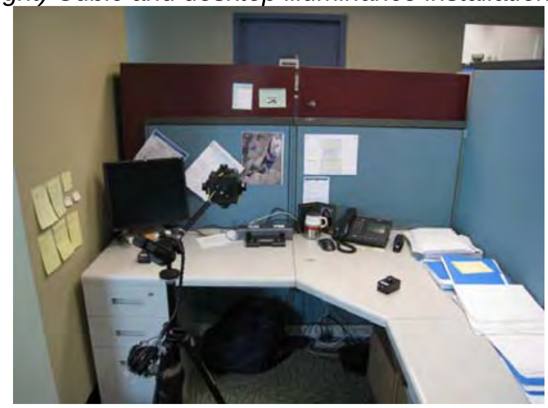
***2.5.2 Physical measurements.*** Each measurement wave included a 5-day site visit to the organization by NRC research staff. Photometric measurements were the principal focus of the site visits. At each visit, we made several reflectance measurements of key surfaces; these were the basis for the values reported above in Table 5. We also made detailed photometric measurements by day and by night.

The most important measurements were the night-time electric lighting measurements in selected workstations of all furnishing types. The luminance measurements included calibrated high-dynamic-range (HDR) images of the viewpoint of a seated occupant (see Figure 5A), from which luminance and derived luminance variability metrics were created using Photosphere (Ward, 2005) and the recommendations provided by Reinhard (2006). We also took spot luminance measurements on the ceiling. For illuminance, we measured cubic illuminance at the location of the head of a seated occupant and took two desktop illuminance measurements (see figure 5B). For the WS-60U, WS-76U, and WS-81U luminaires at $T_0$ and $T_1$, we repeated all of these measurements for five combinations of dimmer settings: target workstation at 100%, adjacent workstations at 100%, 50%, and 0%; and, target workstation at 0%, adjacent workstations at 50% and 100%. The settings will provide information concerning the degree of spill from one workstation to another. At $T_2$ we measured only the 100%-100% condition, in order to have time to visit a larger number of workstations.

During the daytime (principally afternoons), we made illuminance measurements at $T_0$, $T_1$, and $T_2$, and luminance measurements at $T_1$ and $T_2$ in a convenience sample of workstations in each building. The luminance measurements for the occupant's field of view were based on calibrated HDR images; spot measurements were taken of the maximum and minimum ceiling luminance. We also recorded the location of windows, their orientation, and the blinds and sky conditions. The daytime lighting measurements took the conditions as found, but the choices of locations were restricted in that the measurement ranges of the equipment did not permit direct sunlight on any sensor.

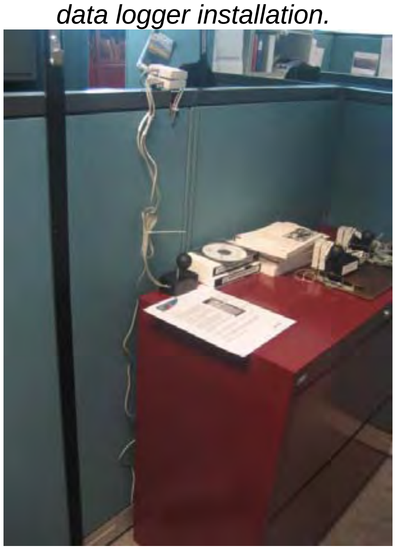
***Figure 5.*** *Luminance and illuminance equipment, shown on a floor with old furnishings. A (Left), Camera setup for HDR photography. B (Right) Cubic and desktop illuminance installation.*





We also assessed the acoustic conditions in the old and new layouts at $T_0$, to determine whether or not either layout created acoustic conditions substantially different from recommended practice. These measurements used the NRC-produced SPMSoft system to assess sound transmission between workstations and to calculate speech intelligibility indices (Bradley & Gover, 2008). This measurement involves placing a sound generator to produce a known sound in one workstation and a sound level meter in an adjacent workstation, connected to a computer running the software.

***Figure 6.*** *Temperature and humidity data logger installation.*



On all three site visits, we collected air and radiant temperatures and relative humidity at 20 locations spread across the three buildings, with some placed on floors of each furniture/lighting combination. The air temperatures were recorded at three heights: ankle, desk, and panel top, using a custom combination of off-the-shelf data loggers (Figure 6). The loggers were installed on Monday afternoon of each site visit week and removed on Thursday night or Friday morning; we used the data collected during working hours on Tuesday, Wednesday, and Thursday.

#### *2.5.3 Archival organizational data.*

The linked mechanisms map predicted that where lighting and furnishings conditions improved satisfaction, there would be lower lighting energy use and fewer facilities complaints. We therefore sought to obtain lighting energy use and facilities management records from the host organization for the three buildings over the study period.

# 3.0 Results

## 3.1 Questionnaire Data Analysis Strategy

Table 8 summarizes the dependent variables from the questionnaire, their measurement scales and (where appropriate) the internal consistency reliability calculated based on the full sample.

***Table 8**. Dependent variables, in conceptual groups.*

| **Construct** | **Dependent variables(DV)** | **Abbreviation** | **Scale** | **# Scale Items** | **Reliability** $T_0$ | $T_1$ | $T_2$ |
|---|---|---|---|---|---|---|---|
| Lighting Appraisal | Office Lighting Survey, 10 questions | OLS1-9 | 0-1 | 1 | | | |
| | | OLS10 | -1, 0, 1 | 1 | | | |
| | Satisfaction with Windows & Daylight | SWD1-3 | 0-1 | 1 | | | |
| Room Appearance | Attractiveness | Attract | 0-99 | 5 | .95 | .96 | .96 |
| | Illumination | Illum | 0-99 | 3 | .83 | .86 | .89 |
| Mood | Arousal | Arousal | 1-9 | 1 | | | |
| | Pleasure | Pleas | 1-9 | 1 | | | |
| Overall Environment | Overall Environmental Satisfaction | OES | 1-7 | 2 | .70 | .80 | .81 |
| | Workplace Image | WI | 1-7 | 3 | .91 | .91 | .92 |
| Environmental Satisfaction Components (COPE) | Satisfaction with Lighting | Sat_L | 1-7 | 5 | .81 | .81 | .79 |
| | Satisfaction with Ventilation & Temperature | Sat_VT | 1-7 | 3 | .85 | .84 | .85 |
| | Satisfaction with Acoustics & Privacy | Sat_AP | 1-7 | 10 | .91 | .92 | .92 |
| Renovation Satisfaction | Satisfaction with furnishings | COP19 – COP23 | 1-7 | 1 | | | |
| | Satisfaction with view | SWD4 | 0-99 | 1 | | | |
| Job Satisfaction | Job Satisfaction | JS1 | 1-7 | 1 | | | |
| | Organizational Commitment | OC | 1-7 | 6 | .86 | .87 | .88 |
| | Intent to Turnover | IT | 1-7 (lower is better) | 3 | .74 | .75 | .77 |
| Health | Visual Complaints – Frequency | VC_F | 0-4 (lower is better) | 4 | .75 | .73 | .79 |
| | Visual Complaints – Intensity | VC_I | 0-4 (lower is better) | 4 | .75 | .73 | .78 |
| | Physical Complaints – Frequency | PC_F | 0-4 (lower is better) | 3 | .65 | .64 | .72 |
| | Physical Complaints -- Intensity | PC_I | 0-4 (lower is better) | 3 | .67 | .67 | .74 |
| Absenteeism | Absenteeism – Own Illness | AB1 | 0-5 (lower is better) | 1 | | | |
| | Absenteeism – All (paid time off) | AB2 | 0-5 (lower is better) | 1 | | | |
| Motivation | Unsolvable anagrams – attempts | UA_TRIES | 0 – unlimited | | | | |
| | Unsolvable anagrams – time | UA_TIME | 0 – 300 sec | | | | |
| Cognition | Anagrams – correct | A_COR | 0 – 4 | | | | |
| | Anagrams – attempts | A_TRIES | 0 – unlimited | | | | |
| | Anagrams – time taken | A_TIME | 0 – 300 sec | | | | |
| Effort | Time to complete survey | DURATION | # minutes | | | | |
| Creativity ($T_0$ only) | Number of novel uses | CNUSUM | 0 - unlimited | | R*w | | |
| | Average use per image | CNUPI | 0 - unlimited | | g(J) | | |
| | Average time per use | CTPU | 0 – 300 sec | | = | | |
| | Average creativity rating | ACR | 1-7 | 2 raters | .83 | | |
| Job Characteristics | Job Demands | JD | 1-7 | 4 | .87 | .86 | .86 |
| | Communication & Social Support | CS | 1-7 | 4 | .83 | .83 | .83 |
| Control Interface | Satisfaction with control interface, 5 items | LC1-5 | 0-4 | 1 | | | |

*Note*. For the scale scores, reliability is expressed as Cronbach's alpha. For the creativity ratings, inter-rater agreement across two raters is expressed as R*wg(J) (LeBreton & Senter, 2008).

This investigation has a complex structure made up of non-orthogonal planned comparisons. It is a quasi-experimental non-equivalent control group design (Shadish, Cook, & Campbell, 2002). We formed a series of planned comparisons to explore the hypotheses of interest while controlling as much as possible for possible confounding variables. Table 8 summarizes these contrasts.

For each planned comparison we first examined the demographic variables for the groups involved in the comparison, to ascertain whether or not there existed possible biases in the form of differing distributions by sex, age, education, job category, tenure with the organization, job demands or communication and social support. Had we found any such differences we would have included the relevant variable as a covariate in subsequent analyses; however, we found none. We were informed, however, that employees in buildings 1 and 2 work on the operational side of the organization, whereas those in Building 3 are predominantly in outreach and public relations/communications functions. One result of this is that many employees in buildings 1 and 2 are unionized, whereas few in Building 3 are governed by collective agreements.

For all analyses involving interval or continuous data, we screened the variables prior to the analysis and excluded outliers (cases with standardized scores > 3), as is common (Tabachnick & Fidell, 2001).

For each contrast, we used the nonparametric statistic chi-squared ($X^2$) to test for differences in responses to the categorical questions of the Office Lighting Survey (OLS). The differences tested were between the observed responses and a normative sample collected by the OLS developers (Eklund & Boyce, 1996), and for differences in response distributions between groups involved in the specified contrast.

For the ordinal and continuous variables, we used multivariate analysis of variance (MANOVA) for simple two-group comparisons. Where we were able to use MANOVA, we have reported statistically significant univariate results only for those models with statistically significant multivariate tests.

We used mixed models for comparisons involving two variables: the contrast and time. Mixed models are able to generate effect estimates even when the research design is unbalanced, as when group sizes are markedly different from one time to another (Kenny, Bolger, & Kashy, 2002). The summary of these planned comparisons and the analysis used is shown in Table 9.

***Table 9.*** *Summary of planned comparisons and analysis types for continuous data.*

| Type | Number | Selection | Comparison | Buildings | Times | Analysis Type |
|---|---|---|---|---|---|---|
| Lighting | L1 | Old Furniture | PARAB vs WS-60U | (1+2) vs 3 | $T_0$, $T_1$, $T_2$ | Mixed |
| | L2A | New Furniture | PARAB vs WS-76U | (1+2) vs 3 | $T_0$ | MANOVA |
| | L2B | New Furniture | WS-76U-C vs WS-81U-C | 3 vs (1+2) | $T_2$ | MANOVA |
| Control | C1A | WS operation | WS-60U-C vs WS-76U | 3, Old vs New | $T_0$ | MANOVA |
| | C1B | New furniture | WS-76U vs WS-81U-C | 3 vs (1+2) | $T_0$ | MANOVA |
| | C2 | Building 1, new | WS-81U vs WS-81U-C | 1 | $T_1$ | MANOVA |
| Furniture | F1 | WS operation | Old vs New | 3 | $T_1$, $T_2$ | Mixed |
| Renovation | R1 | Buildings 1+2 | Old vs New | 1+2 | $T_2$ | MANOVA |

For both the MANOVA and mixed models, we calculated the effect size for statistically significant tests between two groups using Cohen’s d (Cohen, 1988). This statistic shows the size of the mean difference between the two groups as a function of the standard deviation. We have adopted Cohen’s suggestions for interpretation: d = .2 is a small effect (S); d =.5 is a medium effect (M); d >= .8 is a large effect (L).

The Light Right Albany experiment found an interaction of individual control over lighting by time of day, such that individuals with individual control over lighting tended to maintain their persistence over the day whereas those without showed declining persistence (Boyce, et al., 2006b; Boyce, et al., 2003). We tested this hypothesis in the questionnaire data using the time of day at which the individual completed the questionnaire as the source of the interaction. This analysis use multiple regression, described in more detail below under the heading C3. Heading C4 applies to an evaluation of the interface for individual control.

We used structural equation modelling to explicitly test the indirect effects expressed in the Linked Mechanisms Map. This technique is described in greater detail below.

## 3.2 Questionnaire Data

***3.2.1 Lighting comparisons.*** *L1: Old furniture, comparing Parab and WS-60U-C lighting.* This comparison targeted respondents at all three survey times, in open-plan offices with the old style of furniture (whether grey or teal). For the agree/disagree items, we analysed the responses for each time separately. For all other analyses the model was a 2 Lighting x 3 Time Mixed Model; lighting was a between-subjects variable, but time was both repeated measures and between-subjects, as some participants completed only one measurement wave but others responded two or three times. Mixed models are able to test these unbalanced designs (Kenny et al., 2002).

Prior to analysis, we examined the demographic characteristics of the two groups and their reports of job demands and communications/social support. The two groups did not differ in terms of age, sex, education, job type, first language, tenure in the organization, years in the workforce, frequency of office moves in the previous three months, job demands, or communications/social support. Therefore, there were no covariates applied to these analyses.

The results show similar patterns on all occasions. Overall, both lighting designs were appraised as being better than the norms (e.g., ~81-83% of people in the Parab condition rated the lighting as comfortable, compared to 69% of the normative sample). The normative sample dates from the mid-1990s in the northeastern US. At that time most computers had CRT monitors, whereas 96% of this sample used LCD flat monitors. Although parabolic luminaires were designed to reduce reflections in CRTs, their success depends on the intended geometry of luminaire and monitor. Flat-panel monitors are less susceptible to problematic reflections, which might explain the higher number of comfortable people in the present sample; that is, the normative data might no longer hold. Alternatively, it is also possible that the presence of large windows and excellent views outside might influence the lighting appraisals. (Appendix A shows the detailed results for lighting appraisals in the Office Lighting Survey for the three times.)

Significant differences are shown in Figure 7A for two statements: “Overall, the lighting is comfortable here.” “The lighting is poorly distributed here.” Figure 7B shows the pattern for the question “How does the lighting compare to similar workplaces in other buildings?” In all three cases, the WS-60U-C lighting was appraised as better than the Parab lighting at all three times. For the question comparing this to other workplaces, fewer than expected respondents rated the Parab lighting as being better than other similar workplaces, whereas more WS-60U-C respondents than expected rated their lighting as being better than other similar workplaces. The trend toward more people in this group rating the lighting as “same” as other similar workplaces from $T_0$ to $T_2$ might reflect their awareness of the renovation program; as the organization installed new lighting, WS-60U-C could be said to be becoming more “the same” as other similar workplaces within the organization.

***Figure 7A.*** *Per cent agreement with the statements "The lighting is comfortable here" and "The lighting is poorly distributed here", for two lighting conditions at three survey waves. The between-groups comparisons within each survey wave are statistically significant (see Appendix D).*

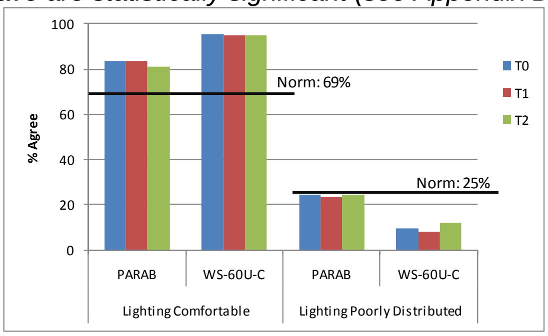
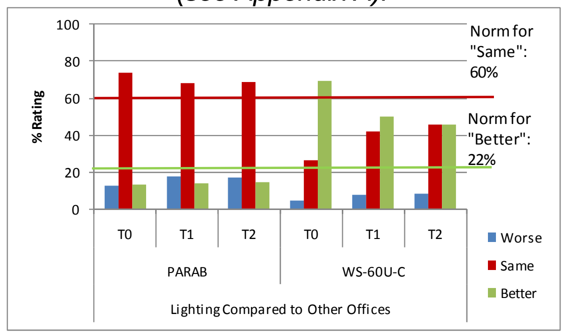



***Figure 7B.*** *Per cent ratings of the lighting as being "worse", "the same" or "better" than lighting in other similar workplaces, for two luminaire types at three survey times. The between-groups comparisons within each survey wave are statistically significant (see Appendix A).*




There were small differences between the lighting conditions on the questions pertaining to satisfaction with windows and daylighting (see Appendix A). There was a small tendency for people in the WS-60U-C group to complain of problems related to direct sunlighting, but they also were more likely to report being able to adjust window blinds. These probably relate more to architectural differences between the buildings than the lighting; the Parab group was in buildings 1 and 2, and the WS-60U-C group was in Building 3.

All the other variables that were measured at the three waves were analyzed in a series of mixed analyses, the results of which are summarized in Tables 10-13. Table 10 shows the list of significant main effects of Lighting. All of the effects were in the predicted direction: the better outcome was found for people with WS-60U-C lighting. The effects were generally small, but the three effects were medium-sized, all for variables related to lighting satisfaction with lighting: (Sat_L), workplace image (WI), and attractiveness (Attract).

There were unexpected effects on four variables related to the furnishings, all small effects. People with WS-60U-C lighting rated their satisfaction with the availability of formal and informal meeting areas, storage space, and the arrangement of their furnishings and equipment, as being better than those with parabolic lighting. These effects are more likely to relate to differences in the buildings (the parabolic lighting was predominantly in buildings 1 and 2, WS-60U-C was only in Building 3), than to differences in the lighting.

***Table 10.*** *Statistically significant main effects of luminaire for contrast L1 (all old furniture) in mixed models, showing test statistics (F), degrees of freedom (df), mean, standard deviation (SD0 and effect size.*

| Dependent Variable | *df* | *F* | PARAB Mean | PARAB SD | WS-60U-C Mean | WS-60U-C SD | Cohen's d | Effect Size Category |
|---|---|---|---|---|---|---|---|---|
| Sat_L | 1, 1349.73 | 55.10*** | 4.73 | 1.22 | 5.41 | 0.98 | 0.56 | M |
| Sat_VT | 1, 1337.03 | 22.24*** | 4.07 | 1.40 | 4.56 | 1.46 | 0.35 | S |
| Sat_AP | 1, 1330.65 | 19.76*** | 3.54 | 1.26 | 3.98 | 1.22 | 0.34 | S |
| WI | 1, 1334.92 | 78.10*** | 4.23 | 1.57 | 5.28 | 1.54 | 0.66 | M |
| OES | 1, 1320.06 | 13.48*** | 4.24 | 1.51 | 4.67 | 1.39 | 0.29 | S |
| Mtg_Areas | 1, 783.25 | 11.76*** | 3.57 | 1.91 | 4.16 | 1.74 | 0.31 | S |
| Inform_Mtg | 1, 776.93 | 8.02** | 3.55 | 1.86 | 4.01 | 1.64 | 0.25 | S |
| StorageSpace | 1, 788.68 | 5.97* | 4.26 | 1.83 | 4.67 | 1.80 | 0.22 | S |
| Furn_Arrang | 1, 786.68 | 4.54* | 4.49 | 1.62 | 4.79 | 1.45 | 0.19 | S |
| Pleas | 1, 1342.92 | 15.90*** | 5.29 | 1.97 | 5.91 | 1.82 | 0.31 | S |
| PC_F | 1, 1097.77 | 5.80* | 1.53 | 0.88 | 1.35 | 0.80 | -0.21 | S |
| PC_I | 1, 1129.28 | 8.68*** | 1.42 | 0.75 | 1.23 | 0.66 | -0.25 | S |
| Attract | 1, 1049.82 | 36.67*** | 48.14 | 23.04 | 59.78 | 20.87 | 0.50 | M |
| Illum | 1, 1048.49 | 19.54*** | 50.17 | 22.04 | 58.35 | 19.73 | 0.37 | S |
| JS1 | 1, 1281.52 | 35.47*** | 5.23 | 1.30 | 5.82 | 1.05 | 0.46 | S |
| OC | 1, 1318.94 | 15.47*** | 4.81 | 0.96 | 5.10 | 0.99 | 0.30 | S |
| IT | 1, 1306.91 | 20.78*** | 2.67 | 1.15 | 2.27 | 1.05 | -0.35 | S |
| Duration | 1, 1229.63 | 4.72* | 25.22 | 12.21 | 23.00 | 11.50 | -0.18 | S |

*Note.* * $p$<.05; ** $p$<.01; *** $p$<.001.

There was one statistically significant interaction of lighting and time, and a few main effects of time. The interaction, which was significant only for the variable workplace image, is shown in Table 11. The effect of lighting on workplace image, although persistent across all the times, was largest at $T_0$.

***Table 11.*** *Interaction effect of lighting and time on Workplace Image, within old furniture.*

| **WI** | df = 2, 851.18 | | F = 5.244** | | | |
|---|---|---|---|---|---|---|
| | **Parab** | | **WS-60U-C** | | **Cohen's** | **Effect Size** |
| | **Mean** | **SD** | **Mean** | **SD** | **d** | **Category** |
| T0 | 4.12 | 1.57 | 5.71 | 1.17 | 0.99 | L |
| T1 | 4.34 | 1.59 | 5.05 | 1.74 | 0.44 | S |
| T2 | 4.22 | 1.54 | 5.10 | 1.55 | 0.55 | M |

*Note.* * $p$<.05; ** $p$<.01; *** $p$<.001.

Tables 12 and 13 show the main effects of time (i.e., measurement wave). Most of these effects are predictable. There was a significant difference in paid time off (AB2) between $T_2$ and $T_1$, which is not surprising given that $T_2$ occurred in September, and many people would have taken summer vacation just before. The return to work in autumn might also explain the small drop in job satisfaction at $T_2$. The effects on cognitive performance, measured on an anagram task, are probably the result of differences in the problem sets; learning is an unlikely explanation because of the large number of people who did not participate at all times. The set used at $T_1$, although randomly selected from a larger set, might have been easier than the sets at the other times. The change in the duration of the questionnaire at $T_1$ compared to $T_0$ is explained by the fact that the 5-min creativity task was presented only at $T_0$. It is less clear why there was a small change in satisfaction with the availability of meeting rooms at $T_1$, nor why there was very small (in real terms; see Table 13) increase in persistence on the unsolvable anagrams at $T_2$.

***Table 12**. Overall main effects of time, and planned comparisons based on estimated marginal means.*

| | Time Effect | | $T_1 - T_0$ | | | | $T_2 - T_1$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **DV** | ***df*** | ***F*** | ***t*** | ***df*** | **d** | **ES** | ***t*** | ***df*** | **d** | **ES** |
| Mtg_areas | 2, 505.82 | 7.571*** | -3.24*** | 562.85 | -0.24 | S | -0.32 | 506.55 | | |
| AB2 | 2, 760.78 | 20.78*** | 1.23 | 950.25 | | | -5.28*** | 748.63 | 0.50 | M |
| JS1 | 2, 815.85 | 3.31* | -0.19 | 964.56 | | | -2.22* | 811.01 | -0.17 | S |
| A_Cor | 2, 652.07 | 21.26*** | 2.58** | 542.03 | 0.31 | S | -6.51*** | 573.39 | -0.61 | M |
| A_Tries | 2, 630.42 | 3.85* | -1 | 608.07 | | | 2.81** | 612.10 | 0.17 | S |
| A_Time | 2, 646.66 | 6.94*** | -3.62*** | 582.29 | -0.40 | S | 2.27* | 604.57 | 0.22 | S |
| UA_Tries | 2, 695.62 | 4.83** | 1.61 | 749.57 | | | 1.65 | 698.32 | 0.20 | S |
| Duration | 2, 792.45 | 26.78*** | -6.02*** | 962.54 | -0.50 | M | -1.23 | 743.24 | | |

*Note.* d is Cohen's d (Cohen, 1986). ES = effect size category, after Cohen (1986).* *p*<.05; ** *p*<.01; *** *p*<.001.

***Table 13**. Observed means and standard deviations for time main effects.*

| | $T_0$ | | $T_1$ | | $T_2$ | |
|---|---|---|---|---|---|---|
| **DV** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| Mtg_areas | 3.96 | 1.85 | 3.51 | 1.92 | 3.52 | 1.88 |
| AB2 | 1.51 | 1.72 | 1.60 | 1.72 | 2.54 | 2.03 |
| JS1 | 5.34 | 1.27 | 5.40 | 1.26 | 5.19 | 1.31 |
| A_Cor | 2.13 | 1.28 | 2.50 | 0.96 | 1.79 | 1.18 |
| A_Tries | 1.21 | 0.29 | 1.17 | 0.28 | 1.22 | 0.28 |
| A_Time | 25.35 | 12.91 | 20.47 | 11.06 | 23.18 | 11.78 |
| UA_Tries | 2.69 | 1.36 | 2.75 | 1.29 | 3.03 | 1.37 |
| Duration | 29.06 | 12.37 | 22.93 | 11.26 | 21.70 | 11.30 |

Creativity data was available for $T_0$ only. Four dependent variables were combined in a MANOVA analysis contrasting the two lighting conditions. There was a statistically significant multivariate effect and one significant univariate effect, summarized in Table 14. People with the WS-60U-C lighting generated somewhat more novel uses per image, although the effect is small.

***Table 14**. Statistically significant results for Creativity MANOVA in contrast L1.*

| | **Wilks' *Λ*** | ***F*** | ***df*** | **Parab Mean** | **SD** | **WS-60U-C Mean** | **SD** | **Cohen's d** | **Effect Size Category** |
|---|---|---|---|---|---|---|---|---|---|
| Creativity | .975 | 2.66* | 4,421 | | | | | | |
| CNUPI | | 7.35** | 1, 421 | 2.04 | 1.35 | 2.61 | 2.17 | 0.38 | S |

*Note*.* *p*<.05; ** *p*<.01; *** *p*<.001.

*L2A – New furniture, comparing PARAB and WS-76U luminaires.* This comparison targeted respondents at $T_0$ only, in open-plan offices with the new style of furniture. None of the participants had individual control over the lighting, because it was withheld from the WS-76U area in Building 3 at $T_0$. We were unable to repeat this contrast at the other times because of a small sample size from the area with parabolic lighting and new furniture at $T_1$ and $T_2$.

Prior to analysis, we examined the demographic characteristics of the two groups and their reports of job demands and communications/social support. The two groups did not differ in terms of age, sex, education, job type, first language, tenure in the organization, years in the workforce, frequency of office moves in the previous three months, job demands, or communications/social support. Therefore, there were no covariates applied to these analyses.

The Office Lighting Survey results were largely as expected, in that more people with WS-76U lighting reported that the lighting is comfortable, well-distributed, and better than in other workplaces, than did people with parabolic lighting (Figure 8 and Appendix A). Although the individual (personal) control was not operative at the time of the survey, 100% of people with WS-76U lighting agreed that the lighting was comfortable, higher than predicted; also none of the people in this group rated the lighting as worse than in other similar offices. The fact that the space and the furnishings were new at the time of the survey probably contributed to this appraisal (see also the comparison C1B, which involved this group). There were no statistically significant differences between the groups in terms of satisfaction with windows and daylight.

***Figure 8A.*** *Per cent agreement with the statements "The lighting is comfortable here" and "The lighting is poorly distributed here", for PARAB and WS-76U luminaire groups at $T_0$. The between-groups comparisons are statistically significant (see Appendix A).*

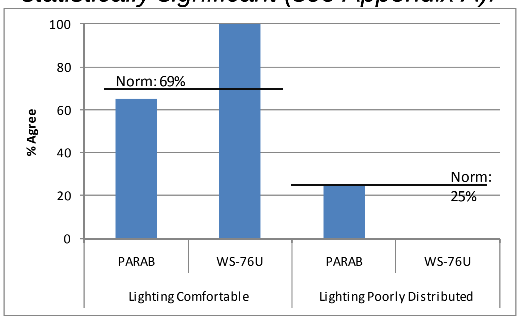
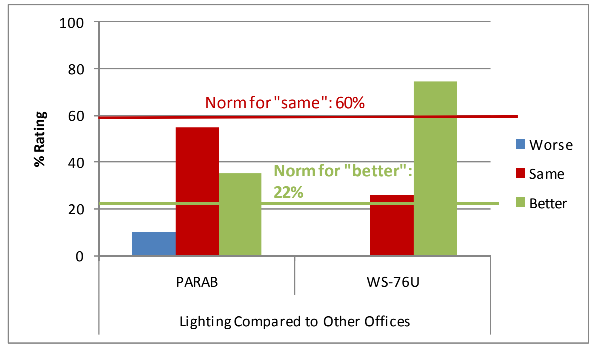



***Figure 8B.*** *Per cent ratings of the lighting as being "worse", "the same" or "better" than lighting in other similar workplaces, for PARAB and WS-76U luminaire groups at $T_0$. The between-groups comparisons are statistically significant (see Appendix A).*




A series of MANOVA tests were run for the conceptual groups of dependent variables, as described above. Table 15 summarizes the results. Statistically significant effects were found for concepts relating to space appearance and environmental satisfaction. These were in the predicted directions, and were quite large. The effects for the Renovation Satisfaction category are probably related to the installation of the new furniture on the floor with parabolic lighting. This was not a complete renovation; the layout did not incorporate all of the features of the new plans. Existing enclosed offices, with full-height walls in the old teal colour, remained on the perimeter, and there were some old workstations remaining on that floor. Moreover, the people on the floors with WS-76U had newly moved (6-8 weeks previously) into brand-new space with new furniture, having previously been accommodated in a variety of other places.

***Table 15.*** *Statistically significant results for MANOVAs in contrast L2A.*

| | Wilks' Λ | F | df | Parab Mean | Parab SD | WS-76U Mean | WS-76U SD | Cohen's d | Effect Size Category |
|---|---|---|---|---|---|---|---|---|---|
| COPE | .802 | 4.13** | 3,50 | | | | | | |
| Sat_L | | 10.23** | 1,52 | 4.97 | 1.17 | 5.82 | 0.79 | 0.83 | L |
| Sat_VT | | 9.88*8 | 1,52 | 4.38 | 1.26 | 5.39 | 1.05 | 0.82 | L |
| Sat_AP | | 5.53* | 1,52 | 3.53 | 0.93 | 4.23 | 1.13 | 0.64 | M |
| Overall Env | .82 | 5.61** | 2,51 | | | | | | |
| OES | | 8.69** | 1,52 | 4.44 | 1.99 | 5.74 | 1.26 | 0.78 | L |
| WI | | 10.16** | 1,52 | 4.08 | 1.32 | 5.21 | 1.21 | 0.84 | L |
| Reno_Sat | .397 | 7.34*** | 6,29 | | | | | | |
| Mtg_Areas | | 35.14*** | 1,34 | 2.23 | 1.09 | 5.17 | 1.59 | 1.46 | L |
| Inform_Mtg | | 43.14*** | 1,34 | 2.31 | 1.25 | 5.39 | 1.41 | 1.53 | L |
| StorageSpace | | 6.88* | 1,34 | 4.00 | 2.08 | 5.48 | 1.31 | 0.84 | L |
| Furn_Arrang | | 4.63* | 1,34 | 4.38 | 1.94 | 5.52 | 1.24 | 0.71 | M |
| Room Appearance | .662 | 13.02*** | 2,51 | | | | | | |
| Attract | | 21.62*** | 1,52 | 54.52 | 21.52 | 76.46 | 13.19 | 1.12 | L |
| Illum | | 21.62*** | 1,52 | 54.88 | 20.43 | 76.88 | 11.09 | 1.21 | L |

*Note*.* *p*<.05; ** *p*<.01; *** *p*<.001.

*L2B — New furniture, comparing WS-76U-C and WS-81U-C luminaires.* This contrast was possible at T2 only, when all of both groups had individual control over the direct lamps in the luminaires. The difference between the groups lay in the use, or not, of the one "indirect", or upward-directed, lamp in the luminaire. The WS-76U-C lighting had only two lamps enabled, and when the occupancy sensor detected no one in the workstation both lamps would turn off after a delay. This system was in place only in Building 3; buildings 1 and 2 had WS-81U-C lighting.

There was one statistically-significant Office Lighting Survey results for this contrast (detailed results are in Appendix A). All of the respondents in the WS-76U-C group rated the lighting as comfortable, but 19% (9 people) in the WS-81U-C did not find it comfortable ($X^2$ (1) = 9.54, $p$<.01). However, exactly in what sense they were uncomfortable is not clear because there were few reported problems in the other questions. Differences in daylight or windows do not explain the difference, as there were none.

There were three statistically significant multivariate tests in the MANOVAs of this contrast. Two were interpretable; the Room Appearance group had a significant multivariate test but no significant univariate tests (Table 16). These differences generally favoured the WS-76U-C group, but they were not clearly related to the difference in the lighting system operation. The effect on satisfaction with lighting was smaller than the other effects, and the mean for satisfaction with lighting for the WS-81U-C group was higher than the mean for other aspects of the physical environment. These results appear more likely to relate to other differences between the buildings, than to the lighting. For example, the WS-76U-C group was in newly-constructed space with a new ventilation system, which could have changed both the ventilation and acoustic conditions in comparison to the two older buildings. The renovation in those buildings, in which the WS-81U groups were located, did not include changes to ventilation.

***Table 16.*** *Statistically significant results for MANOVAs in contrast L2B.*

| | Wilks' Λ | F | df | WS-76U-C Mean | WS-76U-C SD | WS-81U-C Mean | WS-81U-C SD | Cohen's d | Effect Size Category |
|---|---|---|---|---|---|---|---|---|---|
| COPE | .884 | 3.95** | 3,90 | | | | | | |
| Sat_L | | 5.59* | 1,92 | 5.58 | 0.97 | 5.04 | 1.23 | -0.48 | M |
| Sat_VT | | 9.40** | 1,92 | 5.25 | 0.99 | 4.44 | 1.51 | -0.61 | M |
| Sat_AP | | 9.81** | 1,92 | 4.36 | 1.31 | 3.54 | 1.22 | -0.62 | M |
| Overall Env | .891 | 5.55** | 2,91 | | | | | | |
| OES | | 10.90*** | 1,92 | 5.79 | 1.01 | 4.85 | 1.65 | -0.65 | M |
| WI | | 6.27* | 1,92 | 5.33 | 1.20 | 4.58 | 1.63 | -0.50 | M |
| Room Appearance | .898 | 4.56* | 2,80 | | | | | | |

*Note*.* $p$<.05; ** $p$<.01; *** $p$<.001.

***3.2.2 Control comparisons.*** *C1A — Comparing offices in Building 3 (similar luminaire operation, different furnishings), without and with individual control over lighting.* This contrast was between groups of floors in one building at $T_0$ only. There were four original floors with WS-60U-C lighting and three newly-constructed (not renovated) floors with WS-76U lighting and no control. There were small differences between the luminaires that resulted in the different percentages of indirect light, but all the luminaires in this building had only two lamps operating. The old floors had old furniture, but people there had had control over the lighting for several years. The new floors had the new furniture.

The Office Lighting Survey results for this comparison revealed that overall, people in both groups were very pleased with the lighting (see Appendix A for details). There was only one statistically significant difference between the groups, with some respondents in WS-60U-C (7, or 10%) indicating that the light is poorly distributed compared to WS-76U (none) ($X^2$ (1) = 3.87, $p$ < .05). (Note that the WS-76U respondents had new high-reflectance furnishings, which changed the luminance distribution.) There were no differences in satisfaction with windows and daylighting, and both groups indicated a high degree of access to window blinds (Table 24).

There was one statistically significant difference between the groups in the MANOVA tests, for the concept group Room Appearance (Table 17). People in the WS-76U group rated the space as both brighter and more attractive; this is likely to be a function of the furnishings and not of the availability of lighting control.

The lack of sensitivity to the effects of the control manipulation might relate to the comparatively small sample size for the WS-76U group, or to the availability of daylight and view through the large windows on all sides, or to the fact that the floors were new and had not been occupied for long. Given these factors, it might be the case that the availability of individual control to the people with WS-60U-C lighting compensated for the old furniture and its lower reflectance.

***Table 17.*** *Statistically significant results for MANOVAs in contrast C1A.*

| | Wilks' | | | WS-76 | | WS-60U-C | | Cohen's | Effect Size |
|---|---|---|---|---|---|---|---|---|---|
| | **Λ** | ***F*** | ***df*** | **Mean** | **SD** | **Mean** | **SD** | **d** | **Category** |
| Room Appearance | .814 | 10.08*** | 2,88 | | | | | | |
| Attract | | 14.41*** | 1,89 | 76.46 | 13.19 | 62.56 | 18.95 | -0.76 | M |
| Illum | | 20.31*** | 1,89 | 76.88 | 11.09 | 60.47 | 19.64 | -0.88 | L |

*Note*.* *p*<.05; ** *p*<.01; *** *p*<.001.

*C1B — Comparing offices with new furnishings and luminaires (different luminaire operation) without and with individual control over lighting.* This contrast was a comparison of the responses from people with WS-76U lighting and those with WS-81U-C lighting at $T_0$. Unlike the contrast C1A, the furniture was the same in both cases, but the two groups were from different buildings (Building 3, versus Buildings 1 and 2 combined) and had different modes of luminaire operation (2 lamps versus 3).

The non-parametric statistics for the Office Lighting Survey and the satisfaction with windows and daylighting are in Appendix A. People in both groups appraised the lighting as very comfortable and there were no statistically significant differences between them on these variables.

The MANOVA comparisons returned three statistically significant multivariate tests, shown in Table 18 together with the associated statistically significant univariate tests. All of the significant outcomes are in the unexpected direction, favouring the group without control over the workplace lighting. Given that the WS-76U group had fairly recently moved into a brand-new workplace, it seems likely that factors other than the control over the lighting were most influential in these scores. The basic furniture layout and design were very similar for the two groups, although there were local differences in each building and on different floors, so it is not clear why there were such large differences on the renovation satisfaction variables.

***Table 18.*** *Statistically significant results for MANOVAs in contrast C1B.*

| | Wilks' | | | WS-76U | | WS-81U-C | | Cohen's | Effect Size |
|---|---|---|---|---|---|---|---|---|---|
| | **Λ** | ***F*** | ***df*** | **Mean** | **SD** | **Mean** | **SD** | **d** | **Category** |
| COPE | 0.876 | 4.28** | 3,91 | | | | | | |
| Sat_L | | 7.13** | 1,93 | 5.82 | 0.79 | 5.29 | 1.01 | -0.55 | M |
| Sat_VT | | 11.70*** | 1,93 | 5.39 | 1.05 | 4.43 | 1.44 | -0.69 | M |
| Sat_AP | | 7.19** | 1,93 | 4.23 | 1.13 | 3.54 | 1.26 | -0.56 | M |
| Overall Env | 0.928 | 3.58* | 2,92 | | | | | | |
| WI | | 7.02** | 1,94 | 5.74 | 1.26 | 4.94 | 1.52 | -0.55 | M |
| Reno_Sat | 0.738 | 2.96* | 6,50 | | | | | | |
| Desk_area | | 7.44** | 1,55 | 5.52 | 1.20 | 4.24 | 2.03 | -0.69 | M |
| Mtg_Areas | | 8.96** | 1,55 | 5.17 | 1.59 | 3.56 | 2.23 | -0.75 | M |
| Inform_Mtg | | 11.64*** | 1,55 | 5.39 | 1.41 | 3.76 | 1.97 | -0.85 | L |
| StorageSpace | | 7.48** | 1,55 | 5.48 | 1.31 | 4.21 | 1.95 | -0.70 | M |
| Furn_Arrang | | 7.90** | 1,55 | 5.52 | 1.24 | 4.32 | 1.77 | -0.72 | M |

*Note*.* *p*<.05; ** *p*<.01; *** *p*<.001.

*C2 — Comparing similar floors in Building 1, with and without individual control over lighting, at T1.* One floor of Building 1 was renovated between $T_0$ and $T_1$, and people moving into the newly renovated space were not given individual control over their lighting until after the $T_1$ measurement wave, which occurred three months after they had moved in. We compared this group against another floor in the same building that had been renovated and occupied for two years at the time of the measurements.

There were no statistically significant between-groups comparisons for the Office Lighting Survey (see Appendix A), although that might have been partly because the sample sizes were small (on the borderline of what we would report to maintain confidentiality of the data).

Table 19 shows the one statistically significant multivariate and univariate effect for the MANOVA contrasts. People with WS-81U-C lighting had higher ratings of satisfaction with lighting than those without control (WS-81U). This effect is noteworthy because it is large and because it is on the variable that this intervention would be most likely to affect directly. It is unlikely to be related only to annoyance at having been denied the expected control; we would in that case have expected to see other adverse consequences on other outcomes.

***Table 19.*** *Statistically significant results for MANOVAs in contrast C2.*

| | Wilks' $\Lambda$ | *F* | *df* | WS-81U-C Mean | WS-81U-C SD | WS-81U Mean | WS-81U SD | Cohen's d | Effect Size Category |
|---|---|---|---|---|---|---|---|---|---|
| COPE | 0.56 | 4.25* | 3,16 | | | | | | |
| Sat_L | | 13.76** | 1,18 | 5.70 | 1.03 | 3.97 | 1.07 | -1.28 | L |

*Note*.* $p<.05$; ** $p<.01$.

*C3 – Tests for the interaction of time-of-day and individual control over lighting.* In the Light Right Albany Experiment 1, we had found that people with individual control over lighting maintained their performance throughout the day on a vigilance task and continued to persist on an impossible task, whereas those without individual control declined on both measures (Boyce, et al., 2006b). We used a multiple regression approach to test for similar effects in the field study data. We did not have repeated measures over a single day, as we had had in the Albany experimental data; instead these analyses took a between-subjects approach, using the fact that the questionnaires were completed at differing times of day by different people to test for this effect ("start time"). For this analysis we excluded data from people in offices with the PARAB lighting system.

There were two analysis approaches, described in Table 20. The dependent measures that we tested were the number of attempts made on unsolvable anagrams (UA_TRIES) and the amount of time spent on the unsolvable anagrams (UA_TIME) at both $T_0$ and $T_1$. We also examined the speed of performance of the creativity task (CISPAV and CUSPAV), at $T_0$ only. Thus, there were six separate regressions tested for the interaction effect, and 12 (6 each for people with individual control and those without) for the split file approach.

The interaction test approach examined direct effects of having lighting control and of the start time, but was principally designed to identify additionally the interaction of these two variables. We expected to find that the interaction term, entered last, would be a significant predictor of the outcome variable. We then split the data file and ran separate regression models for people without and with individual control over lighting. In this approach we looked for different results for the two groups: We expected that start time would predict performance for people without control (as had been seen in Albany), but not for those with control.

***Table 20.*** *Summary of multiple regression analyses for time-of-day and individual control interaction effects.*

| Analysis | DVs | Step 1 Covariates | Step 2 Predictors | Step 3 Predictor |
|---|---|---|---|---|
| Interaction Test | UA_TRIES_T0<br>UA_TRIES_T1<br>UA_TIME_T0<br>UA_TIME_T1<br>CISPAV_T0<br>CUPSAV_T0 | Job Type<br>Furnishings<br>Luminaire | Lighting Control<br>Start Time | Lighting Control X Start Time |
| Split by Lighting Control | UA_TRIES_T0<br>UA_TRIES_T1<br>UA_TIME_T0<br>UA_TIME_T1<br>CISPAV_T0<br>CUPSAV_T0 | Job Type | Start Time | |

The results of these regressions showed one statistically significant result (Table 21). After controlling for the varying job types, people with individual control at $T_0$ (WS-60U-C and WS-81U-C), looked at fewer images per second in the creativity task if they did the questionnaire later in the day (that is, they spent longer generating novel uses for each image if they did the questionnaire later in the day). This could be interpreted as a benefit of individual control, this apparently greater persistence on the task later in the day by people with individual control; however, it was not observed on any of the other dependent variables, nor was the effect evident in the interaction test.

***Table 21****. Multiple regression results for start time effect on creativity image speed, split by individual control availability.*

| Analysis | DV | β-Job Type | β -Start Time | *df* | $R^2$ | $R^2_{adj}$ |
|---|---|---|---|---|---|---|
| No individual Control | CISPAV_T0 | 0.137 | -0.029 | 2,30 | .019 | .01 |
| Individual Control | CISPAV_T0 | -0.123 | -0.241** | 2,116 | .075** | .06 |

*Note*. ** *p*<.01.

*C4 – Satisfaction with control interface*. The on-screen interface for the individual lighting control consisted of a sliding scale for dimming control that was the same as had been used in the Albany experiments. At $T_2$, respondents who had individual control over lighting were asked the same five questions about the acceptability of the interface as had been asked previously. The results are shown in Table 22. The scale ranged from 0-4, with 2 at the midpoint. The values indicate that respondents found the interface easy to use, although the means are somewhat lower than were observed in the Albany experiment (Boyce, et al., 2006a).

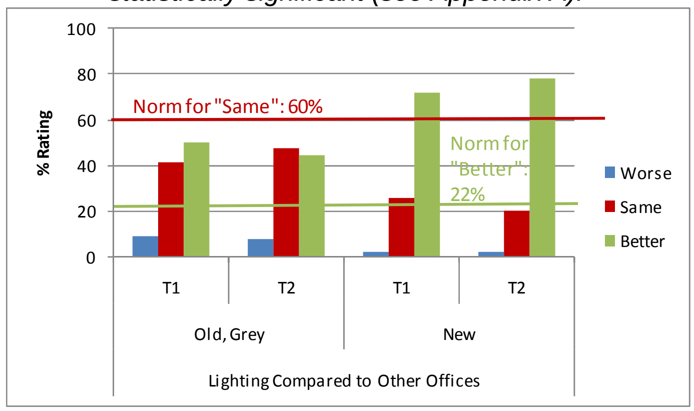
***Table 22****. Descriptive statistics for questions concerning the acceptability of the lighting control interface.*

| Statement | Mean | SD | Median |
|---|---|---|---|
| The lighting control system allowed me to create the lighting conditions I wanted. | 2.77 | 1.13 | 3 |
| The lighting control system was easy to use. | 2.74 | 1.05 | 3 |
| The instructions on how to operate the lighting controls were adequate. | 2.55 | 1.14 | 3 |
| The interface for the lighting controls was easy to use. | 2.71 | 1.04 | 3 |
| When I used the lighting controls, the lighting changed rapidly enough in response to my commands. | 2.80 | 1.04 | 3 |

***3.2.3 Furnishings comparison.*** We conducted one contrast to test the effect of the furniture alone, comparing the data from the old and new floors of Building 3 at $T_1$ and $T_2$. Both groups had similar lighting, with two lamps operating and both being under the occupant's control (WS-60U-C and WS-76U-C respectively) at these times, and the occupants had been in the new floors for approximately a year at the first of these measurement waves.

Only one question on the Office Lighting Survey showed a difference between the two groups. At both times, people with old furniture were less likely than those with new furniture to say that the lighting was better in their offices than in other offices, although both groups were far above the normative levels for this response (the norm for "better" is 22%). This is shown graphically in Figure 9.

***Figure 9.*** *Per cent ratings of the lighting as being "worse", "the same" or "better" than lighting in other similar workplaces, for Old, Grey and New furnishings groups at $T_1$ and $T_2$. The between-groups comparisons are statistically significant (see Appendix A).*




The parametric analyses used mixed models to examine the effects of both furniture and time. These results are shown in Table 23 for the main effects of furniture. All of these effects favour the new furniture. In particular it is noteworthy that there is no difference in satisfaction with lighting, but there are large differences in the ratings of room appearance. The new furnishings were judged to make a more attractive and a brighter space. There were small effects in which the new furnishings were judged to provide better storage space and a better arrangement of furnishings and equipment (as indeed they had been designed to do). There was a small effect in which people in the old furniture group took more tries to solve anagrams than those in the new furniture, but there was no difference between them in the number correctly solved.

***Table 23.*** *Statistically significant main effects of furniture type in mixed models for furniture x time.*

| | | | Old Furniture | | New Furniture | | Cohen's | Effect Size |
|---|---|---|---|---|---|---|---|---|
| **DV** | ***df*** | ***F*** | **Mean** | **SD** | **Mean** | **SD** | **d** | **Category** |
| Sat_VT | 1,233.00 | 11.49*** | 4.49 | 1.46 | 5.09 | 1.20 | 0.43 | S |
| WI | 1,233.96 | 8.32** | 5.10 | 1.62 | 5.65 | 1.22 | 0.37 | S |
| OES | 1,231.09 | 10.28** | 4.69 | 1.41 | 5.26 | 1.27 | 0.41 | S |
| StorageSpace | 1,150.96 | 4.31* | 4.62 | 1.81 | 5.22 | 1.58 | 0.34 | S |
| Furn_Arrang | 1,154.70 | 7.12** | 4.69 | 1.52 | 5.31 | 1.21 | 0.43 | S |
| Attract | 1,199.97 | 36.77*** | 58.99 | 22.03 | 75.84 | 15.05 | 0.79 | L |
| Illum | 1,195.21 | 41.68*** | 58.16 | 20.16 | 74.87 | 14.23 | 0.84 | L |
| A_Tries | 1,152.54 | 9.50** | 1.22 | 0.31 | 1.09 | 0.16 | -0.30 | S |

*Note.* * *p*<.05; ** *p*<.01; *** *p*<.001.

Table 24 summarizes the statistically significant effects of time in these analyses. (There were no interactions of furniture and time.) These effects are broadly consistent with those reported earlier. The drop in pleasure and the increase in paid time off (AB2) from $T_1$ to $T_2$ is likely to be a seasonal effect; the change in performance on the anagram task probably reflects differences in the two sets of problems, as noted earlier.

***Table 24.*** *Statistically significant main effects of time in mixed models for furniture x time.*

| DV | *df* | *F* | $T_1$ Mean | $T_1$ SD | $T_2$ Mean | $T_2$ SD | Cohen's d | Effect Size Category |
|---|---|---|---|---|---|---|---|---|
| Pleas | 1,227.08 | 4.65* | 6.31 | 1.90 | 5.76 | 1.94 | -0.29 | S |
| AB2 | 1,199.14 | 11.04*** | 1.85 | 1.73 | 2.72 | 2.07 | 0.45 | S |
| A_Cor | 1,153.32 | 24.48*** | 2.50 | 1.01 | 1.63 | 1.16 | -0.74 | M |
| A_Tries | 1,152.54 | 7.33** | 1.10 | 0.24 | 1.21 | 0.28 | 0.42 | S |
| A_Time | 1,156.64 | 4.49* | 18.96 | 11.73 | 23.08 | 12.36 | 0.34 | S |

*Note.* * *p*<.05; ** *p*<.01; *** *p*<.001.

***3.2.4 Renovation comparisons.*** Finally, we examined the effect of the overall renovation in buildings 1 and 2. This contrast used only data at $T_2$, to avoid any differences associated with seasonal changes and moving. The Office Lighting Survey showed that overall, the lighting was comfortable for ~ 80 % of respondents in both groups, but a large percentage on the renovated floors judged it to be better than in other workplaces; for the unrenovated floors, a larger percentage than expected judged the lighting to be the same as in other workplaces (Figure 10). There were no between-groups differences in satisfaction with windows and daylighting (see Appendix A).

MANOVA model results for the other variables are summarized in Table 25. The largest effects were for the ratings of room appearance, which were much higher for the renovated floors than for the unrenovated ones. Workplace image was also higher, although with a smaller effect size. The renovation also favourably affected satisfaction with both ventilation and lighting. The effect on satisfaction with lighting was the smallest effect, which is as one would expect based on the Office Lighting Survey results, which showed that the lighting for both groups was comfortable and had few serious problems.

***Figure 10.*** *Per cent ratings of the lighting as being "worse", "the same" or "better" than lighting in other similar workplaces, for unrenovated and renovated floors in Buildings 1 and 2 at $T_2$. The between-groups comparisons are statistically significant (see Appendix A).*

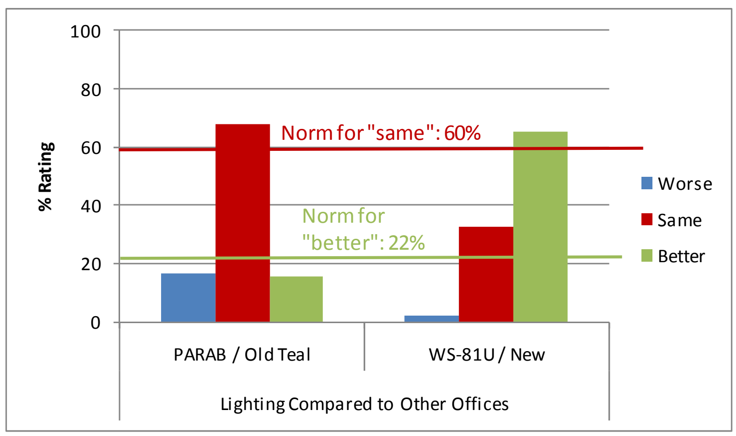



***Table 25****. Statistically significant results for MANOVAs in comparisons between renovated and unrenovated floors.*

| | Wilks' *Λ* | *F* | *df* | Unrenovated Mean | Unrenovated SD | Renovated Mean | Renovated SD | Cohen's d | Effect Size Category |
|---|---|---|---|---|---|---|---|---|---|
| COPE | .971 | 4.14** | 3,411 | | | | | | |
| Sat_L | | 4.04* | 1,413 | 4.73 | 1.20 | 5.12 | 1.18 | 0.32 | S |
| Sat_VT | | 9.20** | 1,413 | 3.97 | 1.42 | 4.66 | 1.35 | 0.48 | M |
| Overall Env | .976 | 5.00** | 2,411 | | | | | | |
| WI | | 9.89** | 1,412 | 4.21 | 1.55 | 4.99 | 1.53 | 0.50 | M |
| Room Appearance | .893 | 19.11*** | 2.320 | | | | | | |
| Attract | | 31.29*** | 1,321 | 48.22 | 23.34 | 70.37 | 19.50 | 0.92 | L |
| Illum | | 37.94*** | 1,321 | 50.91 | 22.13 | 73.80 | 16.01 | 1.01 | L |

*Note.** *p*<.05; ** *p*<.01; *** *p*<.001.

***3.2.5 Structural equation modelling.*** Using the linked mechanisms map developed in the Albany experiments as the starting point (Veitch, et al., 2008), we developed a structural equation model to test the relationships between the variables in the field study. Structural equation modelling (SEM) is a statistical technique for simultaneously solving regression equations to study multiple relationships between factors and the relations between factors and observed variables (Kline, 1997; Ullman, 2001). We used EQS v6.1 for this analysis (Bentler & Wu, 2003).

For this analysis, we used data from the first time that an individual had completed the questionnaire, whether that occasion occurred at $T_0$ or $T_1$ (June 2008 or June 2009). We excluded the $T_2$ data because of the evidence of seasonal effects on some variables. Including people who first participated at $T_1$ increased the sample size, but resulted in the exclusion of creativity data from the initial model (because we had not measured creativity performance at $T_1$).

We simplified the health measurements by creating composite scores for visual discomfort and physical discomfort, by multiplying the frequency and intensity scores for each symptom in the cluster, and then averaging across symptoms.

Preparatory steps for the SEM analysis included screening univariate outliers (those with standardized scores having absolute values > 3) and examining the distributions of all variables to ensure that they did not have excessive values for skewness (> 3) or kurtosis (> 8), following Kline's (1997) recommendations. This resulted in a sample size of 459 cases. The descriptive statistics are shown in Table 26.

***Table 26****. Descriptive Statistics for SEM Sample (N=459).*

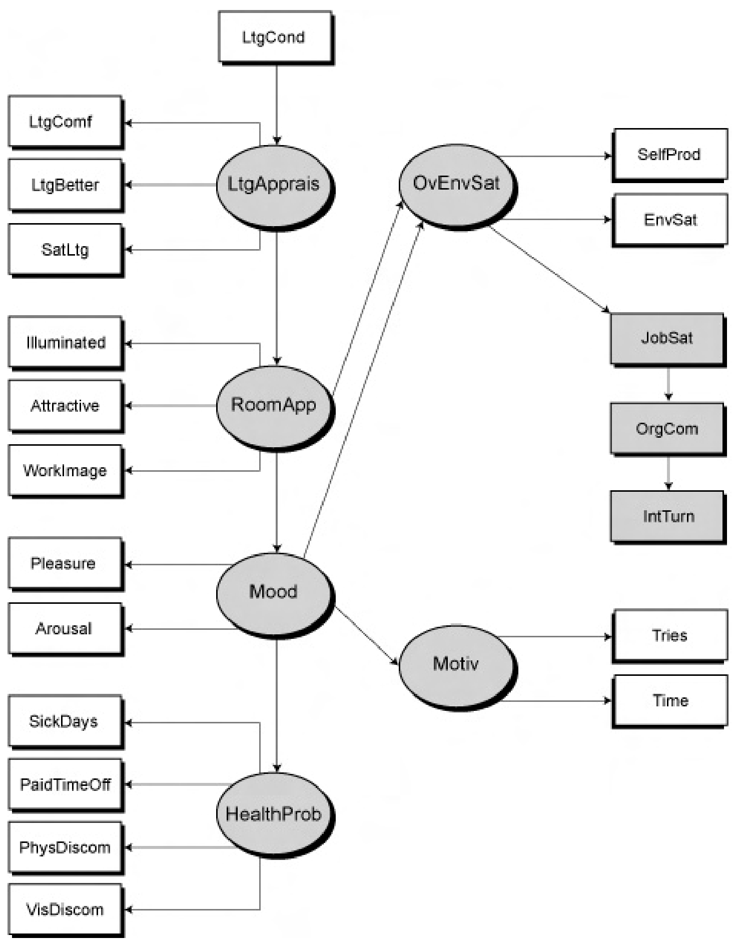
| **Variable or Concept** | **Scale** | **Mean** | **Standard Deviation** | **Median** | **Skewness** | **Kurtosis** |
|---|---|---|---|---|---|---|
| Arousal | 1-9 | 5.01 | 1.79 | 5.00 | 0.03 | -0.95 |
| Pleasure | 1-9 | 5.68 | 1.93 | 6.00 | -0.36 | -0.91 |
| Self-rated Productivity | 1-7 | 4.55 | 1.67 | 5.00 | -0.51 | -0.81 |
| Environmental Satisfaction | 1-7 | 4.53 | 1.63 | 5.00 | -0.39 | -1.12 |
| Lighting is comfortable | 0-1 | 0.88 | 0.33 | 1.00 | -2.29 | 3.24 |
| Lighting is better | 0-1 | 0.18 | 0.66 | 0.00 | -0.21 | -0.75 |
| Job Satisfaction | 1-7 | 5.38 | 1.25 | 6.00 | -1.11 | 0.73 |
| Sickness Absences | | 0.25 | 0.55 | 0.00 | 2.17 | 3.59 |
| Paid Time Off | | 1.45 | 1.61 | 1.00 | 1.06 | 0.05 |
| Illuminated | 1-100 | 55.66 | 22.12 | 58.00 | -0.19 | -0.85 |
| Attractive | 1-100 | 54.70 | 23.37 | 56.25 | -0.16 | -0.90 |
| Workplace Image | 1-7 | 4.57 | 1.67 | 5.00 | -0.45 | -0.86 |
| Visual Discomfort | 0-16 | 1.60 | 1.54 | 1.00 | 1.40 | 1.68 |
| Physical Discomfort | 0-16 | 2.78 | 2.18 | 2.33 | 0.95 | 0.30 |
| Satisfaction with Lighting | 1-7 | 5.01 | 1.15 | 5.20 | -0.55 | -0.39 |
| Organizational Commitment | 1-7 | 4.87 | 0.91 | 4.83 | 0.05 | -0.02 |
| Intent to Turnover | 1-7 | 2.49 | 1.11 | 2.67 | 0.24 | -0.84 |
| Unsolvable Anagrams – Tries | 0-unlimited | 2.60 | 1.11 | 2.00 | 1.34 | 1.55 |
| Unsolvable Anagrams - Time | 0-300 | 109.68 | 61.98 | 103.00 | 0.39 | -0.59 |
| Luminaire | 1-3 | 1.40 | 0.66 | 1.00 | 1.39 | 0.62 |
| Lighting Control | 0-1 | 0.24 | 0.43 | 0.00 | 1.22 | -0.51 |

*Note.* For Luminaire, category 1 = 320 people, category 2 = 94, and category 3 = 45. For Lighting Control, 0 = 349 and 1 = 110 people.

We had hoped to be able to separate the effects of luminaire type, individual control, and furnishings as contributors to the concept "lighting appraisal". This proved impossible, as the three variables were highly intercorrelated. On the basis of both the observed intercorrelations ($r$ > .80 for luminaire – furnishings and for luminaire — control) and logic related to the way the lighting systems were operated (i.e., grouping the luminaires operated in the same way), we decided to characterise the luminous conditions as one variable with three levels: 1 (parabolic, no individual control); 2 (workstation-specific direct-indirect, ambient lamp off, task lamps individually controlled in most cases); 3 (workstation-specific direct-indirect, ambient at 100%, task lamps individually controlled). Because of the furnishing differences this set of ordinal categories also reflects an increasing average luminance.

We began by testing a model based on the individually-measurable concepts in the linked mechanisms map (Figure 1), modified by the unavailability of the creativity data. The initial model is shown in Figure 11.

***Figure 11**. Initial structural equation model.*
*Rectangles denote measured variables. Circles show latent concepts.*




The results for the initial model showed that there were problematic multivariate relationships involving the motivation concept that prevented a stable solution. We re-ran the model with only one indicator of motivation, the number of tries on the unsolvable anagrams. This model resolved without errors, but the connection between mood and motivation was very small and not statistically significant. The most parsimonious and interpretable model is shown in Figure 12. All of the paths in this model are statistically significant and all are in the expected directions. The goodness of fit statistics for this model are summarized in Table 27. The model fit is acceptable, as compared to the recommended values for structural equation models (Byrne, 2006; Kline, 1997).

The model shows that as luminous conditions shift from conventional (fully direct parabolic louvers with no individual control) to individually controllable direct-indirect luminaires, lighting appraisals tend to rise, and in turn this rise is associated with more favourable judgements of room appearance, more positive mood, and fewer health problems. More positive mood and higher room appearance judgements are associated with higher overall environmental satisfaction, higher job satisfaction, higher affective organizational commitment, and reduced intent to turnover.

***Table 27.*** *Goodness-of-fit statistics for final model.*

| | N | $X^2$ | df | $X^2$/df | GFI | AGFI | CFI | NFI | NNFI | SRMR | RMSEA (90%CI) | % Residuals -0.1 to 0.1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Recommended | | | | < 3 | >.90 | >.90 | >.90 | >.90 | >.90 | <.10 | <.10 | > 90% |
| Observed | 459 | 477.29*** | 130 | 3.67 | .90 | .87 | .89 | .86 | .87 | .07 | .08 (.07 - .08) | 91.82 |

*Note.* *** *p*<.001.

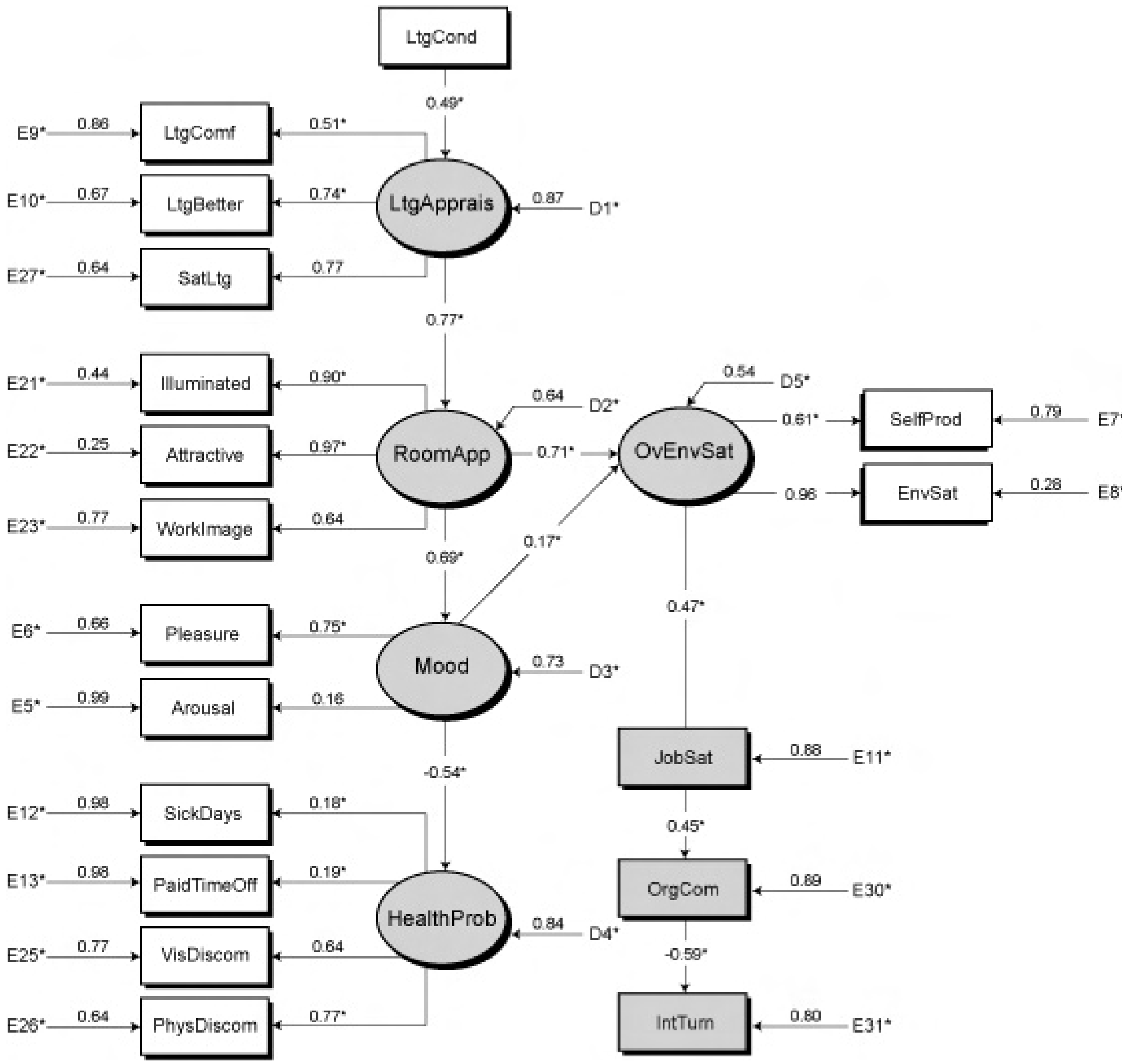
Table 28 shows the full standardized solution for the final model, including the percentage of variance explained in each equation. All of the standardized weights are statistically significant. The standardized weights and the $R^2$ values both follow expected patterns; environmental satisfaction, for example, is strongly predicted, whereas there is relatively little explained variance in the sickness absences or paid time off. These relationships are statistically significant, but other variables (not in this model) are needed to fully explain absences from work.

***Table 28***. *Standardized solution for final model.*

| Variable or Concept | Variable # | Standardized Weight(s) | | Error or Disturbance | $R^2$ |
|---|---|---|---|---|---|
| Lighting is comfortable | = V9 = | .51 F1* | + | .86 E9 | .26 |
| Lighting is better | = V10 = | .74 F1* | + | .67 E10 | .55 |
| Satisfaction with Lighting | = V27 = | .77 F1 | + | .64 E27 | .59 |
| Lighting Appraisal | = F1 = | .49 V35* | + | .87 D1 | .24 |
| Illuminated | = V21 = | .90 F2* | + | .44 E21 | .81 |
| Attractive | = V22 = | .97 F2* | + | .25 E22 | .94 |
| Workplace Image | = V23 = | .64 F2 | + | .77 E23 | .41 |
| Room Appearance | = F2 = | .77 F1* | + | .64 D2 | .59 |
| Arousal | = V5 = | .16 F3 | + | .99 E5 | .03 |
| Pleasure | = V6 = | .75 F3* | + | .66 E6 | .56 |
| Mood | = F3 = | .69 F2* | + | .73 D3 | .47 |
| Self-rated Productivity | = V7 = | .61 F5* | + | .79 E7 | .38 |
| Environmental Satisfaction | = V8 = | .96 F5 | + | .28 E8 | .92 |
| Overall Environmental Satisfaction | = F5 = | .72 F2* + .17 F3* | + | .54 D5 | .71 |
| Sickness Absences | = V12 = | .18 F4* | + | .98 E12 | .03 |
| Paid Time Off | = V13 = | .19 F4* | + | .98 E13 | .04 |
| Visual Discomfort | = V25 = | .64 F4 | + | .77 E25 | .40 |
| Physical Discomfort | = V26 = | .77 F4* | + | .64 E26 | .59 |
| Health Problems | = F4 = | -.54*F3* | + | .84 D4 | .29 |
| Job Satisfaction | = V11 = | .47 F5* | + | .88 E11 | .22 |
| Organizational Commitment | = V30 = | .45 V11* | + | .89 E30 | .20 |
| Intent to Turnover | = V31 = | -.59 V30* | + | .81 E31 | .35 |

*Note*. V35, Luminous Conditions, was an exogenous variable (not explained by others in the model. It was the sole predictor of Lighting Appraisal. * Denotes unconstrained variables.

***Figure 12**. Final structural equation model.*
*Rectangles denote measured variables. Circles show latent concepts. The figure also shows the standardized regression weights; those with * were free to vary.*




## 3.3. Physical Data

***3.3.1 Luminous conditions.*** We assessed luminous conditions with both luminance and illuminance measurements at night and by day. The night measurements are more indicative of differences related solely to the electric lighting and furnishings because all of the buildings took advantage of daylighting.

Table 29 summarizes the average luminances (L) for electric lighting only across all measured workstations, by furnishing and lighting type. In the case of the workstation-specific lighting, these measurements are at 100% output for both the target and adjacent workstations.

***Table 29.*** *Mean (standard deviation) workstation luminances for electric lighting only, from HDR images.*

| Furniture | Lighting | N | Picture Ave L ($cd/m^2$) | Field of View Ave L ($cd/m^2$) | Field of View Log(Max:Min) | Ceiling Ave L ($cd/m^2$) | Ceiling Max L : Min L Ratio |
|---|---|---|---|---|---|---|---|
| Old Teal | PARAB | ~120 | 27 (17) | 19 (9) | 1.56 (0.54) | 62 (94) | 198 (466) |
| Old Grey | WS-60U | 30 | 50 (26) | 19 (6) | 1.18 (0.50) | 149 (98) | 254 (294) |
| New | WS-76U | 29 | 80 (24) | 37 (6) | 1.30 (0.32) | 164 (56) | 133 (97) |
| New | WS-81U | 53 | 103 (42) | 43 (13) | 1.27 (0.38) | 226 (102) | 235 (208) |

*Note*. For the Old Teal furniture / PARAB lighting, N=114 for the ceiling measurements because of equipment problems.

The results show the combined effect of changing the luminaires and the furniture reflectances. Looking at the average luminance across the whole HDR image and at the ceiling average luminance, we see that it is markedly higher for all three WS-type luminaires than for the PARAB luminaires, as would be expected from the increased indirect component. However, the statistics for the approximate 40-degree field of view (i.e., the view within the panels) show the effect of furniture reflectance. The mean luminance in the field of view was the same for both groups with old furniture.

These data also show the effect of the third lamp in the WS luminaires, in the differences between the WS-76U and WS-81U luminaires. The WS-81U workstations had higher luminances, particularly on the ceiling.

Table 30 displays illuminance (E) data for the same workstations. Again, the results show the combination of luminaire and furniture reflectance. Illuminances were lowest for the combination of WS-60U and old grey furniture. Compared to the PARAB condition, this group of workstations had higher-luminance ceilings resulting from the indirect component (see Table 29), but it appears that the low-reflectance panels delivered less of that light to the vertical surfaces (illuminance on the face of the cube, i.e. Eye E) or to the desktop. This combination also had the largest difference between horizontal and vertical directions, as seen in both the vector:scalar illuminance ratio and the ratio of the cube top illuminance to average of the cube side illuminances.

***Table 30.*** *Mean (standard deviation) workstation illuminances with electric lighting only.*

| Furniture | Lighting | N | Desktop E (lx) | Eye E (lx) | Scalar E (lx) | Vector:Scalar Ratio | Cube Top:Side Ratio |
|---|---|---|---|---|---|---|---|
| Old Teal | PARAB | 120 | 485 (144) | 166 (80) | 260 (76) | 2.20 (0.34) | 3.68 (1.07) |
| Old Grey | WS-60U | 30 | 367 (76) | 130 (61) | 242 (59) | 2.34 (0.17) | 4.10 (0.51) |
| New | WS-76U | 29 | 491 (58) | 248 (61) | 343 (44) | 1.96 (0.2) | 3.12 (0.44) |
| New | WS-81U | 53 | 557 (156) | 281 (100) | 396 (100) | 2.04 (0.22) | 3.03 (0.43) |

The nature of the renovation necessarily meant that the luminaire type and furnishings were very highly correlated ($r$ = .90), making it difficult to disentangle the separate effects of each on the luminous conditions. With inter-reflections from surfaces, however, the combination of the surface reflections with the light distributions makes each combination more than the simple sum of the two components. We modelled this using categorical codes for luminaire (1 = PARAB, 2 = WS-60U-C; 3 = WS-76U-C; 4 = WS-81U-C) and furnishings (1 = old teal, 2 = old grey; 3 = new), then multiplying the two to create an interaction term. Regressing all three variables (luminaire, furnishings, and their interaction) at once was not practical because the interaction correlated at $r$ = .97 with the two components. Table 31 shows, instead, a series of multiple regression results for selected photometric quantities as dependent variables. The top row for each dependent variable shows the result for the regression with two individual components. The second row shows the result for the combination variable. In this data set, the photometric quantities are better described using the combination variable than with the two individual components. All of these analyses resulted in overall statistical significance, but not all were interpretable on the basis of the regression weights. For example, desktop illuminance is only weakly explained by any of these variables (3 % - 4 % of variance explained), but neither of the separate components' beta weights were statistically significant, whereas the beta weight for the combination variable was statistically significant (and the explained variance was higher).

Despite the problems of high intercorrelations, the results in Table 31 are interesting and follow expectations. Desktop illuminances were only weakly related to the predictors, having been designed to remain within the range of recommended practices. Illuminance at the eye and the overall picture average luminance, both measures of the quantity of light in the vertical plane for the seated occupant, were strongly related to luminaire and slightly more strongly related to the combination of luminaire and furnishings. The combination was a significant predictor of directionality as measured with the top:side illuminance ratio, as one might expect. Variability in the field of view luminances (field of view log max:min) was weakly predicted by the combination of luminaire and furnishings, probably because these luminances also depended on the objects and decorations in the workstation when the HDR images were taken.

***Table 31.*** *Multiple regressions of workstation lighting and furnishings on selected photometric quantities, electric lighting only.*

| Dependent Variable | F | df | $R^2$ | Lighting Beta weight | Furniture Beta weight | Lighting X Furniture Beta weight |
|---|---|---|---|---|---|---|
| Desktop E | 3.32* | 2, 237 | .03 | .14 | .03 | |
| (lx) | 8.77** | 1,238 | .04 | | | .19** |
| Eye E | 37.23*** | 2, 237 | .23 | .36** | .14 | |
| (lx) | 82.27*** | 1, 238 | .26 | | | .51*** |
| Vector:Scalar | 11.85*** | 2,237 | .09 | .15 | -.43** | |
| Ratio | 18.37*** | 1, 238 | .07 | | | -.27*** |
| Cube Top:Side | 12.34*** | 2, 237 | .09 | -.21 | -.10 | |
| Ratio | 27.90*** | 1, 238 | .11 | | | -.32*** |
| Picture Ave. L | 165.81*** | 2,237 | .58 | .60*** | .18 | |
| ($cd/m^2$) | 333.66*** | 1, 238 | .58 | | | .76*** |
| Field of View | 3.23* | 2,237 | .03 | .06 | -.21 | |
| Log(Max:Min) | 4.26* | 1, 238 | .02 | | | -.13* |

The daytime measurements were taken in afternoons only, and are intended primarily to indicate the range of conditions under which occupants commonly worked during the seasons in which the three measurement waves occurred. We avoided workstations with direct sun to avoid burning out the illuminance sensors, so the range is truncated. Dimmable lighting conditions and shading conditions were measured as found; we had no way to determine the dimmer setting of the luminaires at the moment of the measurements. There are small samples (under 20) for the WS-60U and WS-76U workstations, which further limits generalizations. With this small sample, we will not present averages by lighting or furnishing types in relation to the distance from a window. Despite these limitations, the data are valuable as an indication of the conditions in the offices during working hours when the surveys were completed.

The presence of daylight somewhat reduced the differences between the groups. The luminances were higher (Table 32) than at night (Table 29), as were all of the desktop illuminance averages. The group differences in the conditions we measured by day did not follow the same pattern as they had at night, at least for the particular workstations, lighting choices, and daylight and shading conditions we sampled. For example, it happened that the mean luminance for the WS-60 luminaires was higher than for any of the other groups, which was not true of the measurements with electric lighting only. All of the groups showed more side than overhead light than was the case at night, reflecting the contribution from the windows (compare the cube top:side ratios in Tables 30 and 33).

However, some characteristics persisted. In particular the ceiling average luminances were higher for the three groups of WS-type luminaires (Table 32, from HDR images, and Table 34 from spot measurements).

***Table 32.*** *Mean (standard deviation) afternoon workstation luminances with daylight and electric light, from HDR images.*

| Furniture | Lighting | N | Picture Ave L ($cd/m^2$) | Field of View Ave L ($cd/m^2$) | Field of View Log(Max:Min) ($cd/m^2$) | Ceiling Ave L ($cd/m^2$) | Ceiling Max L : Min L Ratio |
|---|---|---|---|---|---|---|---|
| Old Teal | PARAB | 62 | 114 (234) | 78 (194) | 1.67 (0.52) | 127 (150) | 150 (192) |
| Old Grey | WS-60U | 17 | 146 (142) | 189 (280) | 1.66 (0.69) | 184 (102) | 90 (139) |
| New | WS-76U | 13 | 172 (282) | 75 (90) | 1.47 (0.48) | 195 (132) | 69 (71) |
| New | WS-81U | 38 | 98 (47) | 48 (24) | 1.37 (0.44) | 182 (96) | 231 (229) |

***Table 33.*** *Mean (standard deviation) afternoon workstation illuminances with daylight and electric lighting.*

| Furniture | Lighting | N | Desktop E (lx) | Eye E (lx) | Scalar E (lx) | Vector:Scalar Ratio | Cube Top:Side Ratio |
|---|---|---|---|---|---|---|---|
| Old Teal | PARAB | 78 | 637 (376) | 322 (436) | 380 (262) | 2.01 (0.33) | 2.89 (1.13) |
| Old Grey | WS-60U | 33 | 511 (333) | 355 (413) | 11596 (12560) | 2.88 (1.04) | 2.66 (0.81) |
| New | WS-76U | 23 | 557 (624) | 300 (275) | 11162 (12637) | 2.68 (1.14) | 2.20 (0.89) |
| New | WS-81U | 54 | 506 (174) | 248 (111) | 353 (124) | 1.92 (0.29) | 2.70 (0.58) |

***Table 34.*** *Mean (standard deviation) afternoon ceiling luminances from spot measurements.*

| Furniture | Lighting | N | Ceiling Max L ($cd/m^2$) | Ceiling Min L ($cd/m^2$) |
|---|---|---|---|---|
| Old Teal | PARAB | 62 | 117 (187) | 43 (40) |
| Old Grey | WS-60U | 16 | 698 (252) | 121 (200) |
| New | WS-76U | 9 | 1078 (591) | 90 (61) |
| New | WS-81U | 37-38 | 915 (769) | 91 (51) |

We used multiple regression analysis to examine the effects of luminaire, furnishings, season, time of day, window location, window orientation, sky condition, and blinds status on selected photometric quantities. For this data set, only window location was a statistically significant predictor of daytime luminous conditions. As expected, there was more light (i.e., higher desktop illuminance, higher picture average luminance) when one was closer to the window.

At night, with electric lighting only, we performed five sets of measurements at the WS workstations on the visits at $T_0$ and $T_1$, totalling 39 workstations: 10 WS-60U, 9 WS-76U, and 20 WS-81U. These measurements were performed in order to give an indication of the degree to which conditions at adjacent workstations influenced the target workstation. Table 35 shows the dimmer settings for the target workstations and the adjacent workstations for each measurement.

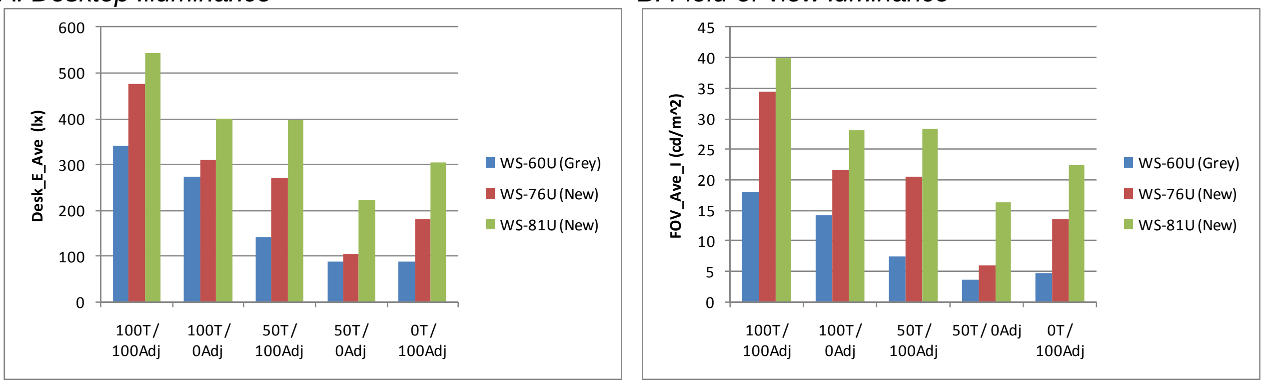
***Table 35.*** *Target and adjacent workstation settings for measurement variations.*

| Target WS | Adjacent WS |
|---|---|
| 100 | 100 |
| 50 | 100 |
| 0 | 100 |
| 50 | 0 |

We examined several photometric variables to understand the effects of both luminaire operation and panel reflectance. Figure 13 shows results for desktop illuminance (i.e., in the horizontal plane) and field-of-view luminance (i.e., across the vertical plane). These track similarly, and show that the panel reflectance and luminaire operation interact. The combination of the three-lamp operation and the high-reflectance panels ensured than the WS-81U luminaires delivered the highest values regardless of the dimmer settings. Indeed, in our sample the average desktop illuminance from adjacent luminaires at 100% for the WS-81U locations was 300 lx. Some individuals might find that they wish to set their dimmers at zero because there is adequate illumination from the surrounding workstations. This could mean, however, that when adjacent WS-81U luminaires switch off because of occupancy sensor operation, there is greater potential for annoyance in the target workstation than for the WS-60U luminaires.

***Figure 13**. Workstation luminous condition for different dimmer settings by luminaire type and furnishings.*

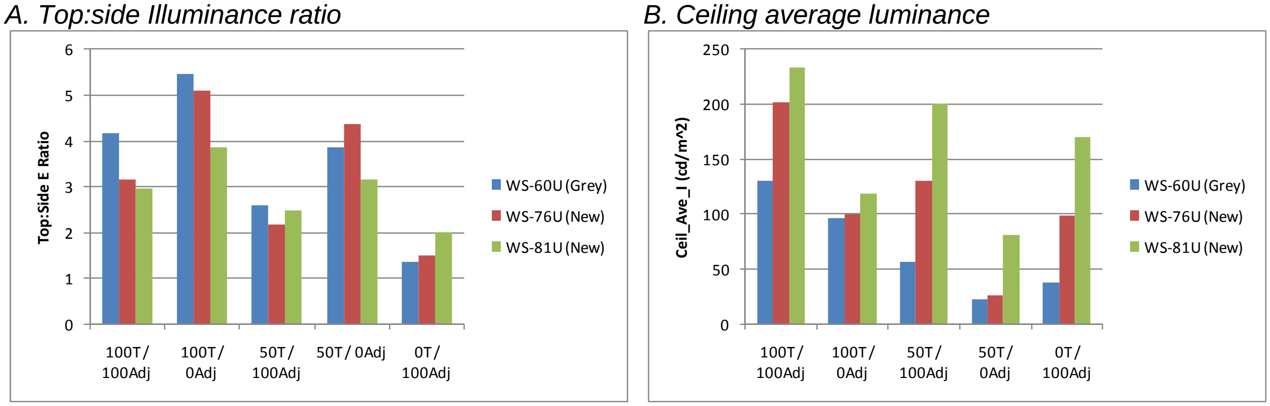
*A. Desktop Illuminance* *B. Field-of-view luminance*




The interaction effect is evident in the similarity between the results for WS-76U and WS-81U luminaires when the adjacent luminaires are at 100% -- when there is more ambient light to reflect from the lighter panels – in contrast with the similarity in results for WS-76U and WS-60U when the adjacent luminaires are at 0%. Figure 14 illustrates this phenomenon. Panel A shows the top:side illuminance ratio from the cubic illuminance head. When there is no light from the adjacent luminaires, WS-60U and WS-76U (both of which have two-lamp operation) provide a greater proportion of direct downlight and therefore a higher top:side ratio. When there is light from the adjacent luminaires, the proportion of side light is higher in the workstations with lighter panels, WS-76U and WS-81U. Panel B shows the results for the ceiling average luminance.

***Figure 14**. Luminous conditions for different dimmer settings by luminaire type and furnishings.*

*A. Top:side Illuminance ratio* *B. Ceiling average luminance*



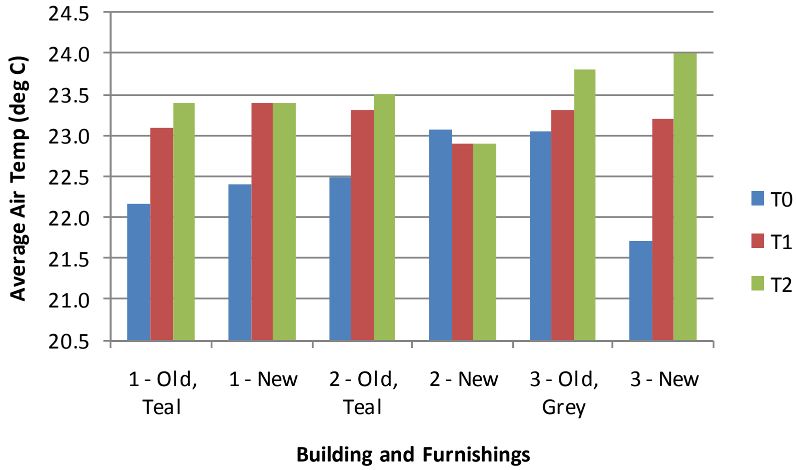

***3.3.2 Thermal conditions.*** During all three site visits we recorded thermal and humidity conditions over three days at twenty locations spread across the three buildings. We examined the data for trends that might indicate differences between the furniture layouts or the buildings, and for evidence of conditions outside the range of recommended practices. There was no evidence of systematic differences across furnishings or building, and the mean temperatures remained within accepted standards

(American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 2004), as Table 36 shows. For easier comparison, the average air temperatures by building and furnishings for each site visit are shown graphically in Figure 15. The air temperature was a bit low at $T_0$ in Building 3 on the newly constructed floors. This could have been an artifact of the new construction, and it was not accompanied by evidence of dissatisfaction with the ventilation or temperature (satisfaction on that scale at $T_0$ was 4.8 for people in Building 3 with the old, grey furnishings, and 5.4 for those with the new furnishings, on a scale from 1-7).

***Table 36.*** *Ambient temperature and relative humidity readings during occupied hours in site visit weeks, by building and furniture type.*

| Wave | Building | Furnishings | Ave RH (%) | StDev RH | Max RH (%) | Min RH (%) | Ave Desk Air T (°C) | StDev Desk Air T (°C) | Max Desk Air T (°C) | Min Desk Air T (°C) |
|---|---|---|---|---|---|---|---|---|---|---|
| $T_0$ | 1 | Old, Teal | 33.6 | 3.7 | 46.4 | 26.8 | 22.2 | 3.4 | 25.4 | 13.4 |
| | 1 | New | 34.6 | 3.8 | 48.4 | 27.9 | 22.4 | 2.9 | 24.7 | 13.5 |
| | 1 | Bldg Ave. | 34.1 | 3.8 | 48.4 | 26.8 | 22.3 | 3.1 | 25.4 | 13.4 |
| | 2 | Old, Teal | 33.4 | 4.0 | 40.5 | 24.9 | 22.5 | 0.9 | 24.0 | 19.8 |
| | 2 | New | 33.5 | 3.6 | 39.3 | 25.5 | 23.1 | 0.9 | 24.6 | 20.1 |
| | 2 | Bldg Ave. | 33.5 | 3.8 | 40.5 | 24.9 | 22.8 | 1.0 | 24.6 | 19.8 |
| | 3 | Old, Grey | 38.6 | 7.8 | 54.9 | 29.3 | 23.1 | 0.6 | 24.6 | 21.3 |
| | 3 | New | 45.3 | 7.4 | 56.1 | 32.8 | 21.7 | 0.4 | 23.6 | 20.8 |
| | 3 | Bldg Ave. | 40.9 | 8.3 | 56.1 | 29.3 | 22.6 | 0.8 | 24.6 | 20.8 |
| $T_1$ | 1 | Old, Teal | 34.7 | 1.7 | 38.6 | 31.0 | 23.1 | 0.3 | 23.6 | 21.8 |
| | 1 | New | 39.7 | 5.9 | 50.4 | 31.7 | 23.4 | 0.5 | 24.3 | 22.0 |
| | 1 | Bldg Ave. | 37.2 | 5.0 | 50.4 | 31.0 | 23.2 | 0.5 | 24.3 | 21.8 |
| | 2 | Old, Teal | 35.0 | 1.7 | 38.5 | 30.4 | 23.3 | 0.4 | 23.8 | 22.1 |
| | 2 | New | 34.3 | 1.6 | 37.7 | 30.4 | 22.9 | 0.5 | 24.1 | 21.4 |
| | 2 | Bldg Ave. | 34.5 | 1.7 | 38.5 | 30.4 | 23.0 | 0.5 | 24.1 | 21.4 |
| | 3 | Old, Grey | 36.0 | 1.3 | 39.2 | 32.3 | 23.3 | 0.4 | 24.3 | 22.0 |
| | 3 | New | 38.8 | 1.4 | 42.0 | 35.2 | 23.2 | 0.8 | 24.3 | 21.2 |
| | 3 | Bldg Ave. | 37.0 | 1.8 | 42.0 | 32.3 | 23.2 | 0.6 | 24.3 | 21.2 |
| $T_2$ | 1 | Old, Teal | 45.1 | 2.9 | 48.9 | 38.3 | 23.4 | 0.4 | 24.5 | 22.2 |
| | 1 | New | 49.4 | 6.1 | 63.9 | 39.3 | 23.4 | 0.5 | 24.4 | 22.4 |
| | 1 | Bldg Ave. | 47.8 | 5.6 | 63.9 | 38.3 | 23.4 | 0.4 | 24.5 | 22.2 |
| | 2 | Old, Teal | 44.8 | 3.1 | 52.1 | 38.3 | 23.5 | 1.3 | 26.0 | 21.0 |
| | 2 | New | 44.9 | 3.5 | 51.1 | 37.0 | 22.9 | 0.9 | 24.5 | 21.0 |
| | 2 | Bldg Ave. | 44.8 | 3.3 | 52.1 | 37.0 | 23.2 | 1.1 | 26.0 | 21.0 |
| | 3 | Old, Grey | 46.7 | 2.4 | 53.0 | 40.1 | 23.8 | 0.7 | 25.5 | 22.0 |
| | 3 | New | 48.3 | 3.3 | 54.4 | 41.0 | 24.0 | 0.6 | 25.6 | 22.8 |
| | 3 | Bldg Ave. | 47.2 | 2.8 | 54.4 | 40.1 | 23.8 | 0.7 | 25.6 | 22.0 |

***Figure 15**. Bar chart showing the average air temperature measured during occupied hours, by building and furniture type, for the three site visits associated with measurement waves.*




***3.3.3 Acoustic conditions.*** At the first site visit, we measured acoustic conditions in eight workstations, during occupied hours, using the SPMSoft system (Bradley & Gover, 2008). Four of the workstations were of the old design, and four of the new. Our aim was to determine whether the change in furnishings led to a change in sound transmission between workstations that might have been an influence on satisfaction. The measurements revealed that both designs were slightly off the target values for speech privacy in offices, which are expressed in terms of the Speech Intelligibility Index, or SII (Acoustical Society of America Standards Secretariat (ASA), 1997). Acceptable speech privacy would be shown by SII < 0.20. The average SII for the four workstations of the old design was 0.27; for the four in the new design, 0.24. These low values are somewhat unexpected because they are considerably lower than the majority of workstations sampled as part of the NRC Cost-effective Open Plan Environments project, where the median workstation had an SII of 0.51 (Veitch, et al., 2003). In the present project our sample of acoustical measurements was very small, and might not be representative of the range of conditions in the three buildings. However, for the present purpose we were satisfied with the result in that we did not observe substantial differences in acoustic conditions between the two furniture types.

## 3.4 Archival Data

***3.4.1 Lighting energy use.*** We had planned to examine archival data for measured power consumption for lighting in the three buildings over the study period. It was not possible to obtain all of the data required for this comparison. Moreover, the organization initiated a competitive energy conservation program shortly before $T_0$, which led to delamping efforts on floors without individual control and to actions such as the removal of the indirect lamps on the workstation-specific luminaires in Building 3. The strong goal of reducing power consumption, and ongoing communications on the topic, over the study period would have confounded the comparison had the data been available. In addition, the calculation of lighting energy use per occupant would have been complicated by the changing occupant density from the old to the renovated/new floors.

However, NRC had previously conducted a year-long investigation of lighting energy use in Building 3, comparing the original PARAB lighting with the WS-81U-C system where occupant density stayed constant. This investigation included examination of the energy reduction contributions from the luminaire layout, the occupancy sensor, the daylight-linked dimming, and the individual control (Galasiu, Newsham, Suvagau, & Sander, 2007). The results are summarized in Table 37. Overall the new lighting installation, with both the direct and indirect components operating, plus all three controls, reduced lighting energy use by 69%. This translates into a drop from an effective lighting power density (LPD) of 10 W/m$^2$ to 3 W/m$^2$. The effective power density is the average maximum power actually used, and is lower than the installed LPD because not all lamps are on at any one time, and if they are on they are not all on at full output.

***Table 37.*** *Lighting and power usage for studied lighting systems (from Galasiu et al., 2007).*

| | LPD W/m$^2$ | Energy Savings % | Peak Load (W/workstation) |
|---|---|---|---|
| **PARAB** | 10 | | 174 |
| **WS-81U (100% output)** | 5.6 | 43 | 97 |
| **WS-81U-C (actual)** | 3 (effective) | 69 | 53 |

***3.4.2 Facilities complaints calls.*** It was not possible to test this hypothesis because the organization did not collect the data in a format suitable for analysis.

## 4.0 Discussion

### 4.1 Lighting Effects on Individuals and Organizations

Novice lighting students learn early that room surfaces are part of the lighting system. This field investigation of a lighting and furnishings renovation has shown that both elements contribute to occupants' evaluations of their workplaces, and that these evaluations predict outcomes that matter to employers.

The pattern of results in this field investigation is clear in showing that luminaires with a substantial indirect component and individual (personal) control over workstation light levels are preferred over those with only direct illumination. The most sensitive comparisons were those with the largest sample sizes (labelled L1 above), between PARAB and WS-60U-C luminaires, all with the old furniture style. This contrast is the closest to the comparison between Base Case 1 and Dimming Control in the Light Right Albany experiments (Boyce, et al., 2003). The results of the two studies are consistent, in that, in both cases participants indicated higher lighting appraisals with workstation-specific luminaires and individual controls. For the question "Is the lighting better, the same or worse here than in other workplaces?", in both studies the parabolic-louvered luminaires showed a higher-than-expected likelihood of being rated as "the same" as other workplaces, and a lower-than-expected likelihood of being rated as "better". For workstation-specific luminaires with control, in both the Albany experiment and the field study, there was a much higher than expected likelihood of the lighting being rated as "better" than in other workplaces.

A previous investigation by our team, conducted in 2004-2005 in Building 3 of the same organization, adds to the evidence that the effect of luminaires with control is real and not attributable to small differences in furnishings nor to between-buildings differences in working conditions. At that time the workstation-specific luminaires in that building had three lamps in operation, making them WS-81U-C luminaires. All of the workstations had the old, grey furniture, but some had parabolic-louvered luminaires. We found that the WS-81U-C luminaires had the same high appraisal ratings as had the Dimming Control luminaires in the Albany experiments, and the PARAB luminaires had the same, normative ratings as had similar luminaires in Albany (Veitch et al., 2010). Similarly, the WS-81U-C luminaires resulted in greater lighting satisfaction than the PARAB luminaires, although we did not observe differences in job satisfaction.

One outcome of the present study was moderately surprising, particularly given the results of our earlier investigation: the high ratings for the PARAB lighting in the lighting appraisals (the Office Lighting Survey). A higher percentage of people than expected rated this lighting as comfortable (>80%, versus 69% expected). This might reflect the greater use of flat-panel monitors in 2008-2009 than in previous years and the attendant reduction in problematic reflections. Alternatively, the daytime lighting measurements offer a possible explanation for this outcome. These buildings enjoyed a high degree of daylight, even in the old furniture layout. This no doubt influenced the questionnaire responses, and could have attenuated differences between the lighting conditions.

This field study with its larger overall sample size was able to detect other benefits of workstation-specific lighting with individual control that were not observed in either the Albany experiments nor our previous field investigation. Even with the old furniture, WS-60U-C lighting was associated with higher lighting satisfaction, higher ratings of workplace image, room attractiveness, and room illumination, higher overall environmental satisfaction, greater feelings of pleasure, and lower frequency and intensity of physical symptoms, higher job satisfaction and organizational commitment and lower intent to turnover (all in comparison to PARAB lighting).

Other contrasts between luminaires showed consistent, if smaller effects, and were not sensitive enough to detect the smaller effects seen in the L1 contrast. The smaller sample sizes of these other contrasts is the most likely explanation for these outcomes. The striking outcome is that none of these contrasts uncovered statistically significant effects that were contrary to the predictions based on the previous laboratory experiments.

Although there were three variations on the degree of indirect contribution, we did not detect clear differences between them. We tested for differences between WS-76U-C and WS-81U-C (all with new furniture) and found few; those we did find favoured WS-76U-C. These could not clearly be associated with the lighting systems. Given the high degree of daylight in the spaces, it seems possible that there is little perceptual difference for occupants between these two modes of operation.

The furnishings comparison in the present field study was imperfect in that the luminaires differed in the degree of indirect component (WS-60U-C versus WS-76U-C in Building 3). However both were operated in the same manner (with two lamps only, both being under the occupant's control). The results are most consistent with the interpretation that they revealed the influence of surface reflectances on occupant appraisals of the lit environment overall. For areas with the new lighting, ratings of the attractiveness and illumination of the room were higher for the new furnishings than for the old, as were ratings of workplace image (the degree to which the workplace design projects the right image for the organization). These same scales also showed large effects in contrasts involving the total renovation in Buildings 1 and 2.

Attempts in the present study to differentiate between the effects of the luminaires and of the individual (personal) control were less successful, showing trends in the expected direction but not clear evidence. These were weak manipulations in comparison to the experimental approach taken previously (Boyce, et al., 2003; Newsham, et al., 2004), with confounds that reduced the strength of causal inference and with small sample sizes. Individual control was an element of the most highly-rated lighting system, but its individual contribution to that high rating cannot be clearly separated out with these data. Previous experiments found that giving individuals control over workstation lighting has valuable outcomes by virtue of enabling individuals to achieve their chosen lighting conditions (Newsham & Veitch, 2001; Newsham, et al., 2004), a phenomenon that is consistent with the overall results of this field investigation.

The overall pattern of results fits well with predictions from the scientific literature. Lighting systems with an indirect component have been rated as more satisfactory in both the laboratory (Boyce, et al., 2003; Houser, Tiller, & Hu, 2004; Newsham, et al., 2004) and in the field (Hedge, Sims, & Becker, 1995; Veitch, et al., 2010). The photometric data collected in the present study point to higher average scene luminance and higher ceiling luminance as characteristics of the lit environment that trigger this result.

The combination of automatic (occupancy and daylight harvesting) and individual controls used here does result in there being variation in light levels in any given workstation as a result of changes in adjacent locations. Our analysis of these spill effects showed that the contribution from one workstation to another had the potential to be large; however, there was no evidence from the questionnaire data to suggest that this had an adverse effect on either room appearance judgements or annoyance. The substantial daylight contribution in these buildings no doubt masks the changes in electric lighting resulting from the controls. In a space with less daylight it is possible that the variation in electric lighting could be problematic; this is a topic for future investigations in other buildings.

This field study was able to go a step further than previous investigations, to test an integrated theoretical model in which luminous conditions were indirectly associated with outcomes relevant to organizations and their bottom lines. The model was developed previously by Veitch et al. (2008) who used the Light Right Albany data to demonstrate connections between lighting appraisals, room appearance judgements, mood, and health symptoms. People who rated their lighting as better (regardless of lighting design) rated the office as more attractive, their own mood as more pleasant, and their physical symptoms at the end of the workday as less severe while their own performance was rated as better. These links held in three independent replications.

The Albany experimental setting was not able to replicate effects that develop over the longer term, but this field study was able to do so. Data from the present study supported the basic framework while extending the model to include the luminous conditions as a predictor and expanding the final outcomes to include absenteeism as well as at-work symptoms and a chain of outcomes from overall environmental satisfaction through job satisfaction to organizational commitment and intent to turnover. The final model fit the data acceptably well, with all paths being statistically significant and relationships in the predicted directions. People with high-reflectance furnishings coupled with workstation-specific direct-indirect lighting and individual (personal) control show higher lighting appraisals; those with higher lighting appraisals show higher ratings of room appearance; those with higher ratings of room appearance show more favourable moods; those with more favourable moods show fewer health problems including fewer days off. In addition, people who rate room appearance more highly and who are in a more pleasant mood show higher ratings of overall environmental satisfaction, and in turn these people show higher job satisfaction, higher organizational commitment, and lower intent to turnover.

To our knowledge this is the first study to link luminous conditions indirectly to outcomes that have clear financial consequences for organizations in a single structural equation model, and with a large sample size. This is a stronger test than was possible with the Albany data, which it has conceptually replicated (Veitch, et al., 2008). The previous NRC investigation offers some support, in that we observed a statistically significant chain from job satisfaction through organizational commitment to intent to turnover using mediated regression (Veitch, et al., 2010), a sequence that has support from the organizational psychology literature (Wilson, Dejoy, Vandenberg, Richardson, & McGrath, 2004). For instance, Rousseau and Aubé (2010) found that a measure of average satisfaction with ambient conditions predicted affective organizational commitment and moderated the effect of perceived supervisor support on affective organizational commitment. Although there are many steps in this chain, and there is no doubt that other variables also influence these outcomes, these data show that luminous conditions matter. People who rate their lighting as better are less likely to experience physical and visual discomfort and somewhat less likely to be off sick; they are also less likely to intend to leave the organization. If good-quality lighting only resulted in more attractive spaces, the chain of relationships would stop at room appearance. Lighting conditions in employee offices affect organizational productivity through effects on employees.

## 4.2 Limitations

This field investigation necessarily has limitations. The nature of the research design, a renovation, ensured that there would be very different group sizes, because only a limited number of employees would receive the renovation during the study. The renovation moved more slowly than planned, which resulted in far fewer renovated floors during the study than originally expected. This exacerbated the group-size inequalities.

Field research by its nature reduces the strength of causal inference. We lacked the ability to randomly assign employees to offices, as would have been done in an experimental setting. We tested for those between-groups differences for which we had data, and found none on those variables. We cannot rule out other differences between the groups from having biased the results. However, the fact that the most important effects showed similar patterns across various contrasts and that the results replicate the previous laboratory work gives us confidence that the results may be attributed to differences in luminous conditions rather than to other between-groups differences.

The host organization has a very strong energy conservation ethic and programs in place to push employees to save energy. The programs include a floor-by-floor competition to encourage energy savings and annual pay incentives associated with corporate energy savings. This has resulted in a heightened awareness of such issues as switching off when there is no occupancy sensor, and have also led to localized choices on the PARAB floors to delamp some parabolic-louvered luminaires in sparsely-occupied areas in order to save energy (where switching off is not possible). This heightened involvement of employees in their work environments could have influenced their satisfaction — either improving it in all areas as employees are excited by and involved in the energy savings competition, or decreasing it for those who do not like the actions being implemented..

The fact that the investigation involved only one host organization is both a strength and a limitation. There are no between-organization differences to confound the results. However, there may be peculiarities in any single organization that might fail to replicate elsewhere (such as the energy conservation ethic described above). Given the cost and difficulty of conducting an investigation of this type it might be unrealistic to expect a replication elsewhere, but if possible it would be desirable.

## 4.3 Conclusions

One of the challenges in promoting energy-efficient lighting has been overcoming inertia, both the inertia associated with higher first costs for new lighting equipment and that associated with taking the risk to do something different. The goal of the Light Right Consortium has been to demonstrate that energy-efficient lighting can also be high-quality lighting; that is, to show that there exists a lighting solution that will benefit individuals, their employers, and the environment. In its Phase 1 market survey, the Light Right Consortium found that 99% of lighting decision-makers reported considering occupant satisfaction when choosing a lighting solution, and 70% would consider effects on employee retention or recruitment (www.lightright.org). Phase 2 of the Light Right Consortium was the Albany experiments (Boyce, et al., 2003; Veitch, et al., 2008). The experiments showed that a workstation-specific direct-indirect luminaire with individual control was the most highly rated lighting design. Moreover, it demonstrated through linked mediated regression an indirect path between lighting appraisal and important health and satisfaction outcomes. The authors suggested that with this pair of experiments lighting research had reached the limit of possible laboratory demonstrations of the value of lighting design to organizations, and that the time had come to undertake a field investigation.

This field study is that investigation. Compared to a traditional fixed grid design of recessed parabolic-louvered luminaires, the workstation-specific direct-indirect luminaire with individual control delivered a more comfortable lit environment that was appraised as being better than other offices. Coupling the luminaire with a high-reflectance room surface delivered added improvements. This combination delivered luminous conditions that were associated with better outcomes for individuals in the form of fewer health problems and greater environmental and job satisfaction, and better outcomes for organizations in the form of fewer health problems and higher employee retention. Other NRC research had previously demonstrated dramatic energy savings with this design (Galasiu, et al., 2007) in comparison with the parabolic-louvered grid design. Rubinstein and Enscoe (2010) reported substantial energy savings for a workstation-specific direct-indirect luminaire design with occupancy sensors only; occupants appeared to be more satisfied with this design than with a design featuring rows of suspended direct-indirect luminaires controlled at the room level.

Energy-efficiency is unarguably an important societal, even planetary, goal. However, seeking lighting energy efficiency at the expense of individuals or their organizations is unlikely to succeed. Organizations will balk at the initial costs, or they will fear that a change only to save energy might adversely affect employees. If they perceive that the lighting change poses a risk to organizational success, they will not undertake it. Happily, these results show not a risk, but a reward, for the adoption of workstation-specific direct-indirect luminaires with individual control, daylight harvesting, and occupancy sensors. In addition to the energy savings associated with the lighting layout and three forms of control (Galasiu, et al., 2007), this lighting design can improve lighting appraisals and satisfaction, and is associated with reduced health problems and improved employee retention. This brings the results well into line with the desires expressed by lighting decision-makers in the market survey activity that began the work of the Light Right Consortium.

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# Appendix A: Office Lighting Survey Results

***Table A1.*** *Comparison L1 — Office Lighting Survey results, comparing Parab and WS-60U-C lighting, all with old furniture, at three times.*

| | Norm | | $T_0$ | | | | | $T_1$ | | | | | $T_2$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Agree %** | **Group** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** |
| 1. Overall, the lighting is comfortable. | 69 | Parab | 435 | 17 | 83 | 42.45*** | 6.15* | 415 | 16 | 84 | 41.44*** | 6.35* | 344 | 19 | 81 | 23.56*** | 6.85** |
| | | WS-60U-C | 64 | 5 | 95 | 20.72*** | | 76 | 5 | 95 | 23.53*** | | 59 | 5 | 95 | 18.52*** | |
| 2. The lighting is uncomfortably bright for the tasks … | 16 | Parab | 435 | 89 | 11 | 7.98** | 2.54 | 413 | 91 | 9 | 13.21*** | 1.40 | 344 | 90 | 10 | 7.84** | 1.67 |
| | | WS-60U-C | 65 | 95 | 5 | 6.27* | | 76 | 95 | 5 | 6.52* | | 59 | 95 | 5 | 5.23* | |
| 3. The lighting is uncomfortably dim for the tasks that I perform. | 14 | Parab | 436 | 89 | 11 | 2.76 | 2.67 | 414 | 88 | 12 | 1.61 | 0.00 | 344 | 87 | 13 | 0.42 | 0.88 |
| | | WS-60U-C | 65 | 95 | 5 | 4.75* | | 76 | 88 | 12 | 0.29 | | 59 | 92 | 8 | 1.50 | |
| 4. The lighting is poorly distributed here. | 25 | Parab | 435 | 75 | 25 | 0.04 | 7.38** | 415 | 76 | 24 | 0.42 | 9.51* | 343 | 76 | 24 | 0.05 | 4.58* |
| | | WS-60U-C | 64 | 91 | 9 | 8.33** | | 76 | 92 | 8 | 11.86*** | | 59 | 88 | 12 | 5.43* | |
| 5. The lighting causes deep shadows. | 15 | Parab | 436 | 89 | 11 | 6.09* | 2.39 | 415 | 89 | 11 | 4.40* | 2.54 | 343 | 89 | 11 | 4.14* | 0.99 |
| | | WS-60U-C | 65 | 95 | 5 | 5.50* | | 76 | 95 | 5 | 5.65* | | 59 | 93 | 7 | 3.13 | |
| 6. Reflections from the light fixtures hinder my work. | 19 | Parab | 436 | 92 | 8 | 35.55*** | 5.44* | 415 | 92 | 8 | 34.37*** | 2.57 | 344 | 92 | 8 | 26.36*** | 1.65 |
| | | WS-60U-C | 65 | 100 | 0 | 15.25*** | | 76 | 97 | 3 | 13.23*** | | 59 | 97 | 3 | 9.34** | |
| 7. The light fixtures are too bright. | 14 | Parab | 435 | 89 | 11 | 2.27 | 6.12* | 414 | 89 | 11 | 3.37 | 5.03* | 343 | 91 | 9 | 7.86** | 1.97 |
| | | WS-60U-C | 65 | 98 | 2 | 8.38** | | 76 | 97 | 3 | 8.16** | | 59 | 97 | 3 | 5.52* | |
| 8. My skin is an unnatural tone under the lighting. | 9 | Parab | 436 | 87 | 13 | 6.96** | 6.99** | 412 | 87 | 13 | 7.51** | 10.97*** | 342 | 87 | 13 | 8.27** | 0.48 |
| | | WS-60U-C | 65 | 98 | 2 | 4.42* | | 76 | 100 | 0 | 7.52** | | 59 | 90 | 10 | 0.10 | |
| 9. The lights flicker throughout the day. | 4 | Parab | 435 | 94 | 6 | 5.52* | 0.25 | 414 | 91 | 9 | 23.77*** | 5.01* | 343 | 92 | 8 | 11.45*** | 0.05 |
| | | WS-60U-C | 65 | 95 | 5 | 0.06 | | 76 | 99 | 1 | 1.43 | | 59 | 93 | 7 | 1.19 | |

| **Item** | **Norm** | **Group** | **N** | **-1 %** | **0 %** | **+1 %** | **$X^2$** | **$X^2$ BG.** | **N** | **-1 %** | **0 %** | **+1 %** | **$X^2$** | **$X^2$ BG** | **N** | **-1 %** | **0 %** | **+1 %** | **$X^2$** | **$X^2$ BG** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10. How does the lighting compare to similar workplaces in other buildings? | 19/60/22 | Parab | 428 | 13 | 74 | 14 | 35.60*** | 105.85*** | 407 | 18 | 68 | 14 | 16.87*** | 52.84*** | 340 | 17 | 69 | 14 | 14.20*** | 34.25*** |
| | | WS-60U-C | 65 | 5 | 26 | 69 | 85.40*** | | 76 | 8 | 42 | 50 | 36.07*** | | 59 | 8 | 46 | 46 | 20.58*** | |

*Note.* Parab: Parabolic-louvered luminaires. WS-60U-C: Workstation-specific luminaires, 60% uplight, individually controllable. For question 10, -1 = Worse; 0 = Same; +1 = Better. For questions 1 through 9, all normative comparison $X^2$ , df = 1 and between-groups $X^{2,}$ df = 1. For question 10, normative comparison df = 2 and between-group df = 2. * *p*<.05; ** *p*<.01; *** *p*<.001.

***Table A2**. Comparison L1 — Satisfaction with windows & daylighting, comparing PARAB and WS-60U-C lighting, all with old furniture, at three times.*

| | Norm | | $T_0$ | | | | | $T_1$ | | | | | $T_2$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Agree %** | **Group** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** |
| 1. Direct sunlight sometimes bothers my eyes | 50 | Parab | 430 | 56 | 44 | 6.78** | 0.69 | 415 | 57 | 43 | 8.97** | 3.32 | 344 | 60 | 40 | 14.24*** | 4.30* |
| | | WS-60U-C | 65 | 51 | 49 | 0.02 | | 76 | 46 | 54 | 0.47 | | 59 | 46 | 54 | 0.42 | |
| 2. Direct sunlight sometimes makes me too hot | 50 | Parab | 431 | 56 | 44 | 6.52* | 0.01 | 415 | 58 | 42 | 11.47*** | 4.81* | 344 | 60 | 40 | 14.24*** | 0.74 |
| | | WS-60U-C | 65 | 55 | 45 | 0.75 | | 76 | 45 | 55 | 0.84 | | 59 | 54 | 46 | 0.42 | |
| 3. I can adjust a window blind when I want to | 50 | Parab | 427 | 37 | 63 | 28.85*** | 6.83 | 412 | 40 | 60 | 17.95*** | 3.89* | 342 | 40 | 60 | 12.74*** | 5.91* |
| | | WS-60U-C | 64 | 20 | 80 | 22.56*** | | 76 | 28 | 72 | 15.21*** | | 59 | 24 | 76 | 16.29*** | |

*Note.* Parab: Parabolic-louvered luminaires. WS-60U: Workstation-specific luminaires, 60% uplight, individually controllable. All normative comparisons, $X^2$ df = 1 and between-groups $X^{2,}$ df = 1.. * $p$<.05; ** $p$<.01; *** $p$<.001.

***Table A3.*** *Comparison L2A — Office Lighting Survey results, comparing offices having PARAB and WS-76U luminaires, all with new furniture, at $T_0$ only.*

| | **Norm** | | **$T_0$** | | | | |
|---|---|---|---|---|---|---|---|
| **Item** | **Agree %** | **Group** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** |
| 1. Overall, the lighting | 69 | PARAB | 20 | 35 | 65 | 0.15 | 14.04*** |
| is comfortable. | | WS-76U | 35 | 0 | 100 | 15.72*** | |
| 2. The lighting is uncomfortably bright for the | 16 | PARAB | 20 | 70 | 30 | 2.92 | 6.04* |
| tasks that I perform. | | WS-76U | 35 | 94 | 6 | 2.76 | |
| 3. The lighting is uncomfortably dim for | 14 | PARAB | 20 | 90 | 10 | 0.27 | 0.35 |
| the tasks that I perform. | | WS-76U | 35 | 94 | 6 | 2.00 | |
| 4. The lighting is poorly | 25 | PARAB | 20 | 75 | 25 | 0.00 | 9.63** |
| distributed here. | | WS-76U | 35 | 100 | 0 | 11.67*** | |
| 5. The lighting causes deep | 15 | PARAB | 20 | 90 | 10 | 0.39 | 3.63 |
| shadows. | | WS-76U | 35 | 100 | 0 | 6.18* | |
| 6. Reflections from the light | 19 | PARAB | 20 | 85 | 15 | 0.21 | 5.55* |
| fixtures hinder my work. | | WS-76U | 35 | 100 | 0 | 8.21** | |
| 7. The light fixtures are too | 14 | PARAB | 19 | 68 | 32 | 4.88* | 9.00** |
| bright. | | WS-76U | 35 | 97 | 3 | 3.61 | |
| 8. My skin is an unnatural | 9 | PARAB | 20 | 90 | 10 | 0.02 | 3.63 |
| tone under the lighting. | | WS-76U | 35 | 100 | 0 | 3.46 | |
| 9. The lights flicker | 4 | PARAB | 20 | 90 | 10 | 1.88 | 3.63 |
| throughout the day. | | WS-76U | 35 | 100 | 0 | 1.46 | |

| **Item** | **Norm** | **Group** | **N** | **-1 %** | **0 %** | **+1 %** | **$X^2$** | **$X^2$ BG** |
|---|---|---|---|---|---|---|---|---|
| 10. How does the lighting compare to similar | 19/60/22 | PARAB | 20 | 10 | 55 | 35 | 2.47 | 9.78** |
| workplaces in other buildings? | | WS-76U | 35 | 0 | 26 | 74 | 57.00*** | |

*Note.* For question 10, -1 = Worse; 0 = Same; +1 = Better. For questions 1 through 9, all normative comparison $X^2$ , df = 1 and between-groups $X^2$, df = 1. For question 10, normative comparison df = 2 and between-group df = 2. * *p*<.05; ** *p*<.01; *** *p*<.001.

***Table A4****. Comparison L2A — Satisfaction with windows & daylighting, results, comparing offices having PARAB and WS-76U luminaires, all with new furniture, at $T_0$ only.*

| | **Norm** | | **$T_0$** | | | | |
|---|---|---|---|---|---|---|---|
| **Item** | **Agree %** | **Group** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** |
| 1. Direct sunlight sometimes | 50 | PARAB | 20 | 65 | 35 | 1.80 | 0.95 |
| bothers my eyes | | WS-76U | 35 | 51 | 49 | 0.03 | |
| 2. Direct sunlight sometimes | 50 | PARAB | 20 | 60 | 40 | 0.80 | 0.04 |
| makes me too hot | | WS-76U | 35 | 57 | 43 | 0.71 | |
| 3. I can adjust a window blind | 50 | PARAB | 20 | 35 | 65 | 1.80 | 0.53 |
| when I want to | | WS-76U | 35 | 26 | 74 | 8.26** | |

*Note.*. All normative comparisons, $X^2$ df = 1 and between-groups $X^2$, df = 1.. * *p*<.05; ** *p*<.01; *** *p*<.001.

***Table A5.*** *Comparison L2B — Office Lighting Survey results, comparing offices having new furnishings and luminaires, but different luminaire operation; data from $T_2$ only.*

| | Norm | | $T_2$ | | | | |
|---|---|---|---|---|---|---|---|
| **Item** | **Agree %** | **Group** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** |
| 1. Overall, the lighting is comfortable. | 69 | WS-76U-C | 46 | 0 | 100 | 20.67*** | 9.54** |
| | | WS-81U-C | 48 | 19 | 81 | 3.37 | |
| 2. The lighting is uncomfortably bright for the tasks that I perform. | 16 | WS-76U-C | 46 | 96 | 4 | 4.65* | 2.84 |
| | | WS-81U-C | 48 | 85 | 15 | 0.07 | |
| 3. The lighting is uncomfortably dim for the tasks that I perform. | 14 | WS-76U-C | 46 | 96 | 4 | 3.56 | 2.00 |
| | | WS-81U-C | 48 | 88 | 13 | 0.09 | |
| 4. The lighting is poorly distributed here. | 25 | WS-76U-C | 46 | 89 | 11 | 4.90* | 0.29 |
| | | WS-81U-C | 48 | 85 | 15 | 2.78 | |
| 5. The lighting causes deep shadows. | 15 | WS-76U-C | 46 | 91 | 9 | 1.43 | 0.81 |
| | | WS-81U-C | 48 | 96 | 4 | 4.42* | |
| 6. Reflections from the light fixtures hinder my work. | 19 | WS-76U-C | 46 | 93 | 7 | 4.65* | 0.00 |
| | | WS-81U-C | 48 | 94 | 6 | 5.07* | |
| 7. The light fixtures are too bright. | 14 | WS-76U-C | 46 | 96 | 4 | 3.56 | 0.62 |
| | | WS-81U-C | 48 | 92 | 8 | 1.28 | |
| 8. My skin is an unnatural tone under the lighting. | 9 | WS-76U-C | 46 | 96 | 4 | 1.22 | 0.17 |
| | | WS-81U-C | 48 | 94 | 6 | 0.44 | |
| 9. The lights flicker throughout the day. | 4 | WS-76U-C | 46 | 100 | 0 | 1.92 | |
| | | WS-81U-C | 47 | 100 | 0 | 1.96 | |

| **Item** | **Norm** | **Group** | **N** | **-1 %** | **0 %** | **+1 %** | **$X^2$** | **$X^2$ BG** |
|---|---|---|---|---|---|---|---|---|
| 10. How does the lighting compare to similar workplaces in other buildings? | 19/60/22 | WS-76U-C | 45 | 2 | 20 | 78 | 82.30*** | 2.58 |
| | | WS-81U-C | 48 | 4 | 33 | 63 | 47.03*** | |

*Note.* For question 10, -1 = Worse; 0 = Same; +1 = Better. For questions 1 through 9, all normative comparison $X^2$ , df = 1 and between-groups $X^{2,}$ df = 1. For question 10, normative comparison df = 2 and between-group df = 2. * *p*<.05; ** *p*<.01; *** *p*<.001.

***Table A6.*** *Comparison L2B — Satisfaction with windows & daylighting, results, comparing offices having new furnishings and luminaires, but different luminaire operation; data from $T_2$ only.*

| | Norm | | $T_2$ | | | | |
|---|---|---|---|---|---|---|---|
| **Item** | **Agree %** | **Group** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** |
| 1. Direct sunlight sometimes bothers my eyes | 50 | WS-76U-C | 46 | 43 | 57 | 0.78 | 1.53 |
| | | WS-81U-C | 48 | 56 | 44 | 0.75 | |
| 2. Direct sunlight sometimes makes me too hot | 50 | WS-76U-C | 46 | 37 | 63 | 3.13 | 1.15 |
| | | WS-81U-C | 48 | 48 | 52 | 0.08 | |
| 3. I can adjust a window blind when I want to | 50 | WS-76U-C | 46 | 37 | 63 | 3.13 | 0.45 |
| | | WS-81U-C | 48 | 44 | 56 | 0.75 | |

*Note.*. All normative comparisons, $X^2$ df = 1 and between-groups $X^{2,}$ df = 1.. * *p*<.05; ** *p*<.01; *** *p*<.001.

***Table A7**. Comparison C1A — Office Lighting Survey results, comparing offices in Building 3 (similar luminaire operation, different furnishings), without and with individual control over lighting; data from $T_0$ only.*

| | Norm | | $T_0$ | | | | |
|---|---|---|---|---|---|---|---|
| **Item** | **Agree %** | **Group** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** |
| 1. Overall, the lighting is comfortable. | 69 | WS-76U | 35 | 0 | 100 | 15.72*** | 1.59 |
| | | WS-60U-C | 68 | 4 | 96 | 22.47*** | |
| 2. The lighting is uncomfortably bright for the tasks that I perform. | 16 | WS-76U | 35 | 94 | 6 | 2.76 | 0.09 |
| | | WS-60U-C | 69 | 96 | 4 | 6.97** | |
| 3. The lighting is uncomfortably dim for the tasks that I perform. | 14 | WS-76U | 35 | 94 | 6 | 2.00 | 0.00 |
| | | WS-60U-C | 69 | 94 | 6 | 3.86* | |
| 4. The lighting is poorly distributed here. | 25 | WS-76U | 35 | 100 | 0 | 11.67*** | 3.87** |
| | | WS-60U-C | 68 | 90 | 10 | 7.84** | |
| 5. The lighting causes deep shadows. | 15 | WS-76U | 35 | 100 | 0 | 6.18* | 1.57 |
| | | WS-60U-C | 69 | 96 | 4 | 6.14* | |
| 6. Reflections from the light fixtures hinder my work. | 19 | WS-76U | 35 | 100 | 0 | 8.21** | 0.51 |
| | | WS-60U-C | 69 | 99 | 1 | 13.81*** | |
| 7. The light fixtures are too bright. | 14 | WS-76U | 35 | 97 | 3 | 3.61 | 0.24 |
| | | WS-60U-C | 69 | 99 | 1 | 9.03** | |
| 8. My skin is an unnatural tone under the lighting. | 9 | WS-76U | 35 | 100 | 0 | 3.46 | 0.51 |
| | | WS-60U-C | 69 | 99 | 1 | 4.80* | |
| 9. The lights flicker throughout the day. | 4 | WS-76U | 35 | 100 | 0 | 1.46 | 1.57 |
| | | WS-60U-C | 69 | 96 | 4 | 0.02 | |

| **Item** | **Norm** | **Group** | **N** | **-1 %** | **0 %** | **+1 %** | **$X^2$** | **$X^2$ BG** |
|---|---|---|---|---|---|---|---|---|
| 10. How does the lighting compare to similar workplaces in other buildings? | 19/60/22 | WS-76U | 35 | 0 | 26 | 74 | 57.00*** | 2.25 |
| | | WS-60U-C | 69 | 6 | 28 | 67 | 81.02*** | |

*Note.* For question 10, -1 = Worse; 0 = Same; +1 = Better. For questions 1 through 9, all normative comparison $X^2$, df = 1 and between-groups $X^{2,}$ df = 1. For question 10, normative comparison df = 2 and between-group df = 2. * $p$<.05; ** $p$<.01; *** $p$<.001.

***Table A8.** Comparison C1A — Satisfaction with windows & daylighting, results, comparing offices in Building 3 (similar luminaire operation, different furnishings), without and with individual control over lighting.*

| | Norm | | $T_0$ | | | | |
|---|---|---|---|---|---|---|---|
| **Item** | **Agree %** | **Group** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** |
| 1. Direct sunlight sometimes bothers my eyes | 50 | WS-76U | 35 | 51 | 49 | 0.03 | 0.01 |
| | | WS-60U-C | 69 | 52 | 48 | 0.13 | |
| 2. Direct sunlight sometimes makes me too hot | 50 | WS-76U | 35 | 57 | 43 | 0.71 | 0.00 |
| | | WS-60U-C | 69 | 57 | 43 | 1.17 | |
| 3. I can adjust a window blind when I want to | 50 | WS-76U | 35 | 26 | 74 | 8.26** | 0.17 |
| | | WS-60U-C | 68 | 22 | 78 | 21.24*** | |

*Note.*. All normative comparisons, $X^2$ df = 1 and between-groups $X^{2,}$ df = 1.. * $p$<.05; ** $p$<.01; *** $p$<.001.

***Table A9.** Comparison C1B — Office Lighting Survey results, comparing offices with new furnishings and luminaires (different luminaire operation) without and with individual control over lighting; $T_0$ data only.*

| | Norm | | $T_0$ | | | | |
|---|---|---|---|---|---|---|---|
| **Item** | **Agree %** | **Group** | **N** | **Disagree %** | **Agree %** | $X^2$ | $X^2$ **BG** |
| 1. Overall, the lighting | 69 | WS-76U | 35 | 0 | 100 | 15.72*** | 0.20 |
| is comfortable. | | WS-81U-C | 61 | 3 | 97 | 21.92*** | |
| 2. The lighting is uncomfortably bright for the | 16 | WS-76U | 35 | 94 | 6 | 2.76 | 0.03 |
| tasks that I perform. | | WS-81U-C | 61 | 92 | 8 | 2.76 | |
| 3. The lighting is uncomfortably dim for | 14 | WS-76U | 35 | 94 | 6 | 2.00 | 1.19 |
| the tasks that I perform. | | WS-81U-C | 61 | 93 | 7 | 2.81 | |
| 4. The lighting is poorly | 25 | WS-76U | 35 | 100 | 0 | 11.67*** | 1.17 |
| distributed here. | | WS-81U-C | 60 | 97 | 3 | 15.02*** | |
| 5. The lighting causes deep | 15 | WS-76U | 35 | 100 | 0 | 6.18* | 0.58 |
| shadows. | | WS-81U-C | 61 | 97 | 3 | 6.57* | |
| 6. Reflections from the light | 19 | WS-76U | 35 | 100 | 0 | 8.21** | 0.01 |
| fixtures hinder my work. | | WS-81U-C | 61 | 98 | 2 | 11.95*** | |
| 7. The light fixtures are too | 14 | WS-76U | 35 | 97 | 3 | 3.61 | |
| bright. | | WS-81U-C | 61 | 97 | 3 | 5.82* | |
| 8. My skin is an unnatural | 9 | WS-76U | 35 | 100 | 0 | 3.46 | 0.59 |
| tone under the lighting. | | WS-81U-C | 61 | 100 | 0 | 6.03* | |
| 9. The lights flicker | 4 | WS-76U | 35 | 100 | 0 | 1.46 | 0.20 |
| throughout the day. | | WS-81U-C | 60 | 98 | 2 | 0.85 | |

| **Item** | **Norm** | **Group** | **N** | **-1 %** | **0 %** | **+1 %** | $X^2$ | $X^2$ **BG** |
|---|---|---|---|---|---|---|---|---|
| 10. How does the lighting compare to similar | 19/60/22 | WS-76U | 35 | 0 | 26 | 74 | 57.00*** | 0.01 |
| workplaces in other buildings? | | WS-81U-C | 60 | 0 | 27 | 73 | 94.38*** | |

*Note.* For question 10, -1 = Worse; 0 = Same; +1 = Better. For questions 1 through 9, all normative comparison $X^2$, df = 1 and between-groups $X^2$, df = 1. For question 10, normative comparison df = 2 and between-group df = 2. * $p$<.05; ** $p$<.01; *** $p$<.001.

***Table A10.** Comparison C1B — Satisfaction with windows & daylighting, results, comparing offices with new furnishings and luminaires (different luminaire operation) without and with individual control over lighting; $T_0$ data only.*

| | Norm | | $T_0$ | | | | |
|---|---|---|---|---|---|---|---|
| **Item** | **Agree %** | **Group** | **N** | **Disagree %** | **Agree %** | $X^2$ | $X^2$ **BG** |
| 1. Direct sunlight sometimes | 50 | | 35 | 51 | 49 | 0.03 | 1.08 |
| bothers my eyes | | | 61 | 62 | 38 | 3.69 | |
| 2. Direct sunlight sometimes | 50 | | 35 | 57 | 43 | 0.71 | 0.27 |
| makes me too hot | | | 60 | 52 | 48 | 0.07 | |
| 3. I can adjust a window blind | 50 | | 35 | 26 | 74 | 8.26** | 0.00 |
| when I want to | | | 61 | 26 | 74 | 13.79*** | |

*Note.* All normative comparisons, $X^2$ df = 1 and between-groups $X^2$, df = 1.. * $p$<.05; ** $p$<.01; *** $p$<.001.

***Table A11.*** *Comparison C2 — Office Lighting Survey results, comparing offices having new furnishings, the same luminaire and operation, without and with individual control; $T_1$ data only.*

| | Norm | | $T_1$ | | | | |
|---|---|---|---|---|---|---|---|
| **Item** | **Agree %** | **Group** | **N** | **Disagree %** | **Agree %** | $X^2$ | $X^2$ **BG** |
| 1. Overall, the lighting is comfortable. | 69 | WS-81U | 18 | 22 | 78 | 0.65 | 0.41 |
| | | WS-81U-C | 21 | 14 | 86 | 2.74 | |
| 2. The lighting is uncomfortably bright for the tasks that I perform. | 16 | WS-81U | 18 | 94 | 6 | 1.46 | 0.01 |
| | | WS-81U-C | 21 | 95 | 5 | 1.97 | |
| 3. The lighting is uncomfortably dim for the tasks that I perform. | 14 | WS-81U | 18 | 83 | 17 | 0.11 | 0.44 |
| | | WS-81U-C | 21 | 90 | 10 | 0.35 | |
| 4. The lighting is poorly distributed here. | 25 | WS-81U | 18 | 83 | 17 | 0.67 | 0.44 |
| | | WS-81U-C | 21 | 90 | 10 | 2.68 | |
| 5. The lighting causes deep shadows. | 15 | WS-81U | 18 | 89 | 11 | 0.21 | 2.46 |
| | | WS-81U-C | 21 | 100 | 0 | 3.71 | |
| 6. Reflections from the light fixtures hinder my work. | 19 | WS-81U | 16 | 100 | 0 | 3.75 | |
| | | WS-81U-C | 21 | 100 | 0 | 4.93* | |
| 7. The light fixtures are too bright. | 14 | WS-81U | 18 | 94 | 6 | 1.07 | 0.21 |
| | | WS-81U-C | 21 | 90 | 10 | 0.35 | |
| 8. My skin is an unnatural tone under the lighting. | 9 | WS-81U | 18 | 94 | 6 | 0.26 | 1.20 |
| | | WS-81U-C | 21 | 100 | 0 | 2.08 | |
| 9. The lights flicker throughout the day. | 4 | WS-81U | 18 | 89 | 11 | 2.37 | 0.09 |
| | | WS-81U-C | 21 | 86 | 14 | 5.79* | |

| **Item** | **Norm** | **Group** | **N** | **-1 %** | **0 %** | **+1 %** | $X^2$ | $X^2$ **BG** |
|---|---|---|---|---|---|---|---|---|
| 10. How does the lighting compare to similar workplaces in other buildings? | 19/60/22 | WS-81U | 17 | 18 | 24 | 59 | 14.26*** | 2.29 |
| | | WS-81U-C | 21 | 10 | 10 | 81 | 43.08*** | |

*Note.* For question 10, -1 = Worse; 0 = Same; +1 = Better. For questions 1 through 9, all normative comparison $X^2$ , df = 1 and between-groups $X^{2,}$ df = 1. For question 10, normative comparison df = 2 and between-group df = 2. * *p*<.05; ** *p*<.01; *** *p*<.001.

***Table A12****. Comparison C2 — Satisfaction with windows & daylighting results, comparing offices having new furnishings, the same luminaire and operation, without and with individual control; $T_1$ data only.*

| | Norm | | $T_1$ | | | | |
|---|---|---|---|---|---|---|---|
| **Item** | **Agree %** | **Group** | **N** | **Disagree %** | **Agree %** | $X^2$ | $X^2$ **BG** |
| 1. Direct sunlight sometimes bothers my eyes | 50 | WS-81U | 18 | 50 | 50 | 0.00 | 0.56 |
| | | WS-81U-C | 21 | 62 | 38 | 1.19 | |
| 2. Direct sunlight sometimes makes me too hot | 50 | WS-81U | 18 | 50 | 50 | 0.00 | 1.11 |
| | | WS-81U-C | 21 | 67 | 33 | 2.33 | |
| 3. I can adjust a window blind when I want to | 50 | WS-81U | 18 | 44 | 56 | 0.22 | 0.35 |
| | | WS-81U-C | 20 | 35 | 65 | 1.80 | |

*Note*. All normative comparisons, $X^2$ df = 1 and between-groups $X^{2,}$ df = 1.. * *p*<.05; ** *p*<.01; *** *p*<.001.

***Table A13.*** *Comparison F1 — Office Lighting Survey results, comparing Old and New furniture groups in Building 3 (similar luminaires, same operation; all with individual control), at $T_1$ and $T_2$*

| | Norm | | $T_1$ | | | | | $T_2$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Agree %** | **Group** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** |
| 1. Overall, the lighting is comfortable. | 69 | Old | 80 | 5 | 75 | 22.91*** | 1.26 | 63 | 5 | 95 | 20.28*** | 2.25 |
| | | New | 50 | 1 | 49 | 19.66*** | | 46 | 0 | 100 | 20.67*** | |
| 2. The lighting is uncomfortably. bright for the tasks that I perform | 16 | Old | 80 | 76 | 4 | 7.20** | 2.58 | 63 | 92 | 8 | 3.05 | 0.57 |
| | | New | 50 | 50 | 0 | 9.52** | | 46 | 96 | 4 | 4.65* | |
| 3. The lighting is uncomfortably dim for the tasks that I perform. | 14 | Old | 80 | 70 | 10 | 0.15 | 0.65 | 63 | 92 | 8 | 1.92 | 0.57 |
| | | New | 50 | 46 | 4 | 1.50 | | 46 | 96 | 4 | 3.56 | |
| 4. The lighting is poorly distributed here. | 25 | Old | 80 | 73 | 7 | 11.27*** | 0.29 | 62 | 89 | 11 | 6.22* | 0.00 |
| | | New | 49 | 46 | 3 | 9.31** | | 46 | 89 | 11 | 4.90* | |
| 5. The lighting causes deep shadows. | 15 | Old | 80 | 75 | 5 | 4.80* | 0.31 | 63 | 94 | 6 | 3.70 | 0.22 |
| | | New | 50 | 48 | 2 | 4.75* | | 46 | 91 | 9 | 1.43 | |
| 6. Reflections from the light fixtures hinder my work. | 19 | Old | 80 | 77 | 3 | 12.09*** | 0.32 | 63 | 97 | 3 | 10.25** | 0.68 |
| | | New | 50 | 49 | 1 | 9.39** | | 46 | 93 | 7 | 4.65* | |
| 7. The light fixtures are too bright. | 14 | Old | 80 | 78 | 2 | 8.79** | 1.27 | 63 | 97 | 3 | 6.13* | 0.10 |
| | | New | 50 | 50 | 0 | 8.14** | | 46 | 96 | 4 | 3.56 | |
| 8. My skin is an unnatural tone under the lighting. | 9 | Old | 80 | 80 | 0 | 7.91* | 1.61 | 63 | 90 | 10 | 0.02 | 1.05 |
| | | New | 50 | 49 | 1 | 2.99 | | 46 | 96 | 4 | 1.22 | |
| 9. The lights flicker throughout the day. | 4 | Old | 80 | 79 | 1 | 1.58 | 0.62 | 63 | 94 | 6 | 0.91 | 3.03 |
| | | New | 49 | 49 | 0 | 2.04 | | 46 | 100 | 0 | 1.92 | |

| **Item** | **Norm** | **Group** | N | -1 % | 0 % | +1 % | $X^2$ | $X^2$ BG. | N | -1 % | 0 % | +1 % | $X^2$ | $X^2$ BG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10. How does the lighting compare to similar workplaces in other buildings? | 19/60/22 | Old | 80 | 9 | 41 | 50 | 37.62*** | 6.85* | 63 | 8 | 48 | 44 | 20.09*** | 12.09** |
| | | New | 50 | 2 | 26 | 72 | 74.06*** | | 45 | 2 | 20 | 78 | 82.30*** | |

*Note.* For question 10, -1 = Worse; 0 = Same; +1 = Better. For questions 1 through 9, all normative comparison $X^2$ , df = 1 and between-groups $X^{2,}$ df = 1. For question 10, normative comparison df = 2 and between-group df = 2. * *p*<.05; ** *p*<.01; *** *p*<.001.

***Table A14.*** *Comparison F1 — Satisfaction with windows & daylighting, comparing Old and New furniture groups in Building 3 (similar luminaires, same operation; all with individual control), at $T_1$ and $T_2$.*

| | Norm | | $T_1$ | | | | | $T_2$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Agree %** | **Group** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** | **N** | **Disagree %** | **Agree %** | **$X^2$** | **$X^2$ BG** |
| 1. Direct sunlight sometimes bothers my eyes | 50 | Old | 80 | 44 | 56 | 1.25 | 2.50 | 63 | 48 | 52 | 0.14 | 0.18 |
| | | New | 50 | 58 | 42 | 1.28 | | 46 | 43 | 57 | 0.78 | |
| 2. Direct sunlight sometimes makes me too hot | 50 | Old | 80 | 45 | 55 | 0.80 | 0.01 | 63 | 52 | 48 | 0.14 | 2.55 |
| | | New | 50 | 44 | 56 | 0.72 | | 46 | 37 | 63 | 3.13 | |
| 3. I can adjust a window blind when I want to | 50 | Old | 80 | 29 | 71 | 14.45*** | 1.24 | 63 | 22 | 78 | 19.44*** | 2.84 |
| | | New | 50 | 20 | 80 | 18.00*** | | 46 | 37 | 63 | 3.13 | |

*Note*. All normative comparisons, $X^2$ df = 1 and between-groups $X^{2,}$ df = 1.. * *p*<.05; ** *p*<.01; *** *p*<.001.

***Table A15.*** *Comparison R1 — Office Lighting Survey results, comparing offices in Buildings 1 and 2 at $T_2$ with either the pre-renovation or post-renovation furnishings and luminaires.*

| Item | Norm Agree % | Group | $T_2$ N | Disagree % | Agree % | $X^2$ | $X^2$ BG |
|---|---|---|---|---|---|---|---|
| 1. Overall, the lighting is comfortable. | 69 | Old | 373 | 18 | 82 | 27.25*** | 0.00 |
| | | New | 43 | 19 | 81 | 3.09 | |
| 2. The lighting is uncomfortably bright for the tasks that I perform. | 16 | Old | 373 | 90 | 10 | 10.26** | 0.68 |
| | | New | 43 | 86 | 14 | 0.13 | |
| 3. The lighting is uncomfortably dim for the tasks that I perform. | 14 | Old | 373 | 88 | 12 | 0.86 | 0.09 |
| | | New | 43 | 86 | 14 | 0.00 | |
| 4. The lighting is poorly distributed here. | 25 | Old | 372 | 77 | 23 | 0.52 | 1.11 |
| | | New | 43 | 84 | 16 | 1.74 | |
| 5. The lighting causes deep shadows. | 15 | Old | 372 | 89 | 11 | 5.26* | 1.58 |
| | | New | 43 | 95 | 5 | 3.61 | |
| 6. Reflections from the light fixtures hinder my work. | 19 | Old | 373 | 92 | 8 | 32.02*** | 0.02 |
| | | New | 43 | 93 | 7 | 4.04* | |
| 7. The light fixtures are too bright. | 14 | Old | 372 | 92 | 8 | 10.89*** | 0.06 |
| | | New | 43 | 93 | 7 | 1.76 | |
| 8. My skin is an unnatural tone under the lighting. | 9 | Old | 369 | 88 | 12 | 5.41* | 2.29 |
| | | New | 43 | 95 | 5 | 0.99 | |
| 9. The lights flicker throughout the day. | 4 | Old | 372 | 92 | 8 | 13.96*** | 3.52 |
| | | New | 42 | 100 | 0 | 1.75 | |

| Item | Norm | Group | N | -1 % | 0 % | +1 % | $X^2$ | $X^2$ BG |
|---|---|---|---|---|---|---|---|---|
| 10. How does the lighting compare to similar workplaces in other buildings? | 19/60/22 | Old | 368 | 17 | 68 | 16 | 11.25** | 57.42*** |
| | | New | 43 | 2 | 33 | 65 | 48.02*** | |

*Note.* For question 10, -1 = Worse; 0 = Same; +1 = Better. For questions 1 through 9, all normative comparison $X^2$, df = 1 and between-groups $X^2$, df = 1. For question 10, normative comparison df = 2 and between-group df = 2. * *p*<.05; ** *p*<.01; *** *p*<.001.

***Table A16.*** *Comparison R1 — Satisfaction with windows & daylighting results ,comparing offices in Buildings 1 and 2 at $T_2$ with either the pre-renovation or post-renovation furnishings and luminaires.*

| Item | Norm Agree % | Group | $T_0$ N | Disagree % | Agree % | $X^2$ | $X^2$ BG |
|---|---|---|---|---|---|---|---|
| 1. Direct sunlight sometimes bothers my eyes | 50 | Old | 373 | 60 | 40 | 14.29*** | 0.25 |
| | | New | 43 | 56 | 44 | 0.58 | |
| 2. Direct sunlight sometimes makes me too hot | 50 | Old | 373 | 61 | 39 | 16.73*** | 3.16 |
| | | New | 43 | 47 | 53 | 0.21 | |
| 3. I can adjust a window blind when I want to | 50 | Old | 371 | 40 | 60 | 14.36*** | 0.05 |
| | | New | 43 | 42 | 58 | 1.14 | |

*Note.* All normative comparisons, $X^2$ df = 1 and between-groups $X^2$, df = 1.. * *p*<.05; ** *p*<.01; *** *p*<.001.