The Impacts of Real-time Knowledge Based Personal Lighting Control on Energy Consumption, User Satisfaction and Task Performance in Offices

Yun Gu

School of Architecture
Carnegie Mellon University
Pittsburgh, PA 15213

Thesis Committee:
Volker Hartkopf (Chair)
Vivian Loftness
Richard Day

Submitted in fulfillment of the requirements
for the Degree of Doctor of Philosophy in Architecture

May 2011

© Yun Gu, 2011

ABSTRACT

Current building design and engineering practices emphasizing on energy conservation can be improved further by developing methods focusing on building occupants' needs and interests in conservation. Specifically, the resulting energy effective building performance improvements cannot reach the desired goals, if the resulting indoor environmental conditions do not meet thermal, visual and air quality needs of the occupants. To meet both energy conservation and human performance requirements simultaneously requires to give the occupants information regarding indoor environmental qualities and energy implications of possible individual decisions. This requires that building control components and systems must enable occupants to understand how the building operates and how their own actions meet both their needs and the energy and environmental goals of the building project.

The goal of the research and experiments of this dissertation is to explore if real-time information regarding visual comfort requirements to meet a variety of tasks and to simultaneously conserve energy, improves occupant behavior to meet both objectives. Two workplaces in Robert L. Preger Intelligent Workplace were equipped to test the performance of 60 invited participants in conducting computer based tasks and a paper based task, under three difference lighting controls:

1) Centralized lighting control with no user choice
2) User control of
    - blind positions for daylight shading
    - ceiling based lighting fixture luminance output level
    - task lighting: on/off
3) User control the three components (as listed under point 2 above), with provided simultaneous information regarding energy and related CO_2 emissions implications, appropriate light levels meeting tasks requirements, and best choices in order to meet both task requirements and energy conservation goals/objectives.

The main findings of the experiments are that real-time information (listed under point 3 above) enables users to meet the visual quality requirements for both computer tasks and the paper task, and to conserve significant amounts of electricity for lighting. Furthermore, the 60 invited participants were asked to identify the importance of the four types of provided information tested in point 3 above. While individual users identified the importance of different information categories, the overall assessment were considered to be significant.

Keywords: Individual control, knowledge based manual control, daylight, blind, ceiling luminaire, task light

Contents

Content of Figures:

Content of Tables:

ACKNOWLEDGEMENTS

I would first like to express my sincere thankfulness to Dr. Volker Hartkopf, my Ph.D thesis committee chair. Without you, Dr. Hartkopf, this dissertation would not have been possible. Thank you for your guidance, wisdom, kindly encouragement, and countless patience. Deep thanks also to Professor Vivian Loftness, who provided immense insight for incubating research ideas, helping presenting data and results, and improving my writing. I am very grateful for Dr. Richard Day who instructed the data analysis and helped me interpret the data innovatively in a scientific way. My deep appreciation also goes to Dr. David Archer who supported my research from all aspects and will be a mentor in my life always.

There are many others who contributed to the completion of this dissertation including all members in the Center for Building Performance and Diagnostics. I would like to thank Dr. Khee Poh Lam who gave supportive comments on improving experiment design. James Jarrett helped me on hardware design and wiring. Viraj Srivastava helped on LabVIEW program. Bing Dong gave me inspirations academically and spiritually. Rui Zhang encouraged on the research topic. I also appreciated the graduate students in Bio-statistics Department in University of Pittsburgh who gave useful inputs for the data analysis including Xiaojing Zheng, Dongwan Don Kang, and Zhen Jiang.

The completion of this dissertation would not have been possible without friendship, encouragement and prayer from my friends at Pittsburgh Chinese Church Oakland, in particular: Chunjie Gan, Dorothy Hsu, Yijen W. Lin, Judy Xi, Lingling Duan, Mei-Ru Ooi, and Huiping Xie. I would like to thank my parents for their endless love to support me to finish my Ph.D study during the years. Thank my dear parents for their patient. Finally, I want to express my gratitude for knowing Jesus and being a Christian during the Ph.D study, since when I found the grace and meanings in daily life.

Glossary

The terminology and abbreviations used in this dissertation are listed below:

Comfort

- a physiological experience of a pleasant sensation of thermal, visual, air quality, acoustic condition, as well as psychological, behavioral and social /collective experience. (Brown 2009)

Feedback

- a response that enables you to learn from what you are doing, or from what you and others have done, to understand where you are, and to inform and improve what you plan to do. Feedback can be considered a flow of information through a number of processes and scales over the lifetime of a building (Brown 2009).

Green building / high performance building

- the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle, from siting to design, construction, operation, maintenance, renovation and deconstruction. This practice expands and complements classical building design concerns of economy, utility, durability, and comfort. A green building is also considered a sustainable or high performance building (EIA 2010).

Knowledge-based

- based on real-time measurement of environmental parameters and energy demand which are presented to user in a understandable format.

Individual (manual) control

- ability for occupants to decide personal environment settings, e.g. illuminance level, blind position, temperature of the space.

Occupant/user

- the worker/ person who works in an office building

Post-occupancy evaluation (POE)

- integration of feedback about the level of the workplace's success in supporting the organizational and individual requirements and measurement of environment quality and energy consumption.

Chapter 1 Introduction

1.1 Motivation

1.1.1 Energy savings and greater occupant comfort

The building sector represents 70% of overall U.S. consumption of electricity and 40% of U.S. primary energy, thus efforts to reduce energy consumption are critical to creating sustainable economic development and protecting the natural environment. To date, these goals have emphasized high building performance objectives for optimized energy and resource efficiency, but the future must also account for advancing the health and wellbeing of occupants (Brown, 2009). Since its inception in 1998, the U.S. Green Building Council has grown to encompass more than 14,000 LEED (Leadership in Energy & Environmental Design) projects in the United States and 30 other countries (USGBC, 2010). While evidence from post-occupancy evaluations suggests that green buildings have the potential to enhance indoor environment quality, they still fall short of their full potential. Leaman and Bordass argue that occupant comfort and comfort-related behavior can impact building energy and environmental performance, particularly in green buildings which are thought to be "more fragile in their performance," where it is "more important that everything works well together" (Leaman and Bordass, 2007). Brown and Cole state that "while the availability and use of personal controls was found to be higher in green buildings, the quality of personal control in terms of responsiveness, the absense of immediate and relevant feedback, and poor user comprehension may have led to sub-optimal comfort conditions" (Brown and Cole, 2009). In 2000, Wyon suggests the importance of adopting a "3-I" principle to bring the user back into the control loop. "3-I" represents insight, information and influence (Wyon, 2000). He also said that "the user must understand the way that the building works and the consequences of their actions, so they must be given insight. They must learn to use the control delegated to them. As learning cannot take place without feedback, they must be given online information. Only when they have both insight and information can they be given influence." This dissertation intends to demonstrate the power that insight, information, and influence on reducing energy use, improving user comfort and enhancing idividual ability can have on task performance.

1.1.2 State-of-the-art of studies of occupant behavior in environment operation

A rich body of literature provides solid evidence of the benefits in the implementation of individual environment control in the past few decades. Since the late 1970s, after the first global energy crisis, researchers have documented the benefits of electricity or gas consumption feedback in terms of influencing energy-saving behavior, offering strong evidence of the positive correlation between frequent energy feedback and resource consumption reduction. In this century, building energy dashboards have been developed to give building occupant real-time and historic energy and water data (Lucid Design Group, 2010) (Dashboard, 2010). For example, at Oberlin College, Lucid Design's dashboard for dorm energy and water consumption resulted in a 32% savings in electricity and a 3% savings in water (Peterson, 2007). The gap between the research in field and laboratory studies reveals a need to demonstrate how providing users real-time knowledge and feedback can help achieve design-intended environmental quality, individual comfort, and energy performance.

1.1.3 Office Lighting

The visual environment plays a significant role in the health, mood and productivity of occupants. The efficient and effective design and operation of the visual environment will also support energy savings and waste reduction. A high performance visual environment demands successful integration of daylight without glare, appropriate interior furnishing and finishes, and high performance lighting and advanced controls. In addition, this dissertation contends that in order to understand control options and energy consequences, users need information. The decision to focus on lighting control alone rather than temperature and ventilation control was driven by nearly immediate responses by test subjects in visual settings, through user modification of blinds, ceiling lights and desk lamps.

In the modern world, at least 50% of the working population in developed countries is employed in an office setting (Conway, 2010). The design intention of office lighting environments is assurance of the most beneficial visual environment for task performance, personal comfort, aesthetics, health and safety. One of the main functions is to help user do tasks quickly, accurately and easily (Boyce P. R., 2003). Daylighting refers to the use of direct, redirected, or filtered daylight as a dominant or supplemental light resource for the building interior. Based on a serious of quantitative studies on the benefits of daylight in various types of buildings, Heschong drew the conclusion that daylight helps to improve school student scores, office worker productivity and retail sales (Heschong 2006; Heschong et al., 2002). A solid amount of research has revealed that office workers have a strong preference for daylight as a method for office lighting. These same studies indicate that workers would prefer to pay the price of having an overheated space and high degree of glare resulting from daylight (Langdon, 1966) (Cooper et al., 1973). Users would benefit from a daylighting system designed to provide enough daylight without any undesirable side effects (ABSIC/CBPD, 2004). Heat transfer through the window, glare control and variation of daylight level shall be carefully balanced.

A personalized space environment control provides the possibility to meet different preferences held by each user, whose satisfactory physical conditions may differ from the average recommended standardized condition (Newsham et al., 2009). The benefits of a personal satisfactory preference may not only include greater user satisfaction with the environment, but improved work performance (Baron and Thomley, 1994) and reduced energy consumption (Newsham et al., 2009). Boyce (Boyce et al., 2000) summarized three main desirable impacts resulting from allowing people to adjust illumination. People's preference to be able to lower the illumination level rather than working under fixed lighting contributes to energy savings and reduced utility costs. Different illumination levels required for different tasks can be met by user manipulation. Boyce also showed that users' moods may be improved by being given illumination control. In a survey done by Bordass et al, most office workers expressed a desire to have individual control and perceived improved comfort and enhanced productivity linked with such control (Bordass et al., 1993). A study by Steelcase done in 1999 showed that 75% of users wanted more control over the lighting in their environment (Steelcase, 1999). Personalized office lighting control has become even more necessary because of increased variety of office work. Compared to the middle of 20^{th} century, the nature of office work has changed dramatically, along with the introduction of personal computers and advanced information and communication technologies (Hua, 2007). The office lighting environment must meet a variety of needs based on the nature of work, e.g. paper-based, computer-based, small group discussion, and other types of tasks. Besides the fundamental aspects of office lighting design, making office lighting adaptable to different tasks becomes a key for a success. The same visual environment can be a stimulus or a distraction (Wyon, 2000). The ability to view the outside through a window, helping users release eye-stress, is appreciated by users doing long-term tasks. However, for urgent, short-term, stressful tasks that require 100% focus, window views and the consequence of having less privacy can be undesirable. Setting a monitor against a background with less illumination with would help users achieve greater focus on tasks and tire less easily. For paper-based work, bright lighting on a desktop helps raise levels of mental awareness.

1.2 Research objectives and approaches

This dissertation explores whether user control of office lighting and visual conditions, with real-time knowledge and feedback, contributes to better user satisfaction, energy efficiency and improved task performance. The hypotheses in this paper are tested based on human subject experiments aimed at identifying whether better user satisfaction, energy efficiency and improved task performance are achieved when users are given real-time knowledge and feedback on the suitability of light level, lighting power consumption with related carbon dioxide emission, and design intentions of the space. This dissertation is based on controlled laboratory studies with human subjects. A setting with multiple choices for user modification of the visual environment was created: blinds, task lights and ambient light. Three lighting controls were tested: fixed, manual control, and knowledge-based manual control. User behavior was observed. Task performance was tested. User satisfaction and energy consumption were recorded.

1.3 Dissertation structure and overview

This chapter covers the motivation for the dissertation, the physical attributes of a high performance visual environment, the known impacts of some of these contributions and an introduction to research objectives and approaches.

Chapter 2 summarizes a review of the existing literature on office visual environments and interactions in individualized office environment control. “Green technologies” for office lighting operation are reviewed, including daylight technologies and benefits, automatic and manual control of blinds, personalized control of ceiling lights, and separation of ambient light and task light. The second part of the chapter is an inclusive review exploring why the interaction between user and environmental control system is important, the impacts of knowledge and feedback on occupant manual control, in addition to up-to-date technologies supporting such interactions. Based on this review, three hypotheses and research questions are proposed.

Chapter 3 introduces the experimental design and test environment, together with the design of lighting control interface and algorithms.

Chapter 4 summarizes data analysis methods and statistical results. Each hypothesis was tested to explore user behavior, energy use, user satisfaction and task performance.

Chapter 5 summarizes conclusions of this study, linking energy consumption, user satisfaction and task performance to control with real-time knowledge and feedback. Contributions and limitations of this study and future work are discussed.

Chapter 2 Literature review

2.1 Office lighting environment

Visual quality is the integration of human needs, architecture, economics and the environment. An office lighting environment is meant to provide occupants comfort and enable them to work on a variety of office tasks. For occupant productivity, well-being, and energy efficiency, the Center for Building Performance and Diagnostics developed 7 guidelines for high performance lighting, including: maximizing the use of daylight with no glare, together with advanced control (eBIDS, 2004).

2.1.1 Daylighting in offices

Daylighting is the allowance of natural light into a space through a building façade or ceiling, helping to reduce or eliminate electric lighting usage (Ander, 2003). With glare free design and operation, daylight can help reduce lighting energy consumption by up to 65%. Office workers prefer to have daylight and views in their work spaces, helping to enhance their visual comfort and productivity. Controlling intense direct sunlight is key to ensuring comfort in daylit spaces, which makes shading important. Based on the installation location, there are 3 types: exterior shading, in-window-frame shading, and interior shading. Fixed exterior shading such as overhang, fixed louvers or fins are designed based on window size, space orientation and facility location to block direct sun light into the space. Dynamic shading devices such as blinds or light redirecting louvers can be adjusted to allow daylight into or block it from the space. Dynamic devices are more effective in creating a satisfying daylight environment.

To increase the energy efficiency of an electric lighting system, daylight responsive dimming is a key component. The technology uses a light sensor to monitor light level in a work area, based on which lamp lumen output is dimmed to maintain a certain illuminance level on the working surface. This system allows artificial light to respond to the amount of daylight in the space. The Federal Energy Management Program estimated that 30% of lighting energy consumption can be saved by automatic daylight dimming in private or open perimeter offices (FEMP, 2010). FEMP suggests a combination of task light with daylight dimming for more energy savings.

Beside the visual comfort benefit and lighting energy savings, integrated daylight control is critical for thermal comfort and reducing cooling energy consumption. The solar heating and cooling program at the International Energy Agency stated that lack of consideration for integration may cause the failure of a well designed system (IEA, 2005). In areas with predominantly warm weather, excessive solar heat from direct sunlight causes thermal discomfort and increased cooling energy. Well designed shading devices and control strategies can help reduce annual cooling energy by 5% - 15% (Prowler, 2008). Exterior shading is more effective in blocking solar heat from entering the space (Loutzenhiser et al., 2007). This dissertation will focus on how occupants use blinds to create a visually comforting environment. Blind related thermal comfort is considered, but will not be explored.

Some researchers believe natural human laziness favors automation in all possible aspects of life, which motivates the automated control of blinds for occupant comfort and energy efficiency. Automatic blind control is as favored by office occupants as manual blinds, or automatic blinds with user override (Inoue et al., 1988; Jain, 1998; Bordass, 1994). The application of automated blinds is in the preliminary development stage. Initially, control algorithms were as simple as schedule and orientation based, or single ;solar radiant threshold based (Newsham, 1994; Inoue et al., 1988; Leslie et al., 2005). Later, closed-loop algorithms integrated workplace illuminance, sun angle and other environmental parameters (Guillemin, 2001).

Newsham's study results revealed that occupants closed the blinds if solar energy was above $233 w/m^2$ and they remained closed until the next morning (Newsham, 1994). The simulated results showed that with manual control blinds, mean PPD (predicted percentage of occupants dissatisfied with the thermal environment) was lowered from

22% for no blinds control, to 13% for manual blinds control. Reduced solar gain lowered cooling energy by 7%, while heating energy increased by 17%, and lighting energy increased by 66%. Tzemplikos and Athienitis suggested that the major challenge for real time control is creating an algorithm to determine blind slat angle to reduce glare and heat gain, while at the same time maximizing daylight benefit in the space (Tzemplikos and Athienitis, 2002). They worked on daylight numerical simulations of an office space with an advanced double-glazing window with motorized high reflective blinds between the two glazings. The control algorithm first determined the optimum tilt angle of the blinds in order to transmit the maximum possible amount of daylight without causing glare. Then it determined the illuminance due to daylight at several points on a work surface. With dimmable electric lighting, the lighting energy could be reduced by 75% for an overcast day and over 90% for a clear day compared to a scheduled operation. The impact of the blinds' position on cooling or heating energy was not considered in this study. One simulation study of a south-facing office in Toronto, Canada concluded that the thermal comfort of an occupant close to the window was substantially improved by the provision of window blinds (Newsham, 1994). However, when the lighting was also manually controlled, the blinds imposed an energy penalty.

2.1.2 Automatic and manual control of blinds

Compared to the preliminary stage of automatic control of blinds, manual control of curtain or blinds has a centuries-long history. The record of use of venetian blinds goes as far back as the late eighteenth century (Manning, 1965). Even recently, very few studies have been done on how occupants manually control blinds. Galasiu and Veith reviewed studies of occupant preference and satisfaction in a luminous environment and control systems in a daylit office, which included studies comparing automatic shading control, manual shading control and integrated shading and lighting control. Some of the studies are summarized below (Galasiu and Veith, 2006).

Inoue did a field survey with 800 occupants in two high-rise buildings in Japan (Inoue, 1988). The blinds in the two buildings were automatically controlled based on a timer and solar radiation. During the working hours, the blinds reacted to 60w/m^2 solar radiation. The most common occupant opinion on automatic blinds was: "the blinds operate even when it is not required", followed by "the blinds do the work themselves", then by "the blinds do not operate when it is required".

Bordass did a user satisfaction survey in an office building in the UK installed with automatic blinds (Bordass, 1994). A large majority of people were annoyed mainly because the blinds were perceived to operate at the wrong time. The need to override automated settings is essential to most occupants.

Vine et al. did a study in a mock-up office with 14 office workers (Vine et al., 1998). The experiment was conducted in July. Most days were sunny. Each participant worked in the office for 3 continuous hours in 3 sessions of blind and light control conditions. In session 1, the participant manually set on/off/dimming operation of lighting and blinds. In session 2, an automatic operation integrated the control of lighting and blinds with designed space illuminance at 540-700 lux. The operation of blinds was designed to block direct sunlight. The lighting dimming level responded to compensate for insufficient daylight. Session 3 provided semi-automatic operation with user-preference settings of blinds and lights via a remote controller, allowing users to set indoor illuminance between 240 lux to 1650 lux. In the manual mode, 85% of participants expressed satisfaction with overall lighting conditions. The average light level was 1493±653 lux in the morning and 1030±248 lux in the afternoon, indicating that they preferred higher light levels than those set by the automated control system. The satisfaction rate was the lowest in the automatic blind control mode, where 57% of participants were satisfied with an average illuminance of 593 lux. In the semi-automatic operation condition, the overall user satisfaction rate was 78% with average illuminance of 683 lux.

Inkarojrit did a field survey with 113 office workers who sat within 15 feet of a window and had functional venetian blinds (Inkarojrit, 2006). He found that the control of direct and reflected glare on computer screen was the most frequent reason for users to close blinds. Glare was the reason given for 65% of the times that users closed the blind.

In general, the above studies agree that office occupants prefer manual blind controls or automatic controls with override rather than automatic blind controls with no override. Among these studies, façade surface illuminance, solar radiation, or working surface illuminance determine the movement of blinds. Most office occupants were not dissatisfied with the algorithm deciding when and how the blinds moved. Occupants usually prefer a higher illuminance level than that provided by the algorithm deciding when to close the blinds. With automatic blind control, personal preference could not be met. Another possible reason occupants do not like motorized blind control is that noise from a motor when opening or closing is more annoying compared to manual control. Most manual blinds are not equipped with motors and run quietly.

Meanwhile, a few other studies have observed how occupants control blinds and the related physical environmental conditions. Among the studies, one general conclusion is that office occupants tend to leave blinds in the same position until some disturbance happens, e.g. incoming glare or being overheated. Rubin studied manual blind control patterns in a private office with northern or southern façade orientation (Rubin et al., 1978). Occupants' re-set blinds more often in offices oriented to the south than in offices facing north. Only 50 of 700 observed windows were operated more than once per day. "Users' lack of passion to change a blind's position" is echoed by another study done by Pigg. In a study with 63 private offices, 36% of them never had blinds adjusted between February and May in 1995(Pigg et al., 1996). The most important trigger for occupants to adjust blinds is solar radiation or illuminance in an occupant's working zone, which is dependent upon façade orientation and sky conditions. Rea suggested that long-term perceptions of solar radiation are the key for occupants to set blind positions (Rea, 1984). The sky conditions, façade orientation and the interaction between them were statistically significant in predicting blind position. Lindsay and Littlefair investigated the operation of venetian blinds in 5 office buildings in the UK (Lindsay and Littlefair, 1993). They concluded that blinds were operated in response to amount of daylight and office orientations. Lindsay and Pigg made similar conclusions based on field observations (Lindsay, 1992; Pigg, 1996). The trigger for occupants to adjust blinds is to avoid glare rather than to reduce heat (Raja et al., 2001; Lindsay and Littlefair, 1993). Nicol conducted a study in office buildings in European countries (Nicol, 2001). He suggested that glare control is the primary function for occupants rather than temperature control. Inkarojrit did a field survey in offices for developing predictive venetian blind control models (Inkarojrit, 2006; Inkarojrit, 2005). The primary reason for occupants to adjust blinds is to reduce daylight glare, compared to which thermal comfort and visual privacy are subsidiary reasons.

There are other factors thay may influence occupants' modulation of blind position: visual privacy and visual exposure, views and access to environmental information (Collins, 1976; Heerwagen, 1990), age and gender, etc. Other effects, e.g. physical, physiological, psychological, social factors, etc. and interactions between them make the research of blind control complicated. Some studies found that there is no strong correlation between blind position and environmental conditions (Bülow-Hübe, 2001; Foster and Oreszczyn, 2001).

2.1.3 Personalized control of ceiling light

Manual lighting control had been used in offices for decades before building automation systems or energy management systems were introduced. Technologies for automatic lighting control include: clocks timed to turn on/off based on a predetermined schedule with user override; occupancy sensors that switch lights off when a space remains unoccupied for an extended period; and daylight compensation that dims space lighting from luminaires, responding to daylight from a window or skylight (ANSI/IESNA, 2004). But survey results consistently indicated that building occupants desire more control over their environment, including lighting. Manual control is equivalent to individual control unless a lighting system is wired for each individual office or each area in an open area with independent switches. In this study, individual lighting control implies that each occupant has control over light output from ceiling luminaires and task lights. Bordass did a survey study for multiple office buildings in the UK and found that greater occupant control of a space environment provided more self-estimated productivity (Bordass et al., 1993). Many other field and laboratory studies also demonstrated energy benefits linked with individual lighting controls.

There are three main benefits from individual lighting controls: 1) personal preference can be satisfied with individual control of illuminance; 2) energy savings can be achieved because there are always some occupants who choose illuminance lower than fixed light levels; 3) different requirements for illuminance to do various tasks, e.g. computer-based work, paper-based work, small group discussion, etc. can be easily achieved when occupants individually control lighting.

Personal preference

A wide range of luminaire outputs are selected by occupants when they have individual lighting controls (Moore et al., 2002). Occupants differ in their preference for electric light (Maniccia et al., 1999). The selection of illuminance for different tasks varies widely among individuals (Maniccia et al., 1999). Introducing individual lighting control improved users' ratings of mood, satisfaction and discomfort, but did not improve task performance (Newsham et al., 2004)

Energy savings

Occupants tend to select lower light levels than defined in standards, especially for computer based work (Slater, 1996). Moore studied occupants' manual control of general lighting in open-plan offices with daylight and concluded that users choose to illuminate a wide range of work surface light levels with an average 55% of maximum luminance capacity. Small control zoning was associated with lower luminaire output (Moore et al., 2002). Over 50% of occupants reported that they preferred to have a dimmer device located within their workstation, close to their keyboard or monitor (Maniccia et al., 1999). Boyce identified an average 10% lower luminaire output in individual lighting control compared to scheduled lighting control in windowless offices (Boyce et al., 2000). Manual dimmers alone can achieve 23% energy savings, while over 40% savings can be reached if used together with occupant sensing. Continuous dimming helps save more energy in a space with daylight compared to a space with no daylight (Jennings et al., 1999).

Illuminance requirement for different tasks

In a mock-up laboratory study, Boyce observed that occupants adjusted illuminance for different tasks (Boyce et al., 2000). Self-reported data showed that office occupants change lighting output 50% of the time due to working on computer-based tasks and 15% of the time due to reading printed material (Maniccia et al., 1999). No respondents chose "to save energy" as a reason for adjusting light output. The percentage of working time on a computer decided the average illuminance on the working plane (Moore et al., 2002).

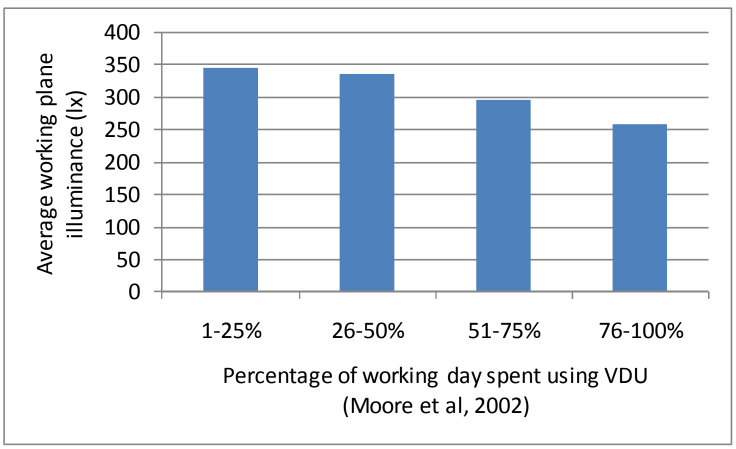

Figure 2.1.1 The relationship between work surface illuminance and timSe spent using computers

The benefits of individualized lighting control have been recognized in the last 10 years by industry and academia. Maniccia did a study with 58 occupants who worked in private offices with daylight (Maniccia et al., 1999). By cooperating with auto-restore motion sensors and manual light dimming, occupants' satisfaction was improved and wasted energy was reduced. Depending on office orientation, 7-23% savings can be achieved by manual dimming control compared to scheduling. Newsham did a between group measurement of individual control of lighting and ventilation compared to centralized control with no user options (Newsham et al., 2009). They found that 10% lighting energy savings were achieved with individual control. Boyce invited 18 temporary employees to work in three different lighting conditions in an office laboratory with no daylight (Boyce et al., 2000). The three lighting designs are: 1) max 1210 lux on a horizontal surface for individual control; 2) max 600 lux on a horizontal surface for individual control; 3) max 500 lux on a horizontal surface with no individual control. The results showed that the average illuminance in individual control is 10% lower than in a fixed system. Individual control relates to higher rated lighting quality and comfort, as well as lower user ratings for task difficulty. Moore did a field study of occupants in 14 open-plan office buildings in the United Kingdom. The occupants had either continuous dimming control or bi-level control for ceiling lights (Moore et al., 2002). The average light output was 50-60% of max light output. The pre-set switch lighting level strongly correlated with later output chosen by the occupants. The work surface illuminance is significantly related to the time that the occupant worked on the computer. Newsham did a repeated measurement study in an open plan office with 50 participants (Newsham et al., 2004). They concluded that individual control improved occupants' mood, room appraisal, satisfaction with lighting environment, glare dissatisfaction and self assessed productivity. Boyce did a between group comparison study in an open-plan office building (Boyce et al., 2006 a, b). 180 participants were divided into 4 groups with different lighting installation. Two of them were different lighting setups with no individual control. One allowed occupants to switch a 3-level desk lamp. One allowed occupants to dim a direct/indirect cubicle luminaire from 0-100% through a computer interface. A wide difference in illuminance choice was observed between individuals. Individual control brought over 90% rated comfort, compared to 80% with no control. Dimming of the ceiling light sustained more motivation and improved performance on a measurement of attention compared to staged-control of the desk lamp.

2.1.4 Separating ambient light and task light

Task-ambient separated lighting, helping to reduce lighting energy, is recommended by several office design guidelines and energy saving guidelines (ABSIC/CBPD, 2004; ANSI/IESNA, 2004; WBDG, 2009). It has been widely accepted that lighting energy can be reduced by lowering ambient light with compensation by local task light wherever higher illuminance is required. Tiller did a before and after study of replacing a centralized ambient ceiling luminaire with a locally switched indirect ceiling luminaire plus task light (Tiller et al., 1995). 75% energy savings were achieved. Veitch and Newsham compared a task-ambient lighting system and an ambient only lighting system in an office laboratory (Veitch and Newsham, 1998). They found 30-60% less lighting power used when people used the task-ambient system with no negative effect on occupant mood, satisfaction or task performance. Yamakawa conducted a mock-up study in an office with participants choosing task light levels at different given ambient light level at 200, 300, or 400 lux (Yamakawa et al., 2000). On average a 100 lux reduction in ambient lighting was compensated by a 30 lux increase in task lighting.

The benefits from task-ambient lighting were not consistently found in other scientific studies. The non-uniform luminance nature of task light may produce negative effects on occupants' visual comfort (McKennan and Parry, 1984). Newsham reported results from 2 laboratory office studies indicating that increased task lighting did reduce chosen ambient light output, but the reduction in lighting power was small, and only about the same as power drawn by the task light (Newsham et al., 2005). Newsham also suggested that participants did not dim ambient lighting further because they preferred to maintain illumination on non-task surfaces, and to avoid extreme luminance rations.

Though scientific research results are equivocal about benefits of task lighting, task-ambient light is provided to occupants in the experiment of this user oriented study. Given options for all control handles, occupants will make decisions on which options to use and how in order to achieve desired and comfortable illuminance for various tasks.

2.2 Knowledge and feedback in occupant manual control

2.2.1 Knowledge and feedback are important in occupant manual control

The benefits of personalized environment operation of thermal comfort, air quality, visual quality etc. have been recognized by building researchers and experts around the world. However, facility management staff members usually have concerns about occupant manual control. Their experience suggests that most building occupants might lack the knowledge to make the 'right' adjustments. They unintentionally or intentionally misuse or mis-set user side control devices because they don't get feedback from the system in time or they don't know how to set up comfortable conditions. It is very likely to cause dissatisfaction and energy waste. Brown conducted several post occupancy studies of green buildings and found that there were gaps between predicted energy performance and measured energy consumption, as well as gaps between assumed comfort level and actual comfort (Brown, 2009). One of the many reasons is that "while the availability and use of personal controls was higher in the green building, the quality of personal control in terms of responsiveness, the absence of immediate and relevant feedback, and poor user comprehension may have led to sub-optimal comfort conditions" (Brown and Cole, 2009). Occupants' comfort-related behaviours were not the same as predicted. Wyon suggested a "3-I" principle to "bringing the user back into the control loop" (Wyon, 2000). The "3-I" represents "insight", "information" and "influence". The user "must understand the way that the building works and the consequences of their actions, so they must be given insight… They must learn to use the control delegated to them, and as learning cannot take place without feedback. They must be given online information. Only when they have both insight and information can they be given influence." Without these three factors, individual control won't be a success. Wyon envisioned a future office where occupants can access building maintenance service. Meanwhile, the system will respond to occupant' requests, report current status, and record complaints.

2.2.2 Impacts of knowledge on occupant manual control

Brown defined "knowledge" as "occupants' awareness and understanding of building environmental features and control systems, gained through their immediate experience in the building and tempered by a broad range of influence such as tacit knowledge, context and culture" (Brown, 2009). Occupants need to be educated on how to use available user side controllers, devices or technologies to create a comfortable environment, as well as consider energy consumption. One general finding of post-occupancy evaluation studies is that tenants seldom receive a detailed explanation of the design intention of the space, the equipment and how the settings relate to energy when moving into an office (Brown andCole, 2008). Green buildings with passive design need more engagement with occupants to actively change space settings according to exterior conditions through opening/closing window and adjusting blind position. For example, opening a window will help reduce cooling and ventilation load when the mechanical system is off. If the mechanical ventilation system is running, opening a window causes an energy penalty. The indication of the on/off status of a mechanical system should be clearly presented to occupants along with the knowledge of the right time to open window.

Some room controllers are not designed to be easily understood. In a field study of office workers' reactions to lighting control, Escuyer determined that the complexity of a remote lighting controller made occupants under-exploit it (Escuyer et al., 2001). The Luxmate remote lighting controller made by Zumtobel has 10 buttons on the front. An illustration of each button's function is printed at the back. Although the on/off and dim buttons are straightforward for occupants to understand, the scene buttons and "a…e" buttons need a manual to explain how to use them. A control panel or screen designed for usability is key for a successful user-centered space environmental operation.

Figure 2.2.1 LUXMATE remote lighting controller

The location or accessibility of control devices is another important issue. Karjalainen and Koistinen interviewed 27 office workers in 12 buildings in Finland about how they used an individual temperature controller as thermostatic valve or room thermostat (Karjalainen and Koistinen, 2007). 75% of participants felt that temperature control was not clearly visible or not easily reachable. 40% of participants reported that they were bothered that the room thermostat did not give any feedback, or the feedback was confusing or misleading. A hidden thermostat has nothing to do with personalized space temperature control. Maniccia asked about preferred dimmer location in private office lighting control (Maniccia et al., 1999). 60% of respondents selected "within their working area", e.g., close to their keyboard or computer monitor. 29% respondents had no preference. Only 11% selected "at the door."

2.2.3 Impacts of feedback on occupant manual control

The term of feedback describes situations where outcome from moment "n" will influence an occurrence of the same event/phenomenon in moment "n+1". Bordass defined feedback in individual control as "learning from what you are doing, or from what you and others have done, to understand where you are, and to inform and improve what you are about to do" (Bordass et al., 2006). Feedback can be considered as information flow through a number of processes and scales over the lifetime of a building (Brown, 2009). Through feedback, occupant will be aware of design intention, historical environmental and energy performance, and current and expected environmental and energy performance.

Matthies developed a heuristic model based on environmental psychology theories and findings for explaining why and how feedback on electric consumption works on customers to reduce consumption (Figure 2.2.2) (Matthies, 2005). The model shows that occupants' habits must be broken up through the process of norm activation, motivation and evaluation so as to encourage more sustainable behavior. Feedback information will help to raise occupant consciousness of environmental problems, relevance of specific behavior and possible control choices. Furthermore, feedback can play a role in motivating occupants through competition between peers, social network, cost and benefits etc.

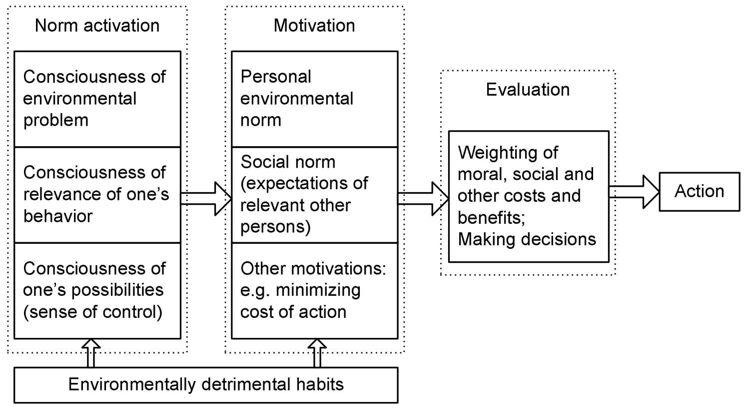

Figure 2.2.2 Matthies 2005 heuristic model of environmentally relevant behavior

One barrier to changing consumption habits is educating general citizenry on the links between daily actions, such as turning on/off lighting, increasing/decreasing room temperature set point opening/closing windows, and the energy consumption and emissions generated from those actions. Most people still do not link their behavior with ecological impact in their mind (Mankoff et al., 2010). With knowledge of this link, people can make better decisions about their actions to minimize their environmental impact. Bamberg pointed out that the weak direct relationship between general environmental concern and specific environmental behaviors is due to an inadequate understanding of how general attitudes influence specific behavior (Bamberg, 2003). He surveyed 380 university students about how acquiring information about green electricity products and the local providers of these products influenced their buying behaviors. The results confirmed that general attitudes like environmental concern cannot influence specific behavior directly. Only the situation-specific cognitions concerning the salient consequences associated with a specific behavior are direct determinants of a specific behavior.

A rich body of studies has been done in residential buildings regarding correlation between feedback of electric or gas consumption and householders' energy usage. Fischer reviewed 15 studies on the influence of giving households feedback on their electricity consumption, with the conclusion that the top three characteristics in successful feedback are “actual consumption”, “frequent feedback” and “involving interaction and choice for households” (Fischer, 2007). Ideally, feedback shall be given immediately after every energy related behavior happens (Geller, 2002). Abrahamse reviewed intervention studies on household energy conservation. He agreed that frequent feedback on energy consumption had positive effects on energy savings (Abrahamse et al., 2005). Providing occupants with feedback on energy consumption, together with saving goals, contributed to significant electric or gas usage reduction. Van Houwelingen and van Raaij did a field study in residential buildings in New Jersey (van Houwelingen and van Raaij, 1989). A 12.3% reduction in natural gas usage was achieved by giving users daily gas consumption feedback, compared to 7.7% saving achieved by those who had received monthly feedback. After stopping the feedback and goal setting for one year, there was no significant difference between the experiment group and controlled baseline group. Peterson examines how different resolutions of socio-technical feedback, combined with incentives, encourage students to reduce resources (Peterson et al., 2007). They introduced an automated data monitoring system to display real-time energy and water usage in the dorm. With feedback, education and incentives, a 32% reduction in electricity was recognized by field measurement, while there was a 3% reduction in usage of water.

Most energy feedback studies were done for residential buildings. There is not much field or laboratory research directly targeting how feedback information changes user environmental behavior in office spaces. Some office survey studies revealed that office occupants were rarely aware of conserving resource. Maniccia did a study of occupant use of manual lighting controls in daylit private offices (Maniccia et al., 1999). When asked about their primary reason for adjusting lighting, 65% of those surveyed selected “for different requirements of computer work or paper work”. 23% selected “to compensate for daylight”. Not one selected “to save energy” as the reason for adjusting light. Without knowledge of environmental quality and energy consumption, most occupants do not spontaneously make ‘right/green’ choices in setting space environmental conditions. One example is that Leslie found that occupants alter blind positions only when they are exposed to extreme discomfort, with no consideration of visual or thermal quality and energy conservation (Leslie et al., 2005).

2.2.4 Technologies supporting interaction between occupants and building systems

Interactivity between a system and occupants makes the system a persuader for changing occupants' behavior, attitude, motivation, and more. Information and communication technologies play an important role in assisting individuals to be in the interactive loop of building control. The technologies provide solutions for data exchange between occupants and building management systems or automation systems. Mattern demonstrated an eMeter system communicating interactively between smart metering and a portable user interface (Mattern et al., 2010). The system consists of three independent components: metering/measurement, a gateway and a portable user interface (Figure 2.2.4). Petersen illustrated a pathway of data flow and an information feedback diagram for an Oberlin college dormitory study. User received environmental education and would get awards for conservation. Real-time and historical energy consumption could be monitored from a website. Karjalainen developed a prototype interface for user-centered room temperature control and tested it on 42 human subjects (Karjalainen et al., 2007). The feedback on time taken to reach desired temperature got positive comments from participants due to the relatively long response time of space temperature (Figure 2.2.5).

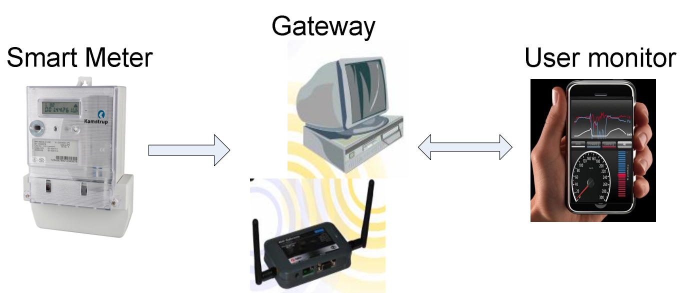

Figure 2.2.3: Smart meter communicating with the mobile user interface

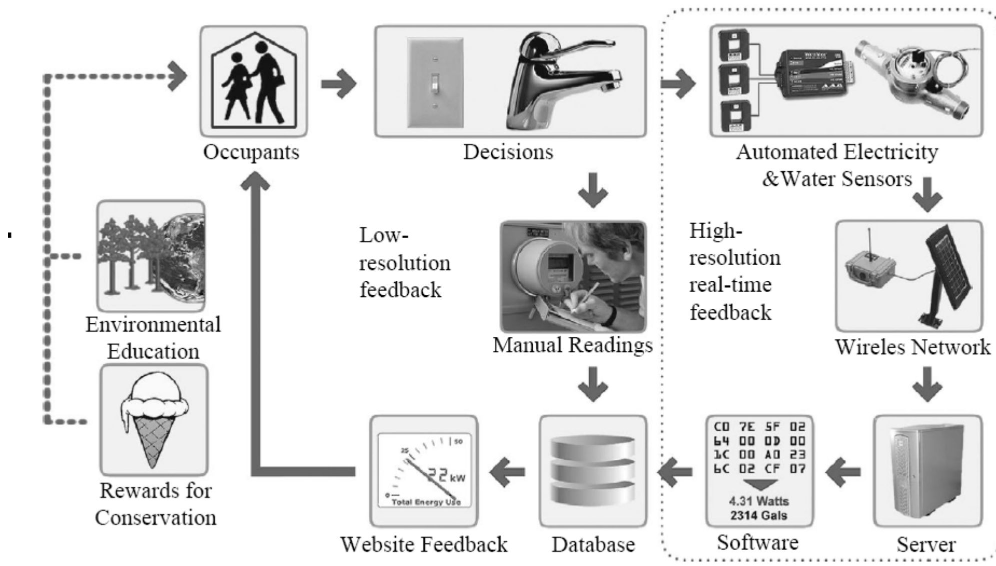

Figure 2.2.4: Pathways of data flow and information feedback on the Oberlin college campus

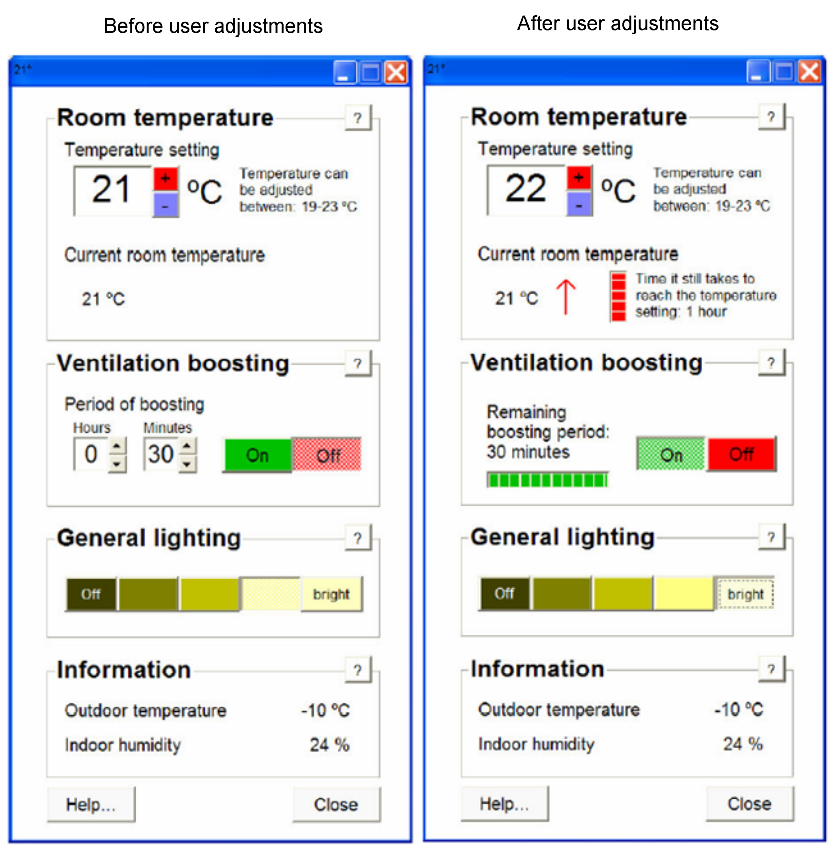

Figure 2.2.5 Space temperature control interface

2.3 Research questions and hypotheses

Knowledge and feedback are important for occupants to understand space environmental quality and concern about energy performance before taking action to adjust space environmental conditions. The theory has been well accepted by researchers in psychology, architects and building engineers (Brown, 2009; Wyon, 2000; Matthies, 2005). Field studies have been done for residential buildings and confirmed that frequent energy consumption feedback helps households to conserve resources. Very few studies address the topic of office occupants' behavior change if they are given real-time knowledge and feedback.

Table 2.3.1 Studies of feedback and information on changing user behavior

Publication	Type	Feedback	Measured results	Integrated with Controls
Matthies 2005	Theory	Electricity consumption		
Mankoff et al 2007	Theory and Field	Related energy/water, cost, CO_2 emissions benefits associated to specific behavior		
van Houwelingen 1989	Field	Daily gas consumption to households	Gas savings	
Fischer 2007	Field	Electricity consumption for household	Electricity savings	
Peterson et al 2007	Field	Real-time energy, water consumption	Energy & water savings	
Karjalainen et al 2007	Laboratory	Real-time environmental and devices settings		√
Gu 2011	Laboratory	Real-time environmental, energy, CO2 emissions, expert recommendations	energy, satisfaction, task performance	√

This dissertation will explore how real time knowledge and feedback influences occupants' behavior in control of a lighting system in a high performance office with daylight. The lighting system defined in this study involves blinds, a ceiling luminaire and a desk lamp. A lighting system, rather than thermal or ventilation systems, is selected for the study for the following reasons. Lighting energy consumption accounts for 40% of total energy usage in office buildings. Savings in lighting energy will make an important difference in total building energy consumption. Daylighting is an important feature in green building that helps reduce electricity expenditure as well as benefits space lighting quality. However, office occupants seldom change blind position unless glare occurs. They will adjust lighting output for different tasks, e.g. computer-based work or paper-based work, but are not motivated by energy savings. It is interesting to study whether real-time knowledge helps occupants to be more active in utilizing daylight as well as to reduce energy consumption without sacrificing lighting quality. Unlike thermal system control or ventilation system control, where there is a lag between new setting and measurement, lighting system responds to a new setting almost instantaneously, which helps to shorten the learning period for achieving a preferred setting compared to temperature or ventilation systems.

Six hypotheses will be tested with human subject experiments as follows:

H1: Providing the occupant of an office with control of blinds, ambient light and task light will reduce power consumption relative to no personal control.

H2: Providing the occupant of an office with control of blinds, ambient light and task light will enhance office occupant satisfaction relative to no personal control.

H3: Providing the occupant of an office with control of blinds, ambient light and task light will improve task performance relative to no personal control.

H4: Providing the occupant of an office with control of blinds, ambient light and task light as well as real-time knowledge including suitability of light levels, related power consumption, equivalent CO_2 emission, and user "advisories", will reduce power demand relative to personalized control with no real-time knowledge as outlined above.

H5: Providing the occupant of an office with control of blinds, ambient light and task light as well as real-time knowledge including suitability of light levels, related power consumption, equivalent CO_2 emission, and user “advisories”, will enhance occupant satisfaction relative to personalized control with no real-time knowledge as outlined above.

H6: Providing the occupant of an office with control of blinds, ambient light and task light as well as real-time knowledge including suitability of light levels, related power demand, equivalent CO_2 emission, and user “advisories”, will improve task performance relative to personalized control with no real-time knowledge as outlined above.

Chapter 3 Experimental design

3.1 Introduction

This chapter gives details of human subject experiment design, test bed setup and the design of an interactive lighting control interface. A controlled human subject experiment is designed to examine how office occupants' control of a lighting environment helps achieve energy savings, user satisfaction improvement and task performance increase. The test bed was set up in a high performance office with daylight, equipped with motorized blinds, dimmable ceiling luminaire and task light. Each study participant did office tasks in three different lighting control conditions. The three conditions were fixed lighting (F), manual control (MC) and knowledge-based manual control (KBMC). Fixed lighting with no user control option represents a typical practice in office lighting operation. In the manual control session, occupants set blind positions, ceiling luminaire output and turned the task light on or/off. The third lighting control option, KBMC gives participants real-time knowledge and feedback information when they manually operate blinds and lights.

3.2 Repeated measures

Based on a small number of pilot observations and data in the literature (Boyce et al., 2003), the basic parameters (means, standard deviations, covariances) for a repeated measures ANOVA were estimated. These estimates were evaluated using the procedure recommended by Cohen (Cohen, 1998) in order to achieve a moderate effect size ($f \sim 0.25$) in the main experiment. Final sample size estimates for the main study were obtained by introducing the results from Cohen's procedure into the G-Power Program (Faul et al., 2010). The G-Power program indicated that given the observed pilot parameters approximately 56 subjects were required in order to have an 80% chance (statistical power) of detecting a true difference between the three levels of lighting control (F, MC, KBMC) with a Type I error of 0.05 and using a one-sided alternative.

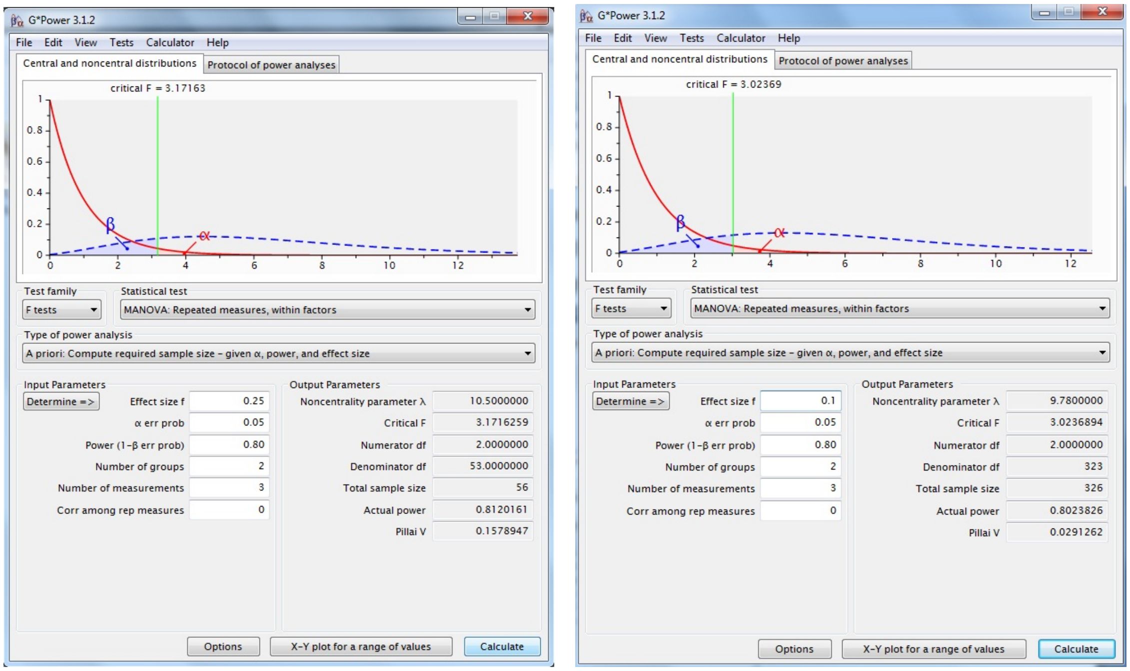

Figure 3.2.1 Sample size to achieve a medium or small effect size

3.3 Participant recruitment

For this study, 60 participants were recruited by posting advertisements on universities' bulletin boards. The participants were required to be between 18 and 40 years old and to have basic English reading, typing and computer skills. Among the 60 participants, 97% of them were college students or graduate students. Although they were not office workers at the moment, they were expected to be white collar office workers in the near future. They were told in the advertisement, as well as the beginning of the experiment, that the experiment would last 3 hours, including 40 minutes to do personal work. Each participant would receive $30 as a minimum compensation with the possibility of an additional bonus based on task performance.

3.4 Test bed design

The experiment was carried out in two open offices located in a university building, the Intelligent Workplace (IW) on the Carnegie Mellon University campus in Pittsburgh, PA, USA. The IW is a laboratory as well as office for faculty, staff and graduate students for the Center for Building Performance and Diagnostics in the School of Architecture. The experiment was carried out during winter break and on weekends when few or no other occupants were in the space from Dec. 2009 to Feb. 2010. The IW, built in 1997, is among the first generation of high performance buildings in the United States, featuring maximized user access to natural conditions including views, daylight and natural ventilation. It is about 6000 square feet, located on the 4^{th} floor of an old academic building. Figure 3.4.1 shows the floor map, orientation and room layout of the IW. Two open-plan spaces, R1 and R2 along the west façade, were chosen to be the test bed for this study. R1 and R2 have similar layouts. Each space is 12 feet by 15 feet, hosting 1 faculty member or 3-4 graduate students. The height of the southern and northern partitions is 5 feet. The east partition is 5 feet high with half its area open as an entrance to the space.

The façade is made from recycled aluminum finished with white matte paint. The glazing area is more than three fourths of the whole façade (Figure 3.4.3). A glass balcony door is located in the middle alongside 2 operable windows. The daylight benefit in the IW is much greater than in a conventional office. To make the conclusion of this study more generalizable to more typical offices with lots of glazing area, the transom section and the bottom of balcony door were covered with white foam board that had a similar light reflection rate to the finish in opaque section of the façade. Two sets of motorized interior blinds, blind A and blind B, can cover the operable window and the adjunct glazing area. The visible transmittance for glass on the operable window is 52%. Space surface reflectance values are estimated as the division of measured luminance and illuminance. Illuminance was measured by Intersil ISL29101 light sensor (Appendix D). Luminance was measured with a Nikon 5400 digital camera and analyzed by the Photolux software suite.

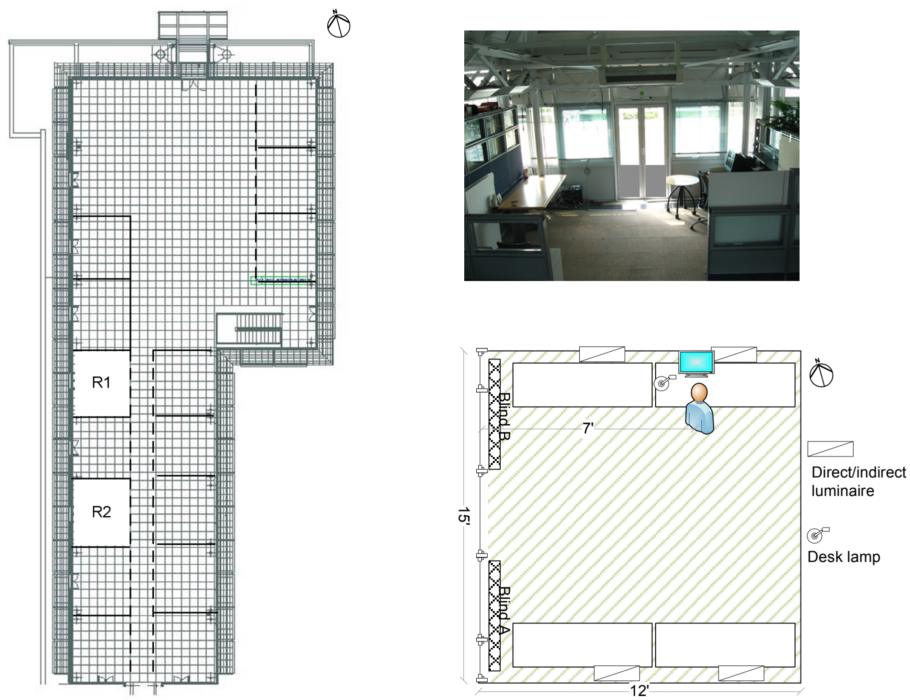

Figure 3.4.1: Floor map and experiment room layout

Figure 3.4.2 Workstation and light sensor locations

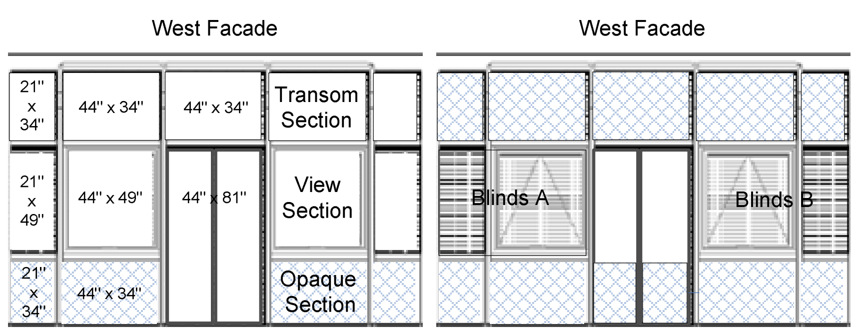

Figure 3.4.3 West façade and glazing area

Table 3.4.3.4.1 Surface material, color, reflectance in the space

	Material	Color	Reflectance
Facade	Aluminum with white paint	White	0.9
Ceiling board	Foam board	White	0.9
Partition	Paper	Beige	0.7
Desk surface	Wood with clear paint	Beige	0.4
Carpet	Nylon	Beige	0.2

Two sets of motorized aluminum venetian blinds, blind A and blind B, are installed as in figure 3.4.2, in front of the operable window and the adjacent glazing area. In the winter season of Pittsburgh, direct sunlight is cast on the working surface in this study only in the late afternoon through the glazing behind blind A. Blind A has little contribution to the amount of daylight in the work area, but functions as a direct sunlight block. Therefore, blind A is called the glare-control blind. Blind B plays the role of the main contributor to determine how much daylight is cast on the working area. Each blind is operated by two motors, one for lifting and the other for lowering. For the convenience of the user's selection and future data analysis, the motor is programmed to set the blind at only three positions: up, closed or open, as illustrated in Figure 3.4.4. In the up position, the blind is lifted to the highest point without blocking daylight or any user view to the outside. In the closed position, the blind covers the whole window and the blind slats are vertical, blocking most daylight from coming into the working area. In the open position, the blind covers the whole window, while the slats are at horizontal position, which allows most daylight into the working area with limited user views to outside.

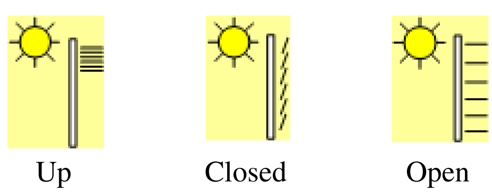

Figure 3.4.4 Three blind positions

Four Zumtobel LaTrave relocatable ceiling luminaires are installed in each working area. The luminaire provides 80% up and 20% down light. Each contains one Osram electronic dimmable ballast (10%-100%) and two 55W Sylvania U-shape lens. The color temperature is 4000K. The Osram electronic ballast is a European product requiring a 230V power supply. The measured power data (Figure 3.4.5) shows tat the lighting power consumption before the step-up transformer is in a linear relationship with the dimming level. The ceiling luminaire evenly provides light on the desktop at a maximum level of 420 lux. A desk lamp with an adjustable arm provides locally intensive light on desktop. A 14W high performance CFL lamp, color temperature 5000K, provides 500-1000 lux extra local illuminance on the desk surface.

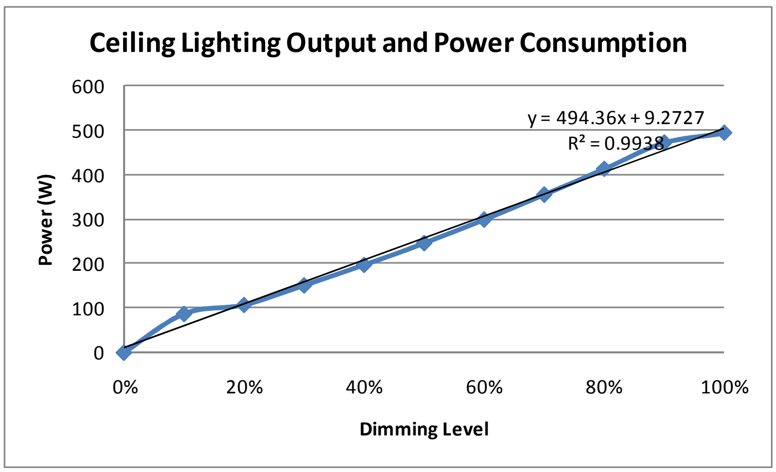

Figure 3.4.5 Measured ceiling light outputs and power consumption

Figure 3.4.6: Zumtobel LaTrave relocatable ceiling luminaire and desk lamp

Three illuminance sensors were deployed in the space. One was attached on a window surface, monitoring vertical illuminance from daylight entering the space on the window surface. The second one was attached to the keyboard to monitor horizontal illuminance falling on the desk surface. The third one measured vertical illuminance on the partition behind the monitor (Figure 3.4.7). The illuminance sensors were wired to a National Instruments data acquisition board DAQ6008. LabVIEW was the control software for this study. Besides acquiring analogue signals from illuminance sensor and acoustics sensor, LabVIEW sent digital output to control the on/off setting of the ceiling lighting and task light. One analogue output reported the dimming level.

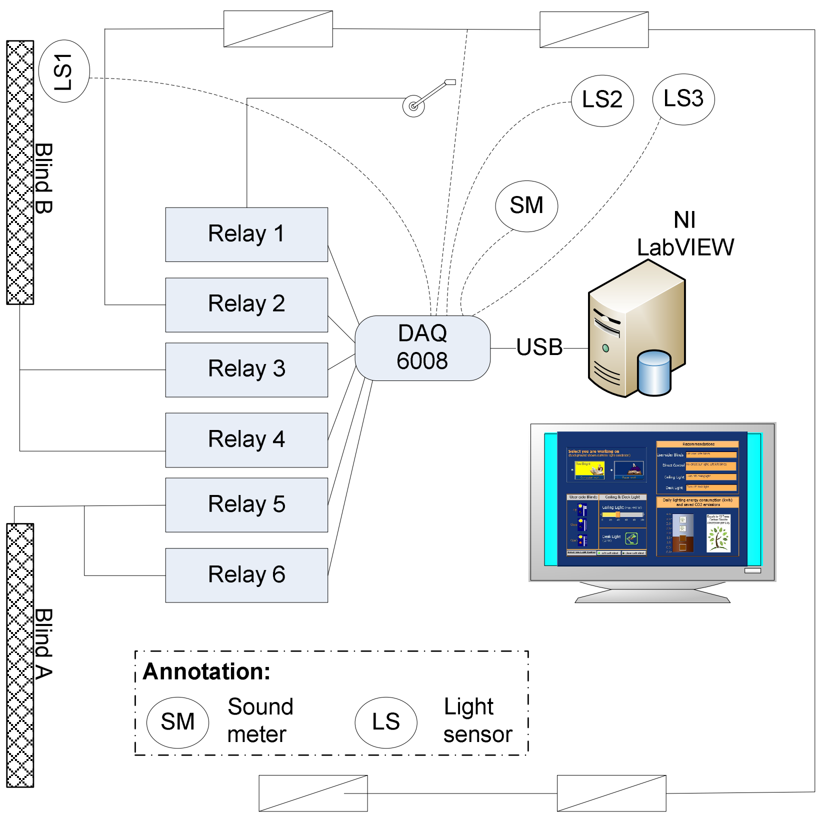

Figure 3.4.7: Sensors, actuators, DAQ, and wiring

Temperature and humidity were measured with an Omega portable 4-in-1 thermometer. They were manually recorded during each lighting control session. The sensor data sheets are in Appendix D.

3.5 Three lighting controls

Sixty human subjects were invited to participate in this experiment. Each participant did 3 rounds of office tasks in 3 continuous hours. In all, 180 data sets were collected. The 3 lighting control sessions were as follows:

Fixed lighting (F):

represents a typical practice in office lighting where ceiling light output is set at a constant level throughout working hours. There is no desk lamp. Blinds are at the same positions.

Manual control (MC):

represents the opportunity that could exist in most typical offices where the user can manually adjust blind positions, ceiling light dimming level and task light on/off settings.

Real- time knowledge based manual control (KBMC):

represents the potential for IT integrated real-time knowledge based manual control so that users can manually adjust blind positions, ceiling light dimming level and task light on/off settings. The real time knowledge addresses: suitability of light level, lighting power consumption, related carbon emission, and expert recommendations.

3.6 Human subject experiment

The Carnegie Mellon University Institutional Review Board (IRB) approved the research protocol for this study on Oct. 16 2009 with the registration number IRB00000603 (Appendix A). A slight modification was approved on Dec. 4. 2009. The experiment was carried out during school winter break from Dec. 29. 2009 to Jan. 9. 2010 and on weekends from Jan. 16. 2010 to Feb. 6. 2010. All participants were recruited from Carnegie Mellon University or the University of Pittsburgh. Participants were required to be between 18 and 40 years old, having basic office work experience, e.g. typing and searching for phone numbers in the yellow pages. As defined by IESNA, the 18 to 40 age group needs a minimum of 200 lux on a working surface for either paper work or computer work. For each session, only one participant worked in each room. The ceiling luminaires in the two rooms barely influence each other, so that their illuminance conditions are independent. Two rounds of experiment were carried out during each experiment day: 9:00 am to 12:00 pm and 1:00 pm to 4:00 pm. Participants worked in three lighting control sessions in 3 continuous hours. The repeated measurement not only helped to eliminate differences between subjects, but also contributed to similar outdoor weather and daylight conditions for the three lighting control sessions.

In the “fixed lighting” session, blind A, the glare-control blind, was set to the “up” position in the morning and closed in the afternoon to prevent direct sunlight in the working space. Blind B, the user-side blind, was set at the “open” position all the time. The ceiling luminaire was at 100% output and the desk lamp was off. In the “manual control” session, participants were allowed to change blinds’ positions, ceiling light output, and the on/off setting of the desk lamp for a suitable lighting condition to help them in doing the tasks through a web-based LabVIEW control interface. The initial condition was the same as the settings in “fixed lighting”. Users had two chances to change blind and lights settings. Once was before working on a computer-based task and the other was before a paper-based task. The real-time knowledge based manual control (KBMC) provided four categories of information: suitability of desk surface light level in term of task type, lighting power consumption and corresponding carbon dioxide emission, and recommendations for the most effective setting strategies.

Participants did the same office tasks repeatedly in three continuous sessions. Although the lighting control options were different across sessions, other settings including temperature, humidity, ventilation rate, and background noise level were. There are other factors that might influence task performance but cannot be controlled. Task performance might be dependent on the task sequence. For example, performance in later sessions might be improved as a result of more practice, or might decrease due to participants getting tired. Randomized sequence design is quite often applied in clinical trial testing, but is not applicable here. The KBMC session can only be presented to participants after the manual control session to avoid the possibility that users’ behavior in the manual control session would be biased by information received during KBMC. This is a quasiexperimental design. To test whether there is a sequence effect on energy consumption, user satisfaction and task performance, 2 sequences of lighting control sessions were designed for this study (Table 3.3.1 & Table 3.3.2). Thirty participants did the experiment in sequence 1 and another 30 participants did it in sequence 2. Based on a discussion with Professor Sara Kiesler (Kiesler, 2009), the human eye adapt easily and quickly to different lighting conditions with no obvious short term effects on task performance. She recommended each session should be at least 1 hour to examine the lighting control's impact on task performance.

Participants were recruited from Carnegie Mellon University and the University of Pittsburgh. Before the experiment, they were told they would be compensated $10 per hour for attendance. The top 20 out of the 60 who scored the highest on the office tasks would get an extra $10 each. In the first half hour in both sequences, participants were introduced to how to work on the office tasks. Fifteen minutes were given for participants to practice. The results of tasks in the training section were not counted in the total score for the extra $10 award.

In the second half hour in each section, participant conducted tasks and filled out questionnaires at the end, reporting their perception of and satisfaction with space light level and other environmental conditions. In the manual control and real-time knowledge based manual control sessions, participants were asked to adjust blind and light settings twice through a web-based LabVIEW interface. In the second and third lighting control sessions, there were 20 – 25 minutes of break time given to participants, but they were asked to stay in the same working area for their eyes to get used to the space lighting condition. In the last 5 minutes of each session, participants filled out a questionnaire (Appendix B) about their perception and satisfaction regarding the lighting quality and control in the section.

Table 3.6.1 Lighting control in sequence 1

Section 1: Fixed lighting (1 hr)	10 min	- sign the research consent form - fill out questionnaire 0 - be trained to do computer tasks and paper task
	15 min	- practice on tasks
	5 min	- do proofreading task on computer
	15 min	- do typing task on computer
	10 min	- do paper task
	5 min	- fill out questionnaire 1
Section 2: Manual control (1 hr)	5 min	- be trained to use control interface to operate blinds and lights - change blind positions and light output to a comfortable level
	20 min	- stay at the desk and do personal work
	user adjusts blind positions and light output for computer tasks	
	5 min	- do proofreading task on computer
	15 min	- do typing task on computer
	user adjusts blind positions and light output for paper task	
	10 min	- do paper task
	5 min	- fill out questionnaire 2
Section 3: Real-time knowledge based manual control (1 hr)	5 min	- be trained to use control interface to operate blinds and lights with feedback and recommendations - change blind positions and light output to a comfortable level
	20 min	- stay at the desk and do personal work
	user adjusts blind positions and light output for computer tasks	
	5 min	- do proofreading task on computer
	15 min	- do typing task on computer
	user adjusts blind positions and light output for paper task	
	10 min	- do paper task
	5 min	- fill out questionnaire 3

Table 3.6.2 Lighting control in sequence 2

Section 1: Manual control (1 hr)	10 min	- sign the research consent form - fill out questionnaire 0 - be trained to do computer task and paper task
	5 min	- be trained to use control interface to operate blinds and lights - change blind positions and light output to a comfortable level
	10 min	- practice on tasks
	user adjusts blind positions and light output for computer tasks	
	5 min	- do proofreading task on computer
	15 min	- do typing task on computer
	user adjusts blind positions and light output for paper task	
	10 min	- do paper task
	5 min	- fill out questionnaire 1
Section 2: Real-time information based manual control (1 hr)	5 min	- be trained to use control interface to operate blinds and lights with feedback and recommendations - change blind positions and light output to a comfortable level
	20 min	- stay at the desk and do personal work
	user adjusts blind positions and light output for computer tasks	
	5 min	- do proofreading task on computer
	15 min	- do typing task on computer
	user adjusts blind positions and light output for paper task	
	10 min	- do paper task
	5 min	- fill out questionnaire 2
Section 3: Fixed lighting (1 hr)	25 min	- stay at the desk and do personal work
	5 min	- do proofreading task on computer
	15 min	- do typing task on computer
	10 min	- do paper task
	5 min	- fill out questionnaire 3

3.7 The office tasks

Based on the literature reviews and expert knowledge, this study assumes that office workers spend twice as much time on computer-based work as they spend on paper-based tasks (Maniccia et al., 1999; Hua, 2007; Steelcase, 2001). Participants did 20 minutes of intensive computer based tasks and 10 minutes of paper-based tasks in the second half hour of each lighting control session.

The computer-based tasks were developed by the National Research Council of Canada (NRC) for evaluating office lighting environments. A proofreading task and a typing task were chosen for this study. Figure 3.7.1 is a screen shot of the proofreading task. Column A and column B were presented on the side of the screen with a column with a check box in the middle. Participants indicated, by placing a mark in a checkbox with the space key, whether character sets in the same row differed. The five-digit numbers in the reference column A were random numbers. The corresponding numbers in column B were the same except that some of the five-digit numbers had one or two different digits. Each page contained 20 lines, with 3-4 different numbers. When one screen was completed, participants continued to another screen by pressing F5. The screen was designed with a white background and text in the font Courier New, size 9. Participants were asked to mark the rows with differences as quickly and accurately as possible within 5 minutes in each section. Data on number of differences correctly identified and false positives were recorded to disk screen-by-screen for the entire time of the task. The performance was be evaluated by proofreading speed (prs) and proofreading accuracy (pra). Prs is the inverse of average time spent to finish one screen. Pra is the number of correctly marked discrepancies divided by the sum of total discrepancies and false marked discrepancies numbers.

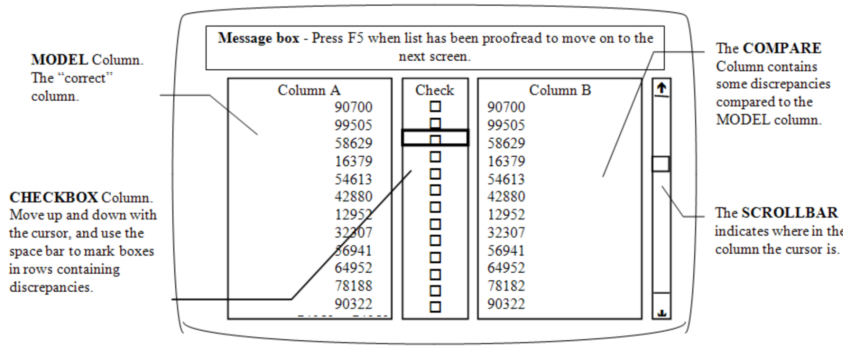

Figure 3.7.1 Proofreading task screen shot

The typing task (Figure 3.7.2) is designed to resemble the typing proficiency test required of applicants seeking placement at agencies for temporary office workers. Model text was presented in one window on the screen with light grey background in the font Arial, size 9. The user was instructed to copy that text into a second window. Any mistakes had to be corrected before the user keyed in the next word. Data on typing speed and errors made were recorded to disk every minute, and summaries were provided for each paragraph completed, and for the entire time of the task. The duration of the typing task in each section was 15 minutes. User performance was evaluated by characters per second (cps).

Searching for phone numbers in the white pages was the paper-based task. Participants were given a page with a list of names and asked to look up and write down as many numbers as possible within 10 minutes (Figure 3.7.3). The evaluation score was the total number found.

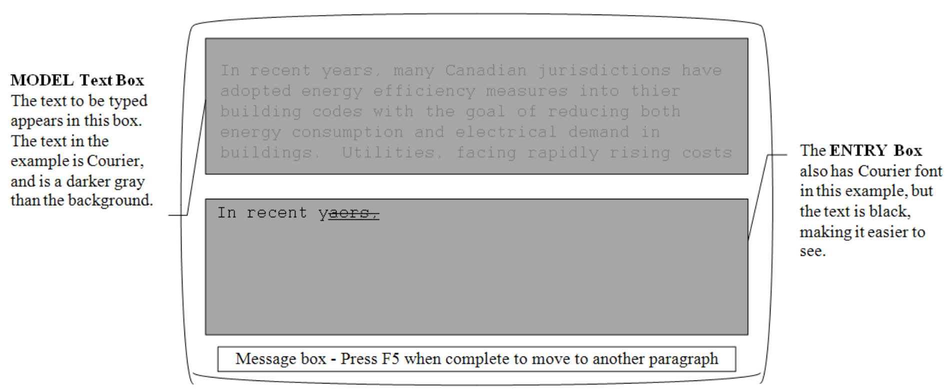

Figure 3.7.2 Typing task screen shot

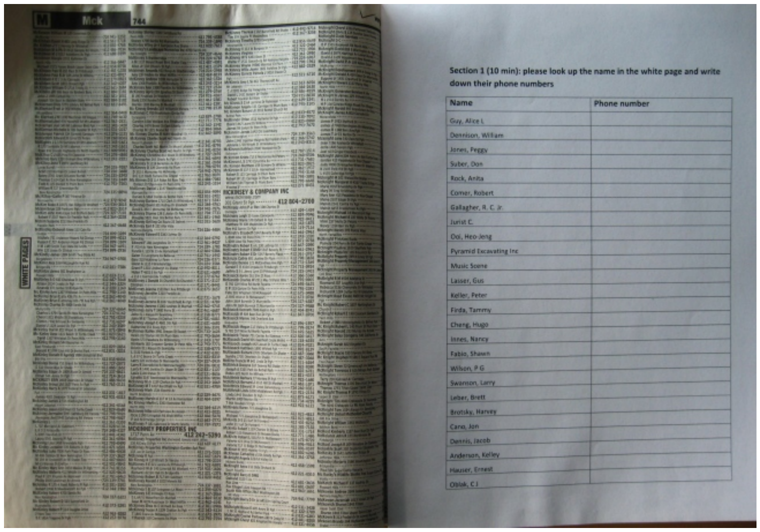

Figure 3.7.3 Searching for phone numbers

3.8 Lighting control interface and recommendation algorithm

3.8.1 Importance of feedback information

Office users are annoyed by the lack of feedback on the current status of environmental settings and feedback on whether a new setting has been accepted by the control system (Escuyer et al., 2001) (Karjalaninen & Koistinnen, 2007). Instantaneous feedback on space settings, such as new temperature set-point with estimated time to reach the new setting, makes it easier for users to make a pleasant environmental setting. Lighting systems usually give quick feedback to users. For example, most ballast today adjusts fluorescent lamp lumen output smoothly with simultaneous response to a dimmer controller. It helps occupants to make a decision to achieve the most satisfying light level. Most blinds also respond quickly to a new position. In this study, it takes about 30 seconds for blinds to change from the "up" position to the fully closed position.

Real-time energy consumption is important in the process of users making decisions on setting light output. In residential buildings, users having frequent feedback on energy consumption tend to use less resources compared to those who do not have feedback

(Geller, 2002). Environmental impact such as carbon dioxide emissions related to energy use is also important for helping users to make decisions. Users who are concerned about environmental sustainability issues such as carbon dioxide emissions are willing to know how their behavior directly links to the emissions. Real-time information regarding environmental issues plays a significant role in users' decisions about how to use and set devices (Mankoff et al., 2007) (Bambert, 2003).

Office occupants are occupants are often insufficiently notified of the design intention of the space they work in. They are very likely to lack the knowledge of passive as well as active technologies that help to achieve lighting, thermal, or air quality comfort. Based on post-occupancy studies of several green buildings, Brown and Cole conclude "… the availability and use of personal controls was higher in green buildings," yet "the quality of personal controls in terms of responsiveness, the absence of immediate and relevant feedback, and poor user comprehension may lead to sub-optimal comfort conditions and or sub-optimal energy performance" (Brown & Cole, 2009). Office occupants need expert knowledge regarding environmental quality and recommendations for setting space.

3.8.2 Lighting control interface

The interface (Figure 3.8.1) to control blinds and lights in the experiment was designed to help users understand all available options to change their space lighting environment. The "Blinds" frame contained three buttons to set the user-side blind (blind A). The LED light on the button indicated the current blind position. In the "Lighting" frame, the slide bar allowed user to adjust ceiling luminaire output from 10% to 100%. Desk lighting could be turned on or off. Two pre-programmed glare-control blind position buttons were in the "Direct Sun Light Control" frame: the up position to allow daylight in and the closed position to block direct sunlight in the working area.

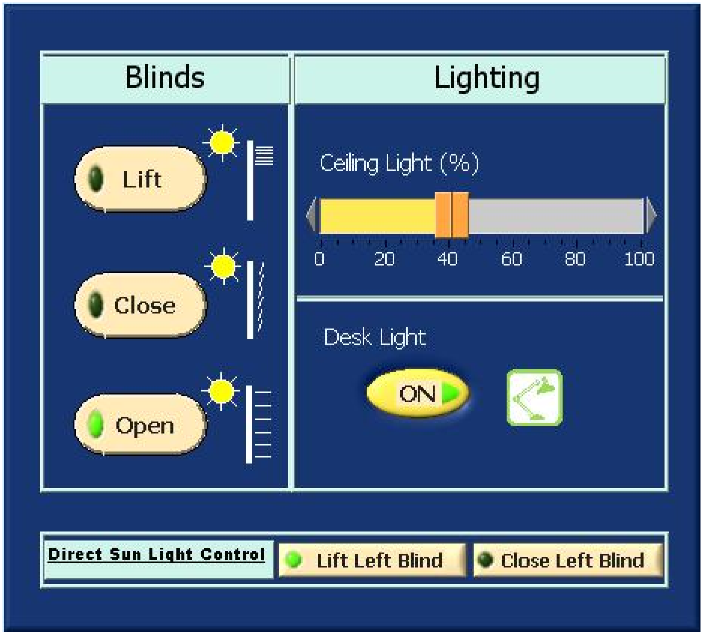

Figure 3.8.1 Manual lighting control user interface

The real-time knowledge based manual control interface was designed to help users understand environmental comfort quality, available "handles" to change the space environment, and related energy and environmental consequences. The office lighting design guide sets the minimum primary work surface illuminance to be 200 lux for the age group younger than 40, 300 lux for the age group between 40 and 55, and 500 lux for the age group older than 55 (IESNA, 2007). ANSI/IESNA recommends that the luminance contrast ratio between monitor and background should be between 3:1 and 1:3 (ANSI/IESNA, 2007). Office workers may lack the knowledge to understand the meaning of illuminance or contrast ratio. If they are given a value of illuminance, e.g. 200 lux, they likely will not be able to relate the number to how to set light output or blind position. The challenge here is to translate real-time measurement to real-time information that every office occupant is able to understand.

The knowledge-based lighting control interface in this study provided four categories of information to office occupants. One category contained information regarding lighting environmental quality. It told users whether the current condition is "too bright", "right amount", or "too dim" based on measured illuminance, task type, standards, and expert knowledge. Another category provided the user with instantaneous feedback about energy consumption that helped users to consider energy consumption and environmental emissions when they decided how to set up their space lighting condition. Linking the user's behavior to emissions, e.g. carbon dioxide consequence of lighting electricity use, encourages office occupants who are concerned about environmental sustainability to reduce energy consumption. The third category gave users recommendations based on the design intention of the space. In this study, the design intention was to maximize daylight benefit and reduce electricity usage. The recommendations not only embedded an optimized solution for environmental quality and energy efficiency, but also helped users to quickly make decisions when several control options are presented. The algorithms for generating feedback and recommendations can be found in the next section.

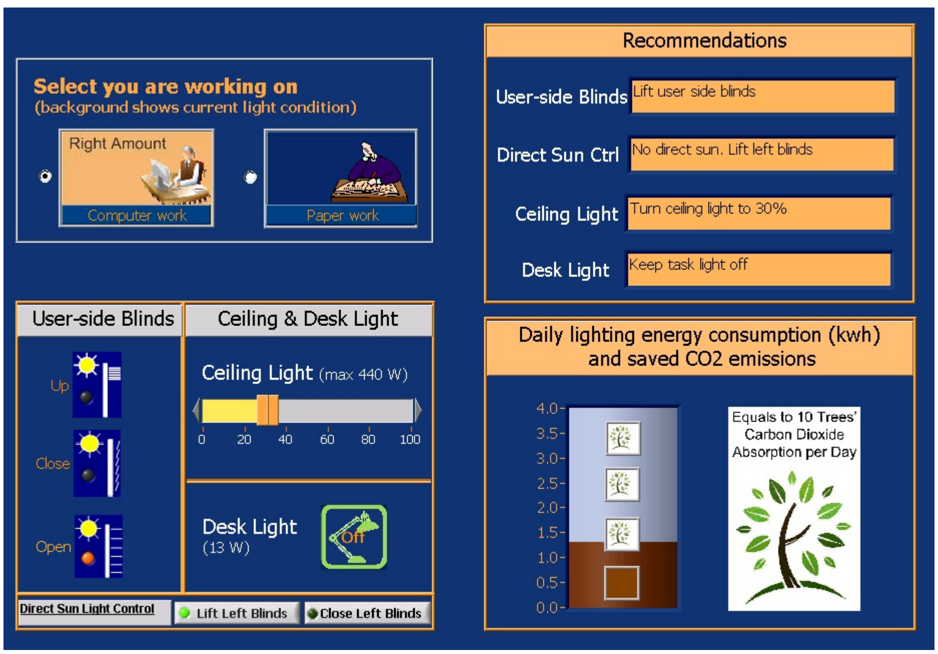

Figure 3.8.2 Real-time knowledge based lighting control user interface

The blinds and lights control buttons presented to users were the same as on the manual control interface in KBMC (Figure 3.8.1). KBMC illustrates the suitability of light level for computer-based work or paper-based work. Real-time lighting power consumption and carbon emission consequences are illustrated in another window frame. Lastly, recommendations of how to set blinds and lights are given. The light level suitability is based on task type (e.g. computer work, paper work), IESNA standard and expert knowledge, and measured real time illuminance on the working surface. The current light level is presented to users in terms of three levels: too bright, right amount, or too dim. Recommendations tell the most effective combination to set blinds' positions, ceiling luminaire output, and task light on/off setting to achieve a comfortable and productive lighting environment to help the user conduct office tasks. The recommendations are based on task type, daylight availability and task requirements. In this laboratory study, participants only stayed in the space for three hours for this study. The daily energy consumption is calculated based on real time power demand of the ceiling luminaire and task light timing calculated across 8 hours. The related carbon dioxide emission is described as the number of trees that absorb the same amount of carbon dioxide in one day to help users get an intuitive understanding of the environmental impact.

3.8.3 Algorithm for expert recommendations

3.8.3.1 Suitability of illuminance on work surface

To keep the contrast ratio between background wall and monitor above a 1:3 ratio, the minimum desk surface light level has to be above 75 lux based on field measurement. For computer-based tasks, if the light level falls below 75 lux, the feedback information tells the user the lighting is "too dim". If the light level is above 300 lux, the feedback information tells the user it is "too bright". Otherwise, it shows "right amount." For paper-based tasks, if the light level falls below 200 lux, it shows "too dim". If the light level is above 1000 lux, it shows too bright.

Table 3.8.1 Suitability of desk top illuminance for computer task and paper task

Tasks	Desk surface Light Level	Suitability
Computer-based tasks	<75 lux	Too dim
	≥ 75 lux & ≤ 300 lux	Just right
	> 300 lux	Too bright
Paper-based task	<200 lux	Too dim
	≥ 200 lux & ≤ 1000 lux	Just right
	> 1000 lux	Too bright

3.8.3.2 Real-time feedback on lighting energy consumption and related carbon emissions

The "Daily Lighting Energy Consumption (kwh)" is calculated as current lighting power consumption (Figure 3.4.5) extrapolated over 8 hours per day. To ease the user's understanding of carbon dioxide emissions, instead of giving CO_2 emission in term of weight, the emission is presented as the number of trees that absorb the same amount of CO_2 in one day. One single mature tree absorbs 0.13 lbs of carbon dioxide per day (McAliney, 1993). The average CO_2 emission from electricity generation in the United States is 1.4 lbs/kwh (eBIDS, 2004).

For example, if the ceiling light is operated at 100% output for 8 hours per day, the "Daily Lighting Energy Consumption" will be:

$$\textit{Daily Lighting Energy Consumption} = 0.44 \times 8 = 3.52 \text{ kwh}$$

$$\textit{Equivalent Carbon Dioxide Emission} = \frac{3.52 \times 1.4}{0.13} = 38 \text{ trees}$$

3.8.3.3 Expert recommendations

This study focuses on office lighting system and space visual comfort. Only the impacts of daylight on space visual environment are included in generating the recommendations rather than daylight's impacts on thermal environment. Integrated lighting and thermal operating rules are also interesting and important to explored in the future. The algorithms are based on the principle of making full use of daylight and view to outside in the context of allowing no direct sun glare in the working area. The user-side blind (blind B) is the main contributor to the amount of daylight cast in the working area. During the winter season, no direct sun light comes through the window behind blind B to cause glare in the working area. KBMC always recommends lifting blind B to the "up" position to maximize daylight benefit and views to outside.

Blind A functions as a glare blocker preventing direct sunlight casting on the working area. In the later afternoon of the winter season, if the sky is in clear or partially clear condition, direct sunlight might cause uncomfortable glare in the working area. KBMC recommends closing blind A. If the algorithm detects no glare, KBMC recommends lifting blind A.

When a user is conducting computer-based tasks, ceiling luminaire output is recommended to be dimmed to the level that keeps desktop illuminance level at least 200 lux (IESNA), while maintaining vertical illuminance on partition at the back of the monitor above 40 lux for a suitable contrast ratio between monitor and the partition. For paper work, the ceiling luminaire is set to keep the work surface at least 200 lux. The desk lamp is recommended to be on when a user is conducting paper-based tasks.

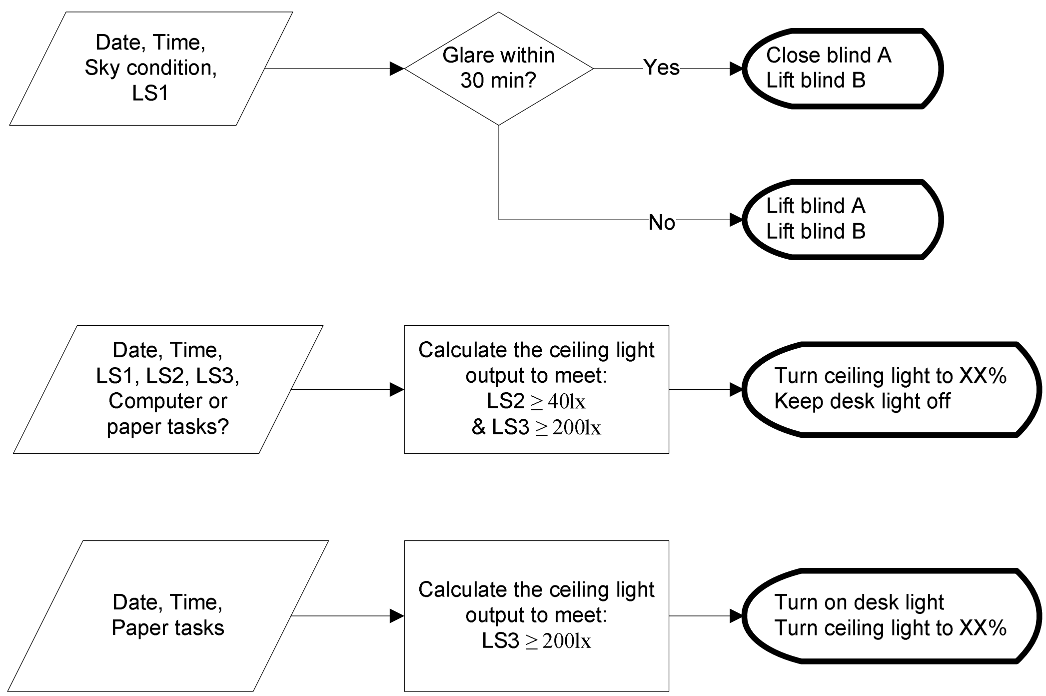

Figure 3.8.3. Algorithm for recommendations for blinds, ceiling light and desk lamp operation

Chapter 4 Data analysis

4.1 Introduction

This chapter is to test the six hypotheses raised in Chapter 2 one by one with the data collected from the human subject experiment. The six hypotheses are:

H1: Providing the occupant of an office with control of blinds, ambient light and task light will reduce power consumption relative to no personal control.

H2: Providing the occupant of an office with control of blinds, ambient light and task light will enhance office occupant satisfaction relative to no personal control.

H3: Providing the occupant of an office with control of blinds, ambient light and task light will improve task performance relative to no personal control.

H4: Providing the occupant of an office with control of blinds, ambient light and task light as well as real-time knowledge including suitability of light levels, related power consumption, equivalent CO_2 emission, and user "advisories", will reduce power demand relative to personalized control with no real-time knowledge as outlined above.

H5: Providing the occupant of an office with control of blinds, ambient light and task light as well as real-time knowledge including suitability of light levels, related power consumption, equivalent CO_2 emission, and user "advisories", will enhance occupant satisfaction relative to personalized control with no real-time knowledge as outlined above.

H6: Providing the occupant of an office with control of blinds, ambient light and task light as well as real-time knowledge including suitability of light levels, related power demand, equivalent CO_2 emission, and user "advisories", will improve task performance relative to personalized control with no real-time knowledge as outlined above.

All assumptions including that thermal condition, air quality, acoustics levels, and sky condition are consistent among lighting control sessions, were checked before the testing of the hypotheses. Blind positions, ceiling luminaire output, and task light settings were compared for examining how participant behaviors of setting lights and blinds were changed.

4.2 Statistical Methods

A linear mixed model (LMM) is used for statistical analysis. A linear mixed model can be viewed as a generalization of the variance component and regression analysis model (Demidenko, 2004). It can handle both fixed and random effects. Fixed effects are factors based on no distributional assumptions of the time-invariant error component. Random-effects are based on distributional assumptions of the time-invariant error components. LMM is adequate to describe repeated measurement in a structure where rows are independent but observations within each row are dependent. LMM can identify two sources of variation: variation between individuals (inter-subject variance) and variation within an individual (intra-subject variance). LMM is also able to handle data sets with missing data, which is another merit for this study. SPSS 18 is the statistics tool used in this study.

4.3 Test of presumptions

4.3.1 Air temperature, humidity and acoustics conditions

The literature review identifies that office occupants' performance at office work is dependent on indoor environmental factors including lighting, air quality (Mendell et al, 2002) (Wargocki et al, 2000), thermal conditions (Witterseh, 2001), and acoustic conditions (Banbury and Berry, 1998). To identify the efforts of lighting control on energy, user satisfaction and task performance, other environmental factors air temperature and humidity, ventilation, and acoustics conditions, were controlled across the lighting control sessions. Before examining the hypotheses, the mixed model analysis is applied to check the consistency of thermal, air quality and acoustics condition during the experiments.

The indoor air temperature was set to 73˚F during all experiments. A façade radiant heating system in the IW delivered heat evenly to the space. A ventilation system delivered outdoor air at 72˚F at a constant volume through a floor diffuser at a low velocity to eliminate drafts. Temperature and relative humidity were recorded at the beginning of each 1-hour session by an Omega portable multi-function meter (Appendix D). Air temperature was 73.5˚F (±1.5˚F) with relative humidity (rh) at 20% (±8%), which met the requirement of winter thermal comfort defined by ASHRAE 55-2004. To simulate a quiet office environment, all experiments were conducted during winter break or weekends during the semester to avoid disturbances from neighboring occupants. Most experiments were carried out when no other occupants were in adjacent spaces.

The weighted sound level (dBA) was recorded every one second. The mean sound levels were almost the same across the three lighting control sessions, as shown in Figure 4.3.1, while the sound level varied by task types. The noise from typing or flipping pages was detected by the sound meter located next to the study participants. Performing a proofreading task only required users to hit up, down and space keys, and generated the least noise among the three tasks. The noise as a consequence of performing tasks was the loudest when study participants were working on typing task. A mixed model analysis revealed no significant difference between sound levels among test sessions.

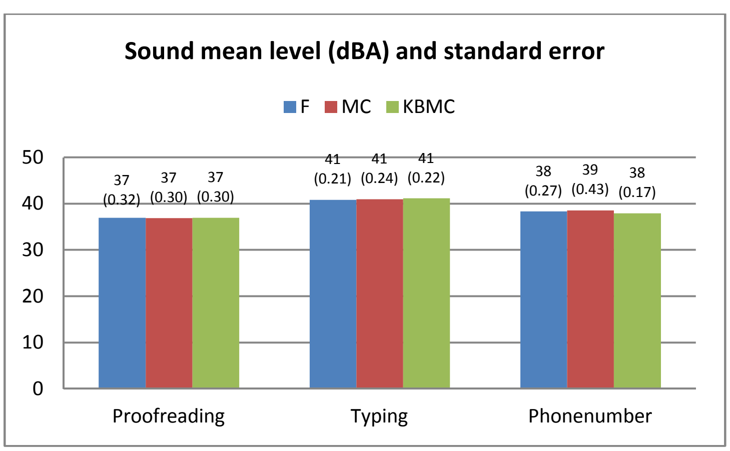

Figure 4.3.1 Sound mean level and standard error by task and lighting controls

Participants were surveyed for satisfaction on temperature, odor, ventilation and noise at the end of each session. All answers were given on a 7 point scale, ranging from -3 for very unsatisfactory, to 0 for neutral, to +3 for very satisfactory. Participants were highly satisfied with the thermal, ventilation and acoustic conditions during the experiment. Mixed model analysis shows no significant difference in user satisfaction with regard to temperature, odor, ventilation and noise among test sessions.

Table 4.3.1: Mean and standard error of user satisfaction with air temperature, odor, ventilation and noise

	Fixed lighting	MC	KBMC
Temperature	2.07 (SE 0.16)	2.02 (SE 0.17)	2.02 (SE 0.16)
Odor	1.82 (SE 0.17)	1.95 (SE 0.16)	1.90 (SE 0.16)
Ventilation	1.78 (SE 0.17)	1.87 (SE 0.15)	1.92 (SE 0.15)
Noise	1.58 (SE 0.21)	1.88 (SE 0.21)	1.78 (SE 0.18)

Note: noise (-3 very unsatisfactory, 0 neutral, +3 very satisfactory)

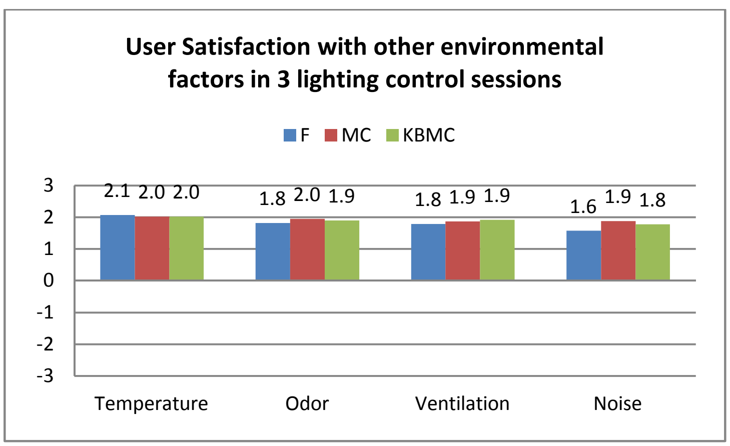

Figure 4.3.2 User satisfaction with other environmental factors in lighting control sessions

Because the thermal, ventilation and acoustic conditions are consistent among lighting control sessions, these environmental factors will not be included in the analysis of energy, satisfaction and task performance,.

4.3.2 Daylight level

Three sky conditions defined by IESNA--clear, partially clear and overcast--were manually recorded. In each 3-hour experiment, there was no significant sky condition change during each experiment. If an experiment began with clear skies, this sky condition continued for at least 3 hours. If an experiment began with overcast sky conditions, it continued until the end of the experiment. Sky conditions contribute significantly to the available amount of daylighting the space. If the amount of daylight in the space significantly varies during a 3-hour experiment, the analysis of blind position and light output will lose the same baseline for comparison.

To verify whether level of daylight was consistent, window surface illuminance was measured and evaluated with a mixed model analysis. In the experimental settings, an outside facing illuminance sensor was attached to the window surface to measure the vertical light level on the facade. Table 4.3.2 shows the mixed model settings that determined whether the daylight amount was different among lighting control sessions. The mean window surface illuminance is summarized in Table 4.3.3.

Table 4.3.2 A mixed model tests of significance to determine difference in illuminance on window surface among three lighting control sessions

Repeated:	Lighting control
Repeated Covariance Type:	Unstructured
Dependent variable:	Illuminance on window surface
Fixed factor(s):	Lighting control
Type III tests of lighting control effects:	Sig. 0.42 (computer task) Sig. 0.24 (paper task)

Table 4.3.3 Mean and standard error of window surface illuminance and standard error (lux)

	Fixed lighting	Manual control	KBMC
Computer task	2303 (SE 177)	2503 (SE 161)	2556 (SE 180)
Paper task	2310 (SE 170)	2599 (SE 168)	2411 (SE 179)

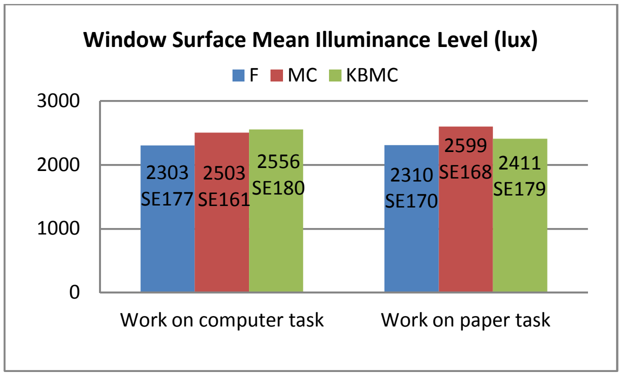

Figure 4.3.3 Window surface illuminance level

There is no significant difference in window surface light level, which means the availability of daylight is consistent for each participant during a 3-hour experiment. Thus, in lighting control session comparisons, daylight will not be a factor influencing power, user satisfaction and task performance.

4.4 Two sequence groups

Participants performed three rounds of office tasks for three continuous hours. To determine whether the order of the three lighting control sessions impacts lighting power demand, user satisfaction and task performance, the three lighting controls were presented to 30 participants in one sequence and the other 30 participants in another sequence (Table 4.4.1).

Table 4.4.1 Two sequences of lighting control sessions

Sequence 1 (30 participants) F → MC → KBMC				**Sequence 2** (30 participants) MC → KBMC → F			
P1	pr→t→pn	pr→t→pn	pr→t→pn	P31	pr→t→pn	pr→t→pn	pr→t→pn
…..	pr→t→pn	pr→t→pn	pr→t→pn	….	pr→t→pn	pr→t→pn	pr→t→pn
P30	pr→t→pn	pr→t→pn	pr→t→pn	P60	pr→t→pn	pr→t→pn	pr→t→pn

Notes: pr – proofreading, t – typing, pn – phone number search

Demographics are recoded for data analysis. Table 4.4.2 summarizes demographics for the two sequence groups. The two sequence groups are significantly different in the

"ESL" (English as Second Language)[1] and "wearing glass or contact lens" groups[2]. In statistical analysis, the two sequence groups will be separated until statistical results indicate there is no difference in power demand, user satisfaction or task performance. Demographics will be controlled as confounding factors in a mixed model.

Table 4.4.2 Demographics summary

Demographics		Frequency	Percentage	Code	Group 1 (30S)	Group 2 (30S)	Sig. 1-way ANOVA
Age							0.60
	18-24	33	55.0%	0	53.3%	57.7%	
	25-40	27	45.0%	1	46.7%	42.3%	
Gender							1.00
	Female	22	36.7%	0	36.7%	36.7%	
	Male	38	63.3%	1	63.3%	63.3%	
ESL							**<0.01**
	Yes	51	85.0%	1	93.3%	76.7%	
	No	9	15.0%	0	6.7%	23.3%	
Earned highest education degree							0.40
	High school	10	16.7%	0	13.3%	20.0%	
	Bachelor/Community college	25	41.7%	1	86.7%	80.0%	
	Graduate degree	25	41.7%	1			
Occupation							0.30
	Student	54	90.0%	0	86.7%	93.3%	
	Office worker/Others	6	10.0%	1	13.3%	6.7%	
Wearing glass or contact lens							**<0.01**
	No	26	43.3%	0	30.0%	56.7%	
	Yes	34	56.7%	1	70.0%	43.3%	
Corrected Visual Acuity							0.53
	20/20	51	85.0%	0	83.3%	86.7%	
	20/25 or worse	9	15.0%	1	16.7%	13.3%	

[1] P-value < 0.01 with one-way ANOVA analysis
[2] P-value < 0.01 with one-way ANOVA analysis

4.5 Energy Demand (H1, H4)

Hypothesis 1 (H1) and hypothesis 4 (H4) involve lighting energy demand. H1 assumes that lighting energy will be reduced if office occupants manually control blinds and lights, compared to them being given fixed settings. H4 expects further energy reduction by providing occupants with real-time knowledge combined with manual control. In these MC and KBMC session, participants set blinds and lights to meet personal preferences for different tasks, once before computer-based tasks and once before paper-based tasks.

4.5.1 Descriptive analysis

Table 4.5.1 and Figure 4.5.1 summarize the means and standard errors of lighting energy demand in each lighting control sessions by sequence groups and tasks.

Table 4.5.1 Lighting energy demand (W) for computer-based tasks and paper-based tasks

		Fixed		MC		KBMC	
		Seq1	Seq2	Seq1	Seq2	Seq1	Seq2
Computer-based task	Mean	504	504	288	270	198	150
	SE	n/a	n/a	29.7	20.4	25.5	20.4
Paper-based task	Mean	504	504	342	300	252	204
	SE	n/a	n/a	13.8	9.9	15	9.9

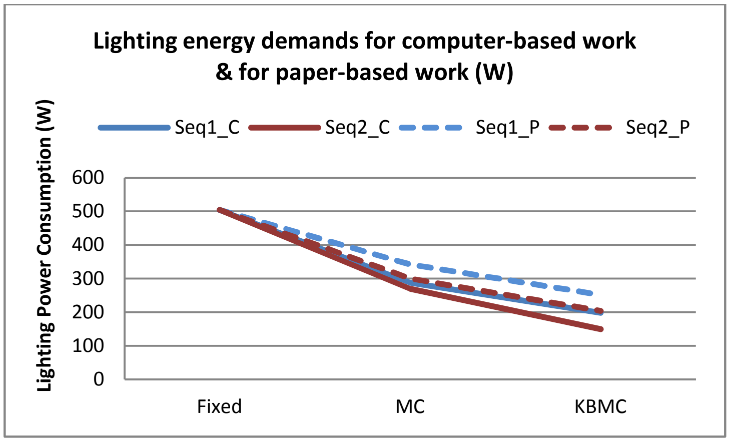

Figure 4.5.1 Lighting energy demands for computer-based tasks and paper-based tasks

Lighting control contributes observable differences to power demand. Participants reduced lighting power levels by half when they manually operated blinds and lights by 45% for computer-based tasks and by 36% for paper-based task. Real-time feedback led participants further reduce lighting power demand by 37% for computer-based tasks and 39% for paper-based task. Participants in both sequence group 1 and 2 followed the same trend line in power demand among lighting control sessions. Consistently, participants set higher levels for paper-based tasks as compared to computer-based tasks. Sequence 2 chose slightly lower overall light levels than in sequence 1, which might be caused by demographic difference.

4.5.2 Mixed model analysis

Mixed models are built to test whether power demands are different between the two sequence groups in a manual control session and in a knowledge-based manual control session. The results (Table 4.5.4) indicate that lighting power demands are not significantly different between the sequence groups.

With fixed ceiling based light, lighting power demand was the same for both sequence groups as well as both computer-based tasks and paper-based tasks. Ceiling luminaires were set at 100% output, while the task light was off. Lighting power demand was 503W.A lack of variance of power demand in fixed lighting makes it impossible for a mixed model to achieve convergence. However, if the interaction between sequence and lighting control is included in the mixed model as a fixed factor, the mixed model will be terminated. Table 4.5.2 shows the mixed model settings to test whether lighting control makes a difference in lighting power without a sequence effect being present. The results (Table 4.5.3) confirm that manual control does contribute to significant lighting power reduction for both computer-based tasks and paper-based task.

Table 4.5.2 Mixed model settings for determining the difference in lighting power demand among three lighting control sessions controlling for age, gender, education occupation, CVA and ESL

Repeated:	Lighting control
Repeated Covariance type:	Unstructured
Dependent variables:	Power demand for computer-based tasks Or power demand for paper-based task
Fixed factor(s):	Light control/ Age/Gender/Education/Occupation/ Corrected visual acuity/ESL/
Selected case(s):	All
Dependent variable(s):	Power demand for computer-based task/ Power demand for paper-based task
Sig of Light control:	<0.01

Table 4.5.3 Estimated mean of power demand controlling for age, gender, education, occupation, CVA and ESL, and the significance by lighting control

Lighting power (W)	Value	Sig. (pairwise comparisons with power in fixed lighting)
for computer-based task in MC	278	<0.01
for paper-based task in MC	321	<0.01
for computer-based task in KBMC	174	<0.01
for paper-based bask in KBMC	228	<0.01

Table 4.5.4 Estimated power demand within MC or KBMC and the significance of task sequence

			Estimated Mean	Std. Error	Sig. of Pairwise comparisons
MC	Computer-based task	Sequence group 1	249	45	0.872
		Sequence group 2	243	44	
	Paper-based task	Sequence group 1	294	43	0.298
		Sequence group 2	255	43	
KBMC	Computer-based task	Sequence group 1	265	37	0.101
		Sequence group 2	212	27	
	Paper-based task	Sequence group 1	284	42	0.094
		Sequence group 2	222	41	

4.5.3 Summary for power demand

The results of the mixed models results (Table 4.5.4) indicate that lighting power demands are not significantly different between the sequence groups. The two sequence groups will be combined in power demand analysis. As illustrated in Figure 4.5.2 the average lighting power demand reduced from 503w in the fixed lighting session, to 278w in the manual control session, and further reduced to 174 W in KBMC when participants worked on a computer-based task. The desktop light level followed the trend of power demand and decreased from 459 lux to 365 lux, and to 222 lux. When participants were working on computer-based tasks, they chose ceiling luminaire output to be on at 54%, providing 365 lux on a desktop with daylight. When participants had real-time knowledge, they further reduced ceiling luminaire output to 34%, providing 222 lux together with daylight. These levels approach the 200 lux that are the minimum allowed by IESNA for a computer-based task.

Table 4.5.5 Lighting power consumption and desktop light level

		Fixed	MC	KBMC
Computer-based task	Desktop light level (lux)	459	365	222
	Lighting Power (W)	503	278	174
Paper-based task	Desktop light level (lux)	464	621	636
	Lighting Power (W)	503	321	228

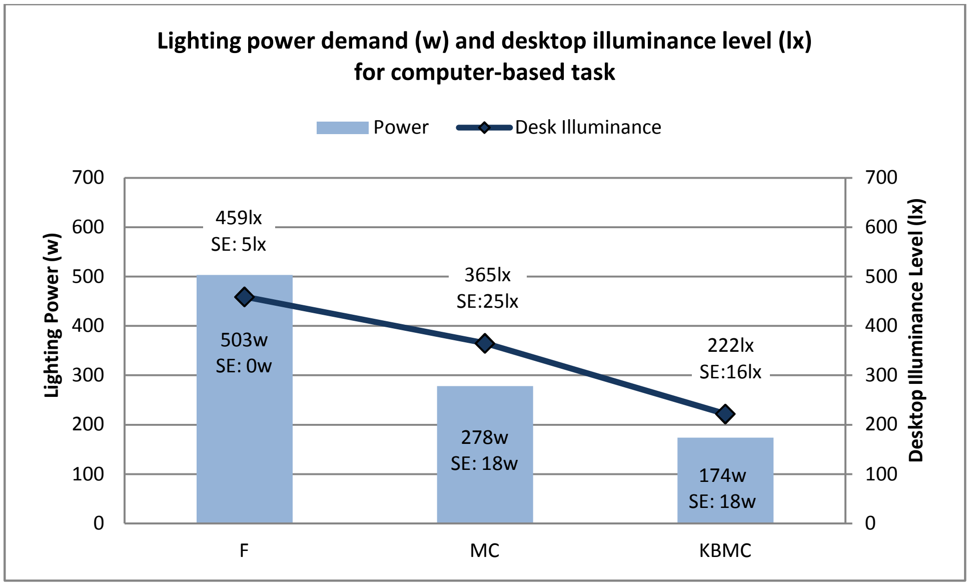

Figure 4.5.2 Lighting power and desktop illuminance level for computer-based task

In the manual control session, when working on paper-based office tasks, 77% participants set ceiling luminaire output less than 80% of full capacity. The mean ceiling luminaire output was 62%. The power demand in manual control session is 321W, significantly lower than 503W in the fixed lighting session (p-value<0.01). Though the power demand was reduced by 36%, the desktop illuminance increased significantly to 621lux (p-value<0.01) because 55% of participants turned on the task light. The task light consumes only 14w. It was efficient to increase the local light level on the desktop for paper-based task at a lower energy cost. Furthermore when participants had real-time knowledge, 95% set the ceiling luminaire at less than 80%. The power demand was further reduced to 228W (p-value<0.01), while the illuminance level was not significantly different from the manual control (P-value=0.74) because more participants chose to use a task light (63%).

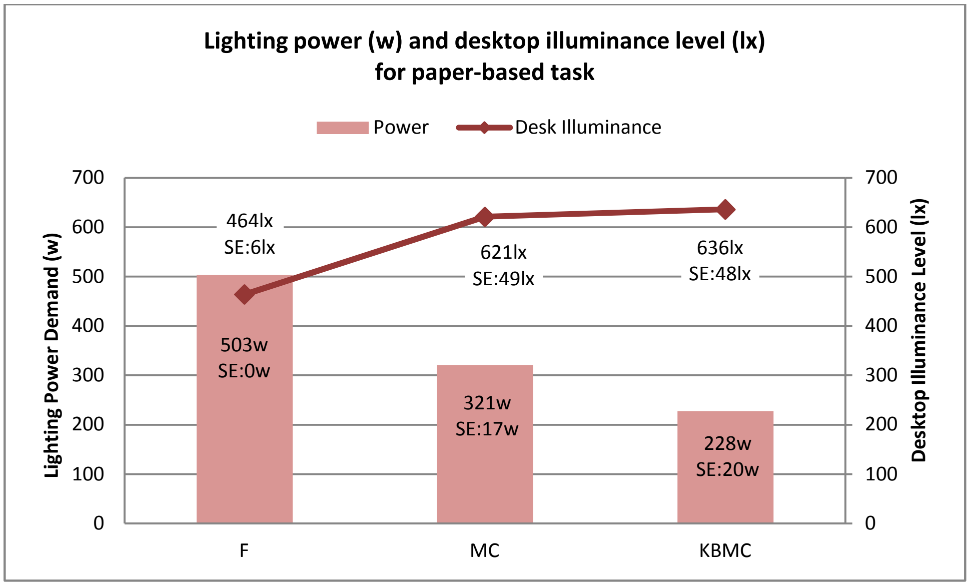

Figure 4.5.3 Lighting power and desktop illuminance level for paper-based task

It is concluded that providing the occupant of an office with control of blinds, ambient light and task light will reduce power demand relative to no personal control. The power demand will be further reduced if real-time knowledge and information are provided to the participant.

Hypothesis 1 that providing the occupant of an office with control of blinds, ambient light and task light will reduce power demand relative to no personal control is strongly supported (p-value<0.01) by the data.

Hypothesis 4 that providing the occupant of an office with control of blinds, ambient light and task light as well as real-time knowledge including suitability of light levels, related power consumption, equivalent CO_2 emission, and user "advisories", will reduce power demand relative to personalized control with no real-time knowledge as outlined above is strongly supported (p-value<0.01) by the data.

4.5.4 Light levels in MC and in KBMC

A mixed model is setup to verify the differences in ceiling luminaire output between MC and KBMC. Real-time knowledge helps users reduce ceiling luminaire output for both computer-based tasks (p-value<0.01) and paper-based tasks (p-value<0.01) (Figure 4.5.4). Based on 60 participants' selections, the mean ceiling luminaire output was reduced from 60% (SE: 6%) in MC to 40% (SE: 7%) in KBMC for computer-based tasks. The results are the same for paper-based task. The reduction of ambient light output contributes to decreased energy consumption.

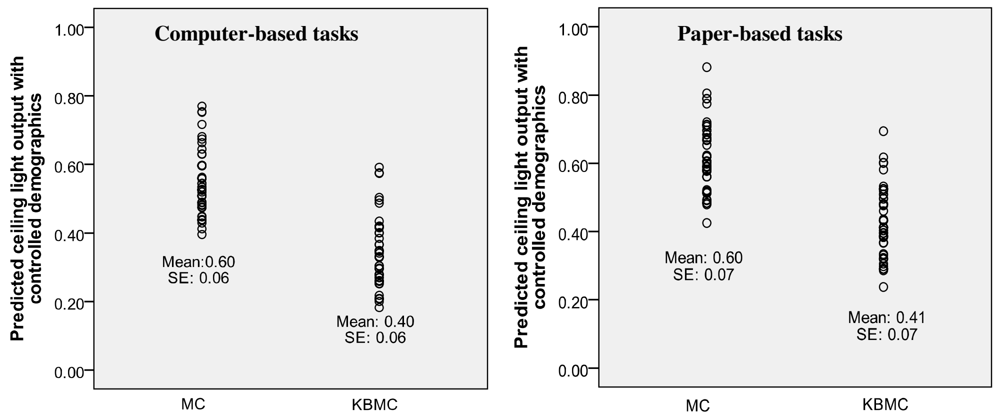

Figure 4.5.4 Percentage of ceiling luminaire output controlling for age, gender, education occupation, CVA and ESL

23% of the study participants used task light for computer-based tasks in MC. They were advised to turn off task light in KBMC. The percentage decreased to 7%, which is significantly lower than in MC (p-value<0.01). When performing paper-based tasks, participants were recommended to turn on a task light in KBMC. Though the percentage increased from 55% in MC to 63% in KBMC, the difference is not statistically different.

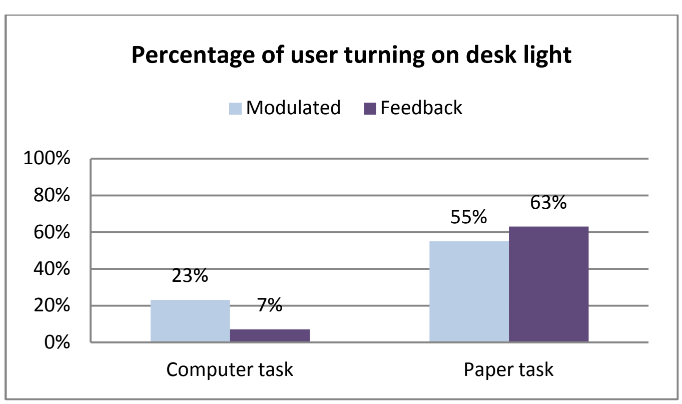

Figure 4.5.5 Percentage of participants turning on desk lamp

4.6 User satisfaction (H2, H5)

Hypothesis 2 (H2) and hypothesis 5 (H5) are related to user satisfaction. H2 assumes that providing occupants of an office with control of blinds, ambient light and task light will enhance office occupant satisfaction. H5 assumes that if occupants are given real-time knowledge, including the suitability of light levels, related power demand, equivalent CO_2 emission, and user advisories, their satisfaction will be further enhanced. User satisfaction is evaluated based on their answers to a questionnaire asking about the perception of light in the room in general, on the desk surface for paper-based tasks, and on the monitor for computer-based tasks. The answers were recorded on a 7-points-scale, ranging from -3 for too dim, to 0 for right amount, to +3 for too bright. The 7-scale perception is converted to 3-scale satisfaction in the data analysis in Table 4.6.1 for easy understanding.

Table 4.6.1 Coding of user satisfaction with light level

Perception of Light Level		Satisfaction with Light Level
±3, ±2		0 (strongly unsatisfied)
±1	→	1 (mildly unsatisfied)
0		2 (satisfied)

4.6.1 Descriptive analysis

User satisfaction with light level in the space is the lowest when light levels are fixed. The satisfaction rate improves with manual control. In KBMC, user satisfaction maintains about the same level as in MC. Sequence does not significantly alter the conclusions. However, for computer-based tasks, participants in sequence 2 had a lower satisfaction rate compared to participants in sequence group 1. One possible reason is that participants in sequence 1 worked on tasks in fixed lighting in the first round, while in sequence 2, participants worked in the fixed lighting session in the last round. With the experience of being able to reduce light level to meet computer task requirements in MC and KBMC, participants were much less satisfied with too much light on the computer monitor when conducting computer-based tasks.

Table 4.6.2 Satisfaction with general light in the space

Satisfaction with general light level		Fixed		MC		KBMC	
		Seq1	Seq2	Seq1	Seq2	Seq1	Seq2
Satisfied	N	20	16	23	23	24	24
	%	66.7%	53.3%	76.7%	76.7%	**80.0%**	**80.0%**
Mild unsatisfied	N	8	10	6	6	5	4
	%	26.7%	33.3%	20.0%	20.0%	**16.7%**	**13.3%**
Strongly unsatisfied	N	2	4	1	1	1	2
	%	6.7%	13.3%	3.3%	3.3%	**3.3%**	**6.7%**

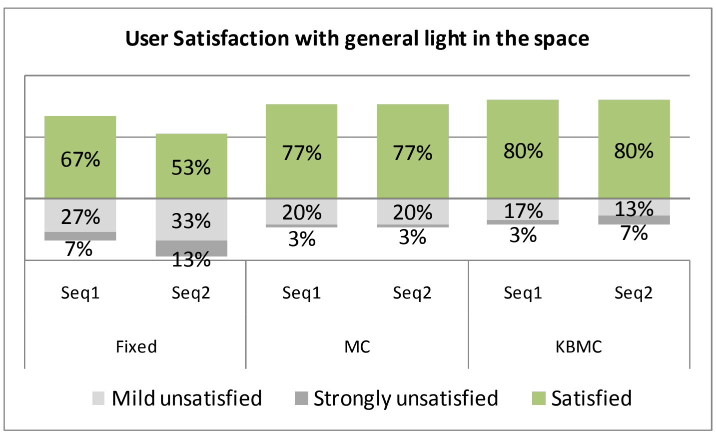

Figure 4.6.1 User satisfaction with general light in the space

Table 4.6.3 Summary of user satisfaction with light level for computer-based tasks

Satisfaction with light level for computer-based tasks		Fixed		MC		KBMC	
		Seq1	Seq2	Seq1	Seq2	Seq1	Seq2
Satisfied	N	20	12	24	19	25	23
	%	66.7%	40.0%	80.0%	63.3%	**83.3%**	**76.7%**
Mild unsatisfied	N	6	8	4	9	4	4
	%	20.0%	26.7%	13.3%	30.0%	**13.3%**	**13.3%**
Strongly unsatisfied	N	4	12	2	2	1	3
	%	13.3%	40.0%	6.7%	6.7%	**3.3%**	**10.0%**

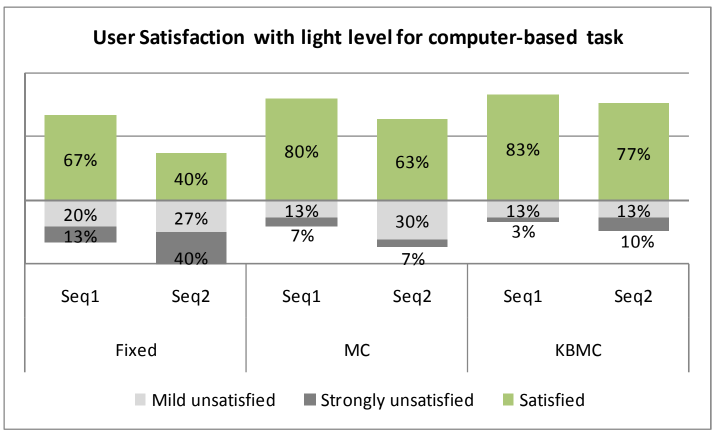

Figure 4.6.2 User satisfaction with light level for computer-based tasks

Table 4.6.4 User satisfaction with light level for paper-based tasks

User satisfaction with light level for paper-based tasks		Fixed		MC		KBMC	
		Seq1	Seq2	Seq1	Seq2	Seq1	Seq2
Satisfied	N	16	16	25	23	24	21
	%	53.3%	53.3%	83.3%	76.7%	**80.0%**	**70.0%**
Mild unsatisfied	N	12	9	4	5	5	8
	%	40.0%	30.0%	13.3%	16.7%	**16.7%**	**26.7%**
Strongly unsatisfied	N	2	5	1	2	1	1
	%	6.7%	16.7%	3.3%	6.7%	**3.3%**	**3.3%**

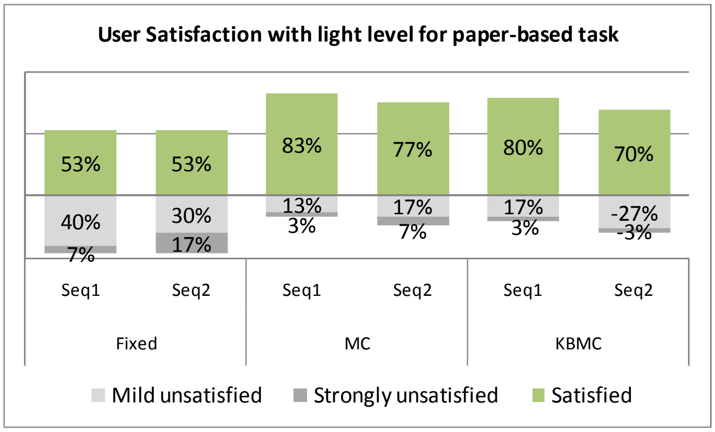

Figure 4.6.3 Users' satisfaction with light level for paper-based tasks

4.6.2 Mixed model analysis

A mixed model is set up as Table 4.6.5 to examine the significance of lighting control effect, sequence effect and their interaction in determining participants' satisfaction with light levels. The satisfaction with light level was dependent variable in mixed model. Three aspects of satisfaction were surveyed including satisfaction with general light level in space, with light level for computer-based task, and with light level for paper-based task. Fixed factors of mixed model include light control, sequence effect, the interaction between light control and sequence, and all demographics. The results (Table 4.6.6) show that lighting control is significant in predicting the three aspects of participants' satisfaction with light level. Neither the sequence nor the interaction between lighting control and sequence is significant in predicting user satisfaction.

Based on the results summarized by Figure 4.6.4 and Table 4.6.7, user satisfaction with light levels improves significantly in the manual control session or the KBMC compared to the fixed lighting session. Giving office occupants real-time knowledge keep the user satisfied with the light level, but does not further improve user satisfaction with the light level over manual control.

Table 4.6.5 Mixed model settings for checking lighting power demand differences among three lighting control sessions controlling forage, gender, education, occupation, CVA and ESL

Repeated:	Lighting control
Repeated Covariance type:	Unstructured
Dependent variables:	User satisfaction in general
Fixed factor(s):	Light control/Sequence/Control ×Sequence Age/Gender/Education/Occupation/ Corrected visual acuity/ESL/
Selected case(s):	All
Dependent variable(s):	Satisfaction with general light level in space/ Satisfaction with light level for computer-based task/ Satisfaction with light level for paper-based task

Table 4.6.6 Significance of lighting control, sequence and the interaction

User satisfaction with	Lighting Control	Sequence	Lighting control × Sequence
Light level in room in general	p-value = **0.02**	p-value = 0.98	p-value = 0.56
Light level on monitor for computer-based task	p-value < **0.01**	p-value = 0.32	p-value = 0.29
Light level on desktop for paper-based task	p-value < **0.01**	p-value = 0.46	p-value = 1.00

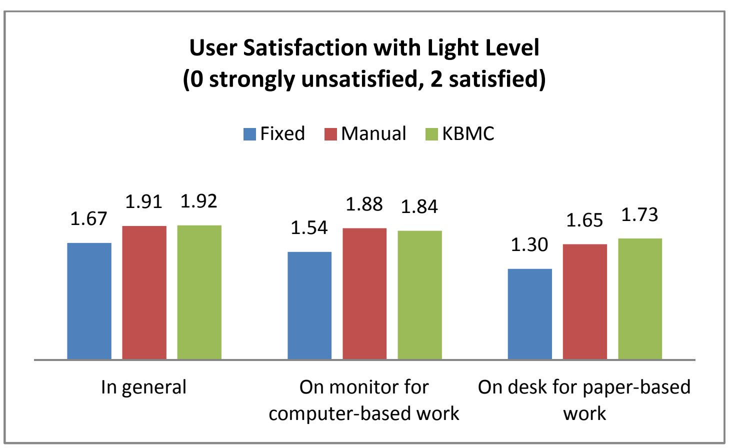

Figure 4.6.4 User satisfaction with light level

Table 4.6.7 Lighting control pairs with significant differences in user satisfaction controlling forage, gender, education, occupation, CVA and ESL

User satisfaction with	Pairwise comparisons	Significance
Light level in room in general	Fixed & MC	**0.02**
	Fixed & KBMC	**0.01**
	MC & KBMC	0.85
Light level on monitor for computer-based task	Fixed & MC	**<0.01**
	Fixed & KBMC	**<0.01**
	MC & KBMC	0.36
Light level on desktop for paper-based task	Fixed & MC	**<0.01**
	Fixed & KBMC	**<0.01**
	MC & KBMC	0.70

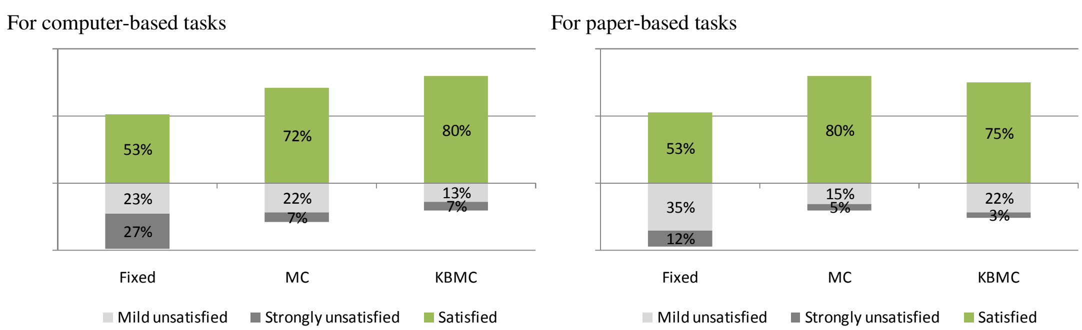

Figure 4.6.5 Participants' perceptions of light level

Hypothesis 2 that providing the occupant of an office with control of blinds, ambient light and task light will enhance office occupant satisfaction relative to no personal control is strongly supported (p-value<0.01) by the data.

Hypothesis 5 that providing the occupant of an office with control of blinds, ambient light and task light as well as real-time knowledge including suitability of light levels, related power consumption, equivalent CO2 emission, and user "advisories", will enhance occupant satisfaction relative to personalized control with no real-time knowledge as outlined above is not supported (p-value>0.20) by the data.

4.6.3 Exploration of participants' perception of light level in different lighting control sessions

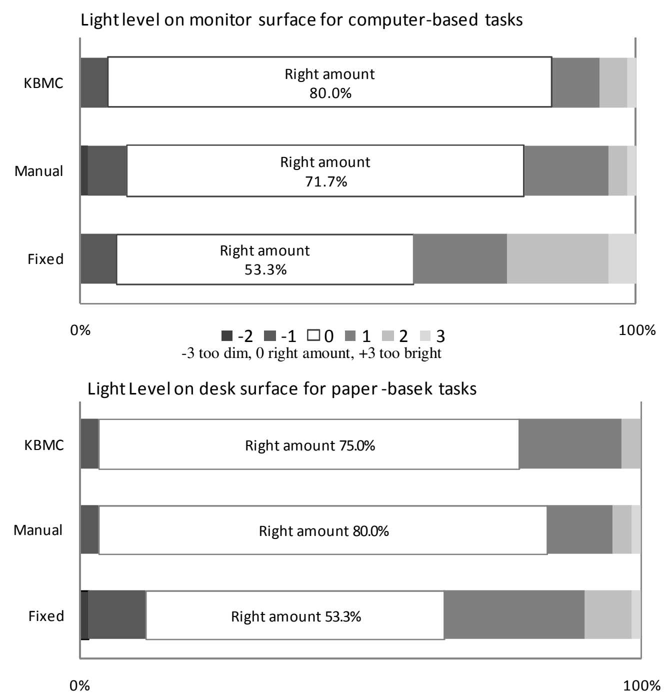

Figure 4.6.6 Perception of light level for computer-based tasks and paper-based tasks

The percentage of participants who perceived the right amount of light level was the lowest when participants worked in fixed light settings without personal control. 40% of participants perceived light level to be bright or too bright when they performed computer-based tasks in fixed lighting. 35% of participants perceived the same when doing paper-based work. The 460 lux illuminance level on the desk is more than sufficient for either computer-based work or paper-based work for the under 40 age group. Not being able to manipulate blind position and light output makes participants satisfied with the lighting environment.

In MC, the mean light level on the desktop is 365 lux for computer-based tasks. 72% of participants perceived the right light level. For the paper-based task, the mean light level was 631lux and 80% of participants perceived the right amount. Though the desktop light level for paper-based tasks in the fixed lighting session was lower than in the manual control session, participants perceived it too bright in the fixed lighting session. In the fixed lighting session, the ceiling electric light provided light evenly over the entire space, which may have caused the illusion of over-brightness, though the working surface was not as highly lit. When the task light was turned on, the local illuminance level increased, but participants did not perceive the working surface to be over-lit.

Real-time knowledge does not significantly change participants' satisfaction when participants had manual control blinds' position and light output, however, it does significantly increase satisfaction over fixed lighting with no manual control. The real-time knowledge still satisfied participants and helped to further reduce power demand.

4.7 Task Performance (H3, H6)

4.7.1 Task performance analysis steps

The three tasks given to a participant were evaluated individually according to the following steps:

Step 1: split the data into sequence group 1 and sequence group 2 to check lighting control effects and sequence effects in predicting task performance.

Step 2: observe the mean and standard error for each aspect of task performance.

Step 3: run a mixed model to check the significance of lighting controls in predicting task performance.

Step 4: run a mixed model controlling forage, gender, education, occupation, CVA and ESL to check the significance of lighting controls in predicting task performance.

Step 5: summarize the performance with the mean and standard deviation of the task performance.

4.7.2 Computer-based proofreading

The proofreading task is given to participants on a computer screen as two columns of numbers (Figure 4.7.1). Participants indicate whether five-digit numbers in the same row differ by placing a mark in a checkbox with the space key. Each page contains 20 rows of five-digit numbers, with 3~4 different numbers. When one screen is completed, participants continue to the next screen by pressing F5. The screen is designed with a white background and text font Courier New, size 9, in black. In each lighting control, participants are given 5 minutes. The performance is evaluated by speed (prs) and accuracy (pra). Prs is the percentage of the screen that is finished in one second. Pra is the number of correctly marked discrepancies divided by the sum of total discrepancies and falsely marked discrepancy numbers.

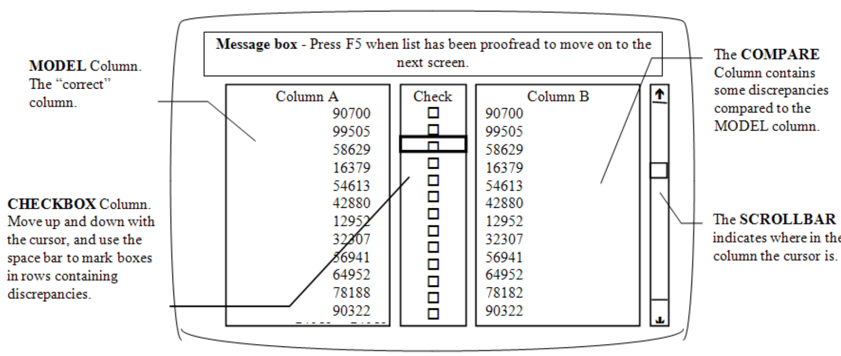

Figure 4.7.1 Screenshot of computer-based proofreading

4.7.2.1 Descriptive analysis for computer-based proofreading speed

Table 4.7.1 and Figure 4.7.2 show the mean and standard errors of the proofreading speeds for two of the sequence groups among the three lighting controls. There is no difference between the proofreading speed in the fixed lighting and manual control. Participants in the first sequence group in KBCM slightly increased their proofreading speed compared with sequence 1 participants in the fixed lighting and manual control groups, while those in KBCM's second sequence group slightly decreased their speed.

Table 4.7.1 Proofreading speed by lighting controls for the sequence group 1 and groups 2

		Fixed		MC		KBMC	
		Seq1	Seq2	Seq1	Seq2	Seq1	Seq2
Prs	Mean	0.030	0.031	0.031	0.031	0.034	0.029
	Standard Error	0.001	0.002	0.001	0.002	0.001	0.002

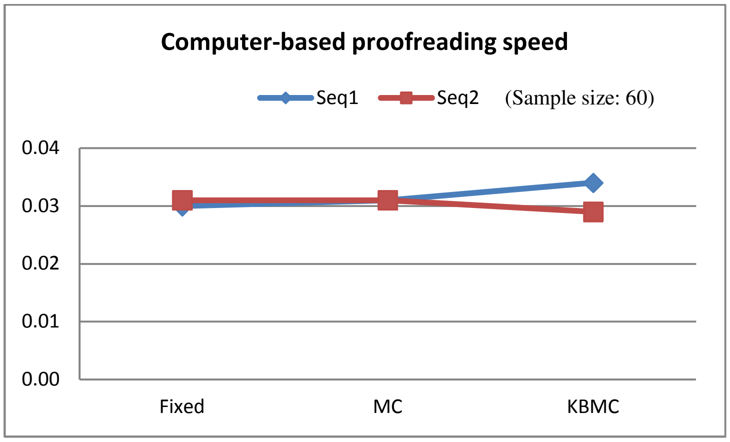

Figure 4.7.2 Proofreading speed

4.7.2.2 Mixed model analysis for computer-based proofreading speed

Mixed model analysis confirmed the results found in the descriptive analysis which showed that neither lighting control nor sequence alone significantly make a difference in proofreading speed, while interaction between lighting control and sequence does make a difference. In KBMC, the difference between the two sequence groups contributes to this interaction effect.

Table 4.7.2 Mixed model settings used to determine the significance of light control, sequence and interaction between the two factors for prediction of proofreading speed

Repeated:	Light control
Repeated Covariance type:	Unstructured
Fixed factor(s):	Light control/Sequence/Control×Sequence
Estimated means for:	Light control

Table 4.7.3 Significance of light control, sequence and interaction in predicting proofreading speed

Source	Numerator df	Denominator df	F	Sig.
Light control	2	58.118	.642	.530
Sequence	1	57.279	.720	.400
Control × Sequence	2	58.118	21.017	.000

Controlling for demographic differences, including age, gender, education level, occupation, level of visual acuity and language background, did not change the significance of the interaction effect between lighting control and sequence; the effect of lighting control and sequence remain insignificant.

Table 4.7.4 Mixed model settings for determining the significance of light control, sequence and interaction in prediction of proofreading speed controlling forage, gender, education, occupation, CVA and ESL

Repeated:	Light control
Repeated Covariance type:	Unstructured
Fixed factor(s):	Light control/Sequence/ Control × Sequence Age/Gender/Education/Occupation/ Level of visual acuity/Language background/
Random factor(s):	Proofreading accuracy

Table 4.7.5 Significance of light control, sequence and the interaction in prediction of proofreading speed controlling forage, gender, education, occupation, CVA and ESL

Source	Numerator df	Denominator df	F	Sig.
Light control	2	56.108	1.302	.280
Sequence	1	51.271	.015	.903
Control × Sequence	2	58.788	8.880	.000

The impact of interaction between light control and sequence makes it difficult to draw a conclusion about whether lighting control enhances, decreases, or makes no difference on proofreading speed.

4.7.2.3 Descriptive analysis for computer-based proofreading accuracy

Table 4.7.6 and Figure 4.7.3 illustrate the mean and standard errors of proofreading accuracy for the two sequence groups and the three lighting control sessions. Participants in sequence group 1 performed the task with greater accuracy compared to participants in sequence group 2. Lighting controls had a different impact on the two sequence groups. Participants in sequence group 1 performed the proofreading task with the same level of accuracy under fixed lighting and manual control, while accuracy decreased in KBMC. Participants in sequence group 2 performed the proofreading task with the least accuracy in the fixed lighting session. Group 2's accuracy increased in the manual control session and further increased in KBMC.

Table 4.7.6 Proofreading accuracy

		Fixed		MC		KBMC	
		Seq1	Seq2	Seq1	Seq2	Seq1	Seq2
Pra	Mean	0.935	0.833	0.937	0.878	0.894	0.882
	Standard Error	0.011	0.023	0.008	0.028	0.012	0.020

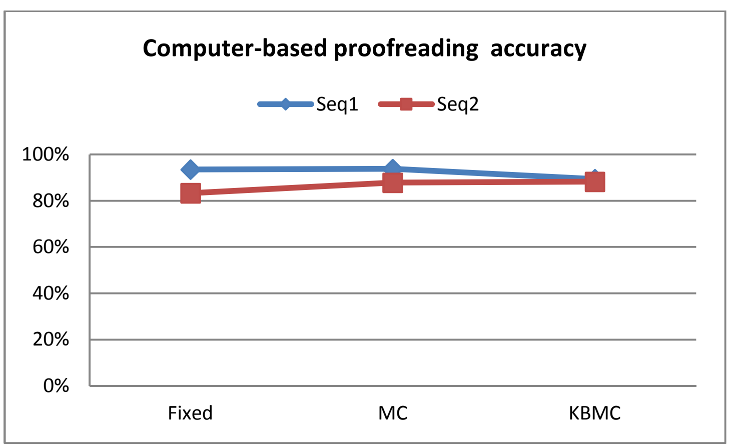

Figure 4.7.3 Proofreading accuracy

4.7.2.4 Mixed model analysis for computer-based proofreading accuracy

The mixed model results confirmed the observation made in the descriptive analysis that there is a significant difference between the two sequence groups in terms of proofreading accuracy. Sequence group 1 performed the task more accurately than sequence group 2. Interaction between lighting control and the sequence groups is also significant in predicting accuracy. In sequence group 1, the participants' performance in the tasks had the highest accuracy in MC, while participants in sequence group 2 performed them with the greatest accuracy in KBMC.

Table 4.7.7 Mixed model settings for determining the significance of light control, sequence and interaction in prediction of proofreading accuracy

Repeated:	Light control
Repeated Covariance type:	Unstructured
Fixed factor(s):	Light control/Sequence/ Control × Sequence
Random factor(s):	Proofreading speed

Table 4.7.8 Significance of light control, sequence and interaction in prediction of proofreading speed

Source	Numerator df	Denominator df	F	Sig.
Light	2	56.707	1.450	.243
Sequence	1	56.805	6.469	.014
Control × Sequence	2	56.707	9.617	.000

controlling for age, gender, education, occupation, CVA and ESL, the interaction between lighting control and sequence only showed marginally significant results in prediction of proofreading accuracy, while the impact of sequence still showed significance. With the presence of the significant sequence effect, lighting control was not significant in predicting proofreading accuracy.

Table 4.7.9 Mixed model settings for determining the significance of light, sequence and interaction in prediction of proofreading accuracy age, gender, education, occupation, CVA and ESL

Repeated:	Light control
Repeated Covariance type:	Unstructured

Fixed factor(s):	Age/Gender/Education/Occupation/ Level of visual acuity/Language background/ Light control/Sequence/ Control × Sequence
Random factor(s):	Proofreading speed

Table 4.7.10 Significance of light control, sequence and interaction in prediction of proofreading speed controlling for age, gender, education, occupation, CVA and ESL

Source	Numerator df	Denominator df	F	Sig.
Light control	2	53.065	2.413	.099
Sequence	1	43.199	4.438	.041
Control × Sequence	2	57.968	2.646	.080

4.7.2.5 Mixed model analysis for computer-based proofreading

Speed-accuracy trade-off effect has been identified by researchers in the fields of psychology, decision science, human-computer interaction and others (Zelaznik et al., 1988; Forster et al., 2003; Zhai, et al., 2004). While a speed-accuracy trade-off effect has been found that the faster the speed, the lower the accuracy in proofreading performance, there is no rule of thumb to quantify the correlation between speed and accuracy. Wilkinson (Wilkinson, 1987) evaluated proofreading speed and accuracy separately for a study comparing performance on a visual display unit and on a paper-based text. The trade-off effect between speed and accuracy makes it difficult to draw conclusion of enhanced or worse proofreading performance unless both speed and accuracy agree on the direction. Additionally, studying speed and accuracy separately in terms of lighting controls is not the interest of this research. One performance score which tells the difference caused of lighting control or other factors is valuable for the research. One equation is proposed for evaluating proofreading performance, the product of the speed and square accuracy: $speed \times accuracy^2$ (Day, 2010). The equation is built based the assumption that office employee is typically required to do the task accurately. Accuracy is usually more weighted than speed. Table 4.7.11 and Figure 4.7.4 illustrate the mean of the proofreading tasks in terms of sequence and lighting control sessions. A difference was found in proofreading performance between the two sequence groups, while lighting control only had a trivial impact on proofreading performance.

Table 4.7.11 Significance of light control, sequence and interaction in prediction of proofreading speed under controlling for age, gender, education, occupation, CVA and ESL

		Fixed		MC		KBMC	
		Seq1	Seq2	Seq1	Seq2	Seq1	Seq2
Pr	Mean	0.0269	0.0216	0.0274	0.0233	0.0271	0.022
	Standard Error	0.00121	0.00142	0.00126	0.00137	0.00124	0.0125

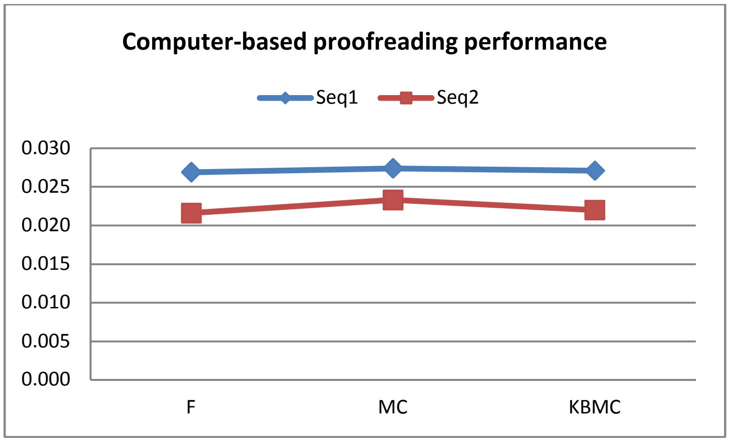

Figure 4.7.4 Proofreading performance in terms of sequence and lighting controls

The mixed model results were consistent with the descriptive analysis which found that lighting control does not have an impact on proofreading performance (p-value=0.19), while the difference found between the two sequence groups was significant (p-value<0.01). Interaction between lighting control and sequence was not significant (p-value=0.53). When demographics were controlled, the sequence effect was no longer significant (p-value=0.11).

Table 4.7.12 Mixed model settings for determining the significance of light control, sequence and interaction in prediction of proofreading speed × accuracy

Repeated:	Light control
Repeated Covariance type:	Unstructured
Fixed factor(s):	Light control/Sequence/Control × Sequence
Random factor(s):	None

Table 4.7.13 Significance of light control, sequence and interaction in prediction of proofreading speed × accuracy²

Source	Numerator df	Denominator df	F	Sig.
Light	2	57.064	1.720	.188
Sequence	1	57.034	7.774	.007
Control × Sequence	2	57.064	.638	.532

Table 4.7.14 Mixed model settings for determining the significance of light control, sequence and interaction in prediction of proofreading speed × accuracy² controlling for age, gender, education, occupation, CVA and ESL

Repeated:	Light control
Repeated Covariance type:	Unstructured
Fixed factor(s):	Age/Gender/Education/Occupation/ Level of visual acuity/Language background/ Light control/Sequence/ Control × Sequence
Random factor(s):	None

Table 4.7.15 Significance of light control, sequence and interaction in prediction of proofreading speed × accuracy² controlling for age, gender, education, occupation, CVA and ESL

Source	Numerator df	Denominator df	F	Sig.
Light control	2	56.516	1.710	.190
Sequence	1	49.851	2.679	.108
Control × Sequence	2	56.516	.631	.536

4.7.2.6 Proofreading performance summary

None of the parameters, lighting control, sequence, or interaction between these two, had an impact on the participants' proofreading performance. Figure 4.7.5 summarizes the predicted mean of the proofreading performance for all three lighting control sessions controlling for age, gender, education, occupation, CVA and ESL.

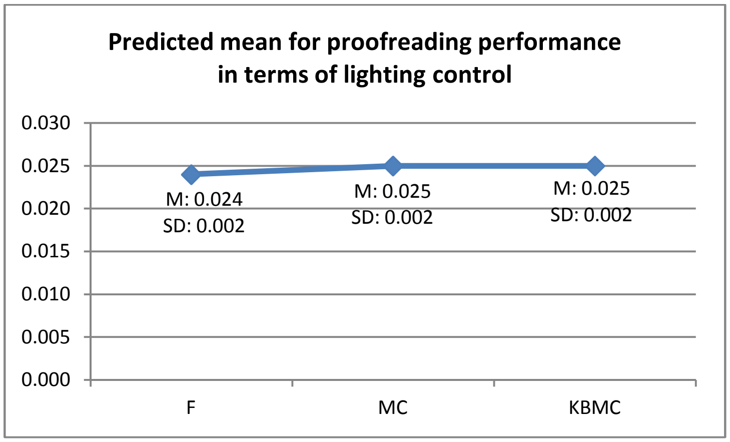

Figure 4.7.5 Predicted mean and standard errors of proofreading performance in terms of lighting control

4.7.3 Typing Task

For the typing task, participants were asked to copy the model text from one window on the top of a computer screen into another window at the bottom of the screen. The participant was required to correct any mistake before they could key in the next word. The participants' typing speed, as characters were keyed excluding errors, was recorded every minute. Participants worked on the typing task for 15 minutes in each session. The participants' typing task performance was evaluated by the number of accurate characters keyed in per second (cps).

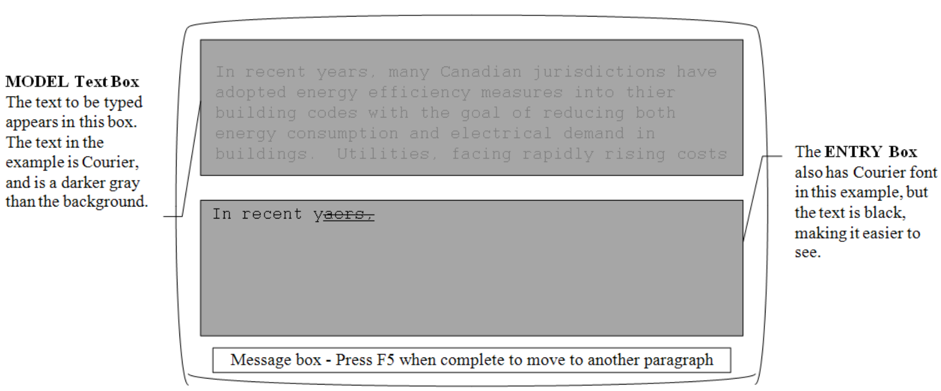

Figure 4.7.6 Screen shot of typing task

4.7.3.1 Descriptive analysis for accurate typing speed

Sequence group 1's mean accurate typing speed was slower than sequence group 2's. We attributed this to the fact that more participants in sequence group 1 are not native English speakers; for 93% of the participants in sequence group 1, English is a second language, compared to 77% of sequence group 2. Here we also analyze order, which refers to the time sequence in which a participant performed each task. Order 1 is the first round in which participant performed the typing task, order 2 refers to the second round, and order 3 refers to the third round. The benefit of practice can be observed from the results showing that typing speed is fastest in the Figure 4.7.8.

Table 4.7.16 Accurate typing speed

		Fixed		MC		KBMC	
		Seq1	Seq2	Seq1	Seq2	Seq1	Seq2
Typing	Mean	2.900	3.588	2.878	3.422	3.069	3.445
	Standard Error	0.153	0.246	0.160	0.226	0.169	0.216

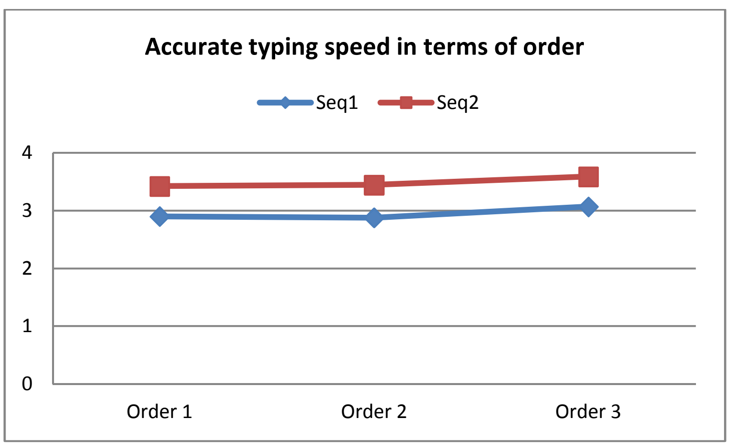

Figure 4.7.7 Accurate typing speeds in terms of order and sequence group

4.7.3.2 Mixed model analysis for accurate typing speed

Figures 4.7.7 and 4.7.8 show us that the more times that participants performed the task, the faster their speed. In the mixed model analysis, lighting control, sequence and order were included as fixed factors to test their significance in predicting proofreading speed.

Order made a significant difference on proofreading speed (Table 4.7.18). Sequence showed marginal significance. Controlling for age, gender, education, occupation, CVA and ESL, the sequence effect was insignificant due to the impact of controlling language background. It still shows order is significant in predicting accurate typing speed.

Table 4.7.17 Mixed model settings for determining significance of light control, sequence and order in prediction of accurate typing speed

Repeated:	Light control
Repeated Covariance type:	Unstructured
Fixed factor(s):	Light control/Sequence/Order
Random factor(s):	None

Table 4.7.18 Significance of light control, sequence and order in predicting accurate typing speed

Source	Numerator df	Denominator df	F	Sig.
Light	2	57.712	1.034	.362
Sequence	1	58.000	3.611	.062
Order	2	86.948	6.710	.002

Table 4.7.19 Mixed model settings for determining significance of light control, sequence and order in prediction of accurate typing speed controlling for age, gender, education, occupation, CVA and ESL

Repeated:	Light control
Repeated Covariance type:	Unstructured
Fixed factor(s):	Light control/Sequence/ Order Age/Gender/Education/Occupation/ Level of visual acuity/Language background
Random factor(s):	None

Table 4.7.20 Significance of light control, sequence and order in prediction of accurate typing speed controlling for age, gender, education, occupation, CVA and ESL

Source	Numerator df	Denominator df	F	Sig.
Light	2	57.666	.990	.378
Sequence	1	51.788	1.938	.170
Order	2	86.900	6.792	.002

4.7.3.3 Accurate typing speed performance summary

Results showed that lighting control made no impact on typing speed accuracy. There was also no difference between the two sequence groups in typing speed. Figure 4.7.9 illustrates the mean value of typing accurate typing speed in terms of lighting control sessions with combined sequence groups.

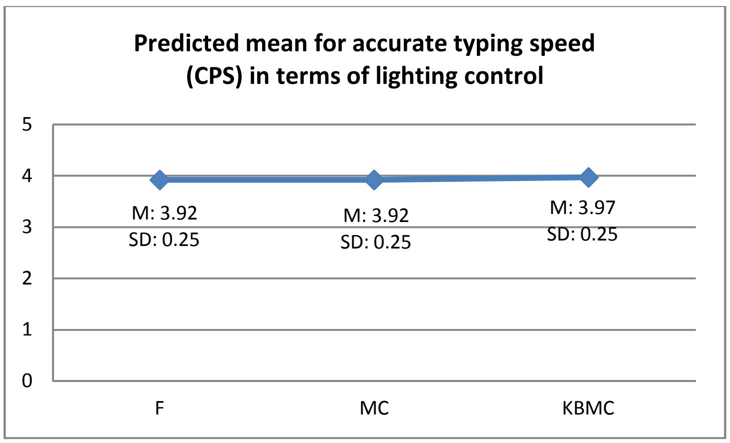

Figure 4.7.8 Accurate typing speed in terms of lighting controls

4.7.4 Paper-based phone-number search

The task of searching for phone numbers in the white-pages was meant to simulate a paper-based office task. Participants were asked to search for as many phone numbers as possible within 10 minutes for given first and last names. The number of phone numbers found were recorded as each participants' performance score.

4.7.4.1 Descriptive analysis for phone-number search performance

There was a slight difference between the two sequence groups in the phone-number search performance. Figure 4.7.10 reveals that lighting control had only trivial impact. The mixed model analysis confirmed that lighting control and sequence effects on the paper-based phone number search were not significant.

Table 4.7.21 Accurate phone-number searching speed

		Fixed		MC		KBMC	
		Seq1	Seq2	Seq1	Seq2	Seq1	Seq2
Phone#	Mean	12.900	13.931	12.200	13.300	12.833	13.400
	Standard error	0.655	0.616	0.637	0.586	0.638	0.537

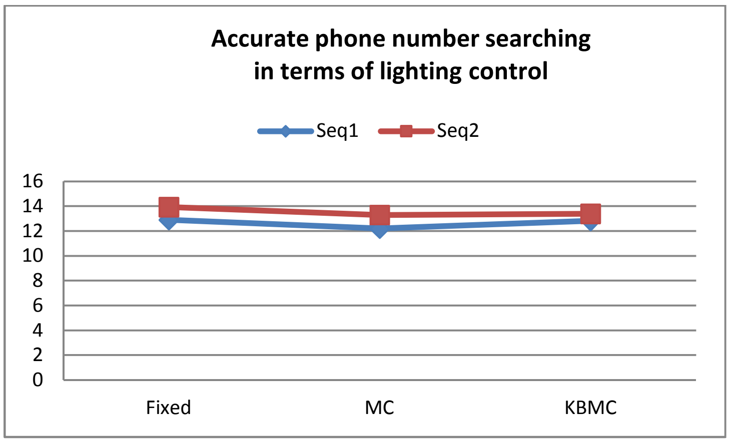

Figure 4.7.9 Accurate phone number search speed in terms of lighting control

4.7.4.2 Mixed model analysis for accurate phone-number searching

Table 4.7.22 Mixed model settings for determining significance of light control, sequence and interaction in predicting accurate phone-number searching

Repeated:	Light control
Repeated Covariance type:	Unstructured
Fixed factor(s):	Light control/Sequence/Control × Sequence
Random factor(s):	None

Table 4.7.23 Significance of lighting control, sequence and interaction in prediction of accurate phone-number searching

Source	Numerator df	Denominator df	F	Sig.
Lighting control	2	91.594	.777	.462
Sequence	1	58.000	1.114	.295
Control × Sequence	2	91.594	1.620	.203

Table 4.7.24 Mixed model settings for determining significance of lighting control, sequence and interaction in prediction of accurate phone-number search controlling for age, gender, education, occupation, CVA and ESL

Repeated:	Lighting control
Repeated Covariance type:	Unstructured
Fixed factor(s):	Lighting control/Sequence/ Control × Sequence Age/Gender/Education/Occupation/ Level of visual acuity/Language background/
Estimated means for:	Lighting control

Table 4.7.25 Significance of lighting control, sequence and interaction in prediction of accurate phone-number search controlling for age, gender, education, occupation, CVA and ESL

Source	Numerator df	Denominator df	F	Sig.
Lighting control	2	91.594	.777	.463
Sequence	1	51.154	2.111	.152
Control × Sequence	2	91.594	1.620	.203

4.7.4.3 Phone-number search performance summary

Figure 4.7.11 shows the predicted mean for accurate phone number search controlling for age, gender, education, occupation, CVA and ESL, obtained from the mixed model.

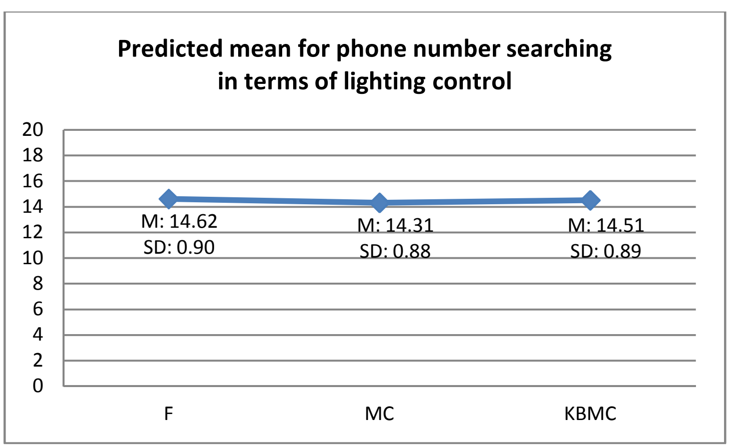

Figure 4.7.10 Predicted mean and standard error for phone-number search in terms of lighting control

4.7.5 Task performance summary

Proofreading:

- Proofreading performance is assessed by speed × accuracy^2. The equation includes the interaction between speed and accuracy, while putting more weight on accuracy because its greater importance in office work evaluation compared to speed.
- Sequence and interaction between sequence and lighting control was **not** significant
- Lighting control was **not** significant in predicting proofreading performance

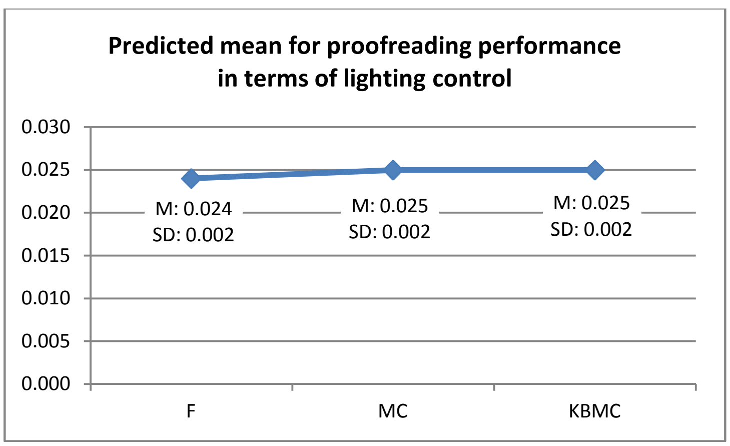

Figure 4.7.11 Predicted mean and standard errors of proofreading performance in terms of lighting control

Accurate typing speed:

- Order played a **significant** role
- Sequence was **not** significant with the presence of order effect
- Lighting control was **not** significant in predicting accurate typing speed with the presence of order effect

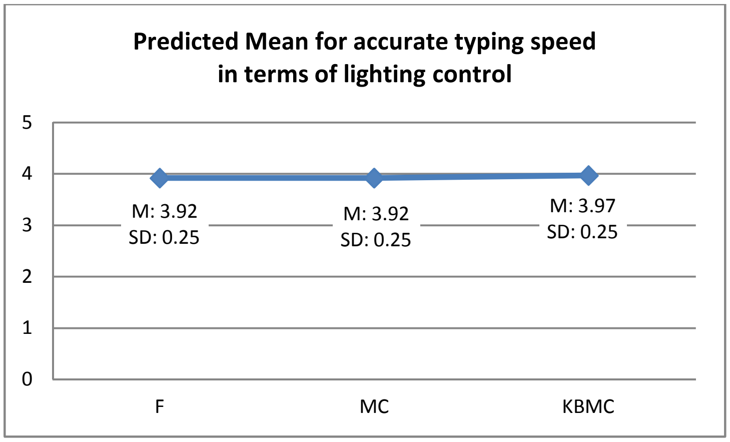

Figure 4.7.12 Predicted mean and standard errors for accurate typing speed in terms of lighting control

Accurate phone-number search speed:

- Sequence and interaction between sequence and lighting control were **<u>not</u>** significant
- Lighting control was **<u>not</u>** significant in predicting accurate phone-number search speed

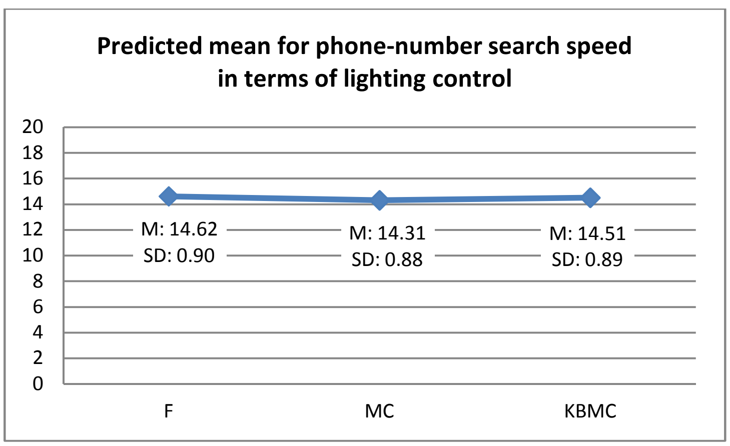

Figure 4.7.13 Predicted mean and standard errors of phone-number search speed in terms of lighting control

Our results showed no significant difference in office task performance across lighting control sessions.

Hypothesis 3 that providing the occupant of an office with control of blinds, ambient light and task light will improve task performance relative to no personal control is not supported (p-value>0.1) by the data.

Hypothesis 6 that providing the occupant of an office with control of blinds, ambient light and task light as well as real-time knowledge including suitability of light levels, related power demand, equivalent CO2 emission, and user "advisories", will improve task performance relative to personalized control with no real-time knowledge as outlined above is not supported (p-value>0.1) by the data.

4.8 Occupant behavior setting blind positions, dimming ceiling luminaire and turning task lighting on/off

4.8.1 Blind position control

As previous described, office occupants have control over two blinds: The user-side blinds mostly contribute to daylight on the working surface (Figure 4.8.1). When the user-side blind is in an "up" position, it provides views to outside and full daylight levels. When the user-side blind is in the down but "open" position, the working area still benefitted around 80% of daylight, but occupants' view to outside was modified. When the blind is down "closed", it blocks most daylight and gives no view to outside. KBMC recommends that the workplace occupants lift the blinds to the "up" position to maximize daylight in working area. Occupants respond to the recommendations. The percentage of occupants who close the user-side blind is significantly (p-value=0.01) reduced by avoiding behavior but no initiating behavior (Figure 4.8.2). The recommendation does not significantly (p-value=0.16) increase the percentage of occupants who set the blind in an "up" position. Real-time knowledge has some impact on occupants' decision making in setting blind positions, but not all. These results agree with the literatures listed in chapter 2, concluding that office occupants will not actively change blind position unless there is direct glare in the working area, with no other trigger evidence to make occupants to change blind positions.

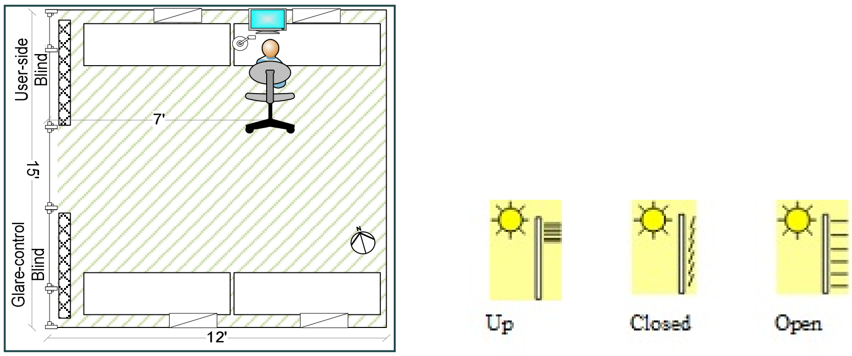

Figure 4.8.1 User-side bind and glare-control blind locations and operable positions

The glare-control blind is located at the window behind the occupant, through which direct sunlight may shine on the working surface in the afternoon (Figure 4.8.1). If there is no direct sunlight shining on work surfaces, occupants were recommended to lift the glare-control blind to the "up" position by the KBMC. Most participants accepted the default "open" position in the morning, for which no action was required. Most occupants did not re-set the blind position when switching from computer-based task to paper-based task.

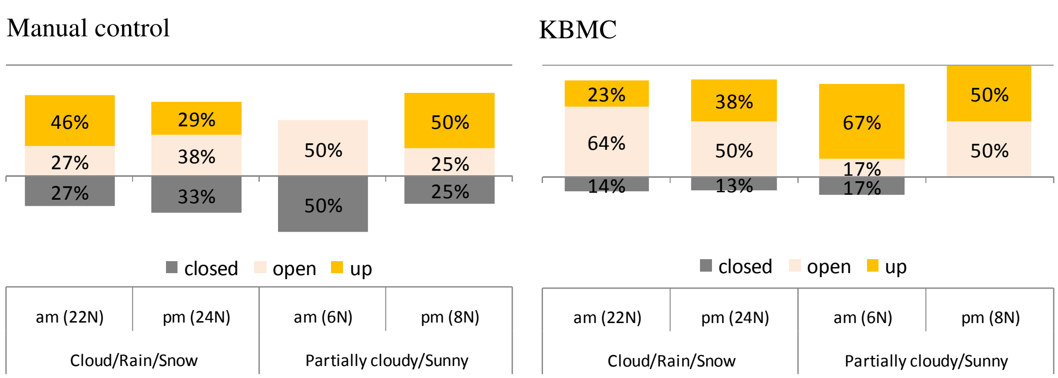

Figure 4.8.2 User-side blind positions for computer-based task

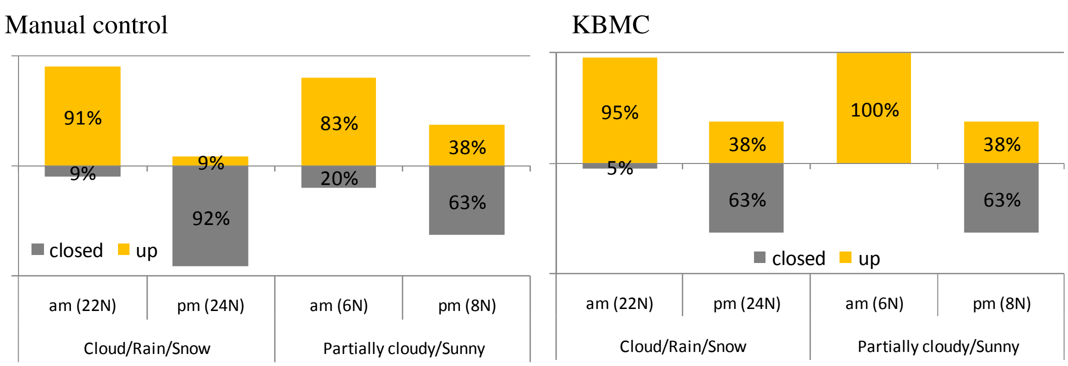

Figure 4.8.3 Glare-control blind position for paper-computer based

4.8.2 Ceiling luminaire output control

The KBMC provides occupants information about their real-time lighting energy use. It recommends to dim ceiling lumniour to meet a minumum 200 lux desktop requirement when computer-based or paper-based tasks are undertaken (IESNA, 2007). 68% of studied participants reduced ceiling luminaire power demand in KBMC, while 20% occupants increased lighting power density. The 12% kept the lighting power the lighting levels almost the same. Real-time knowledge helped most occupants reduce ceiling luminaire output for both computer-based task and paper-based task.

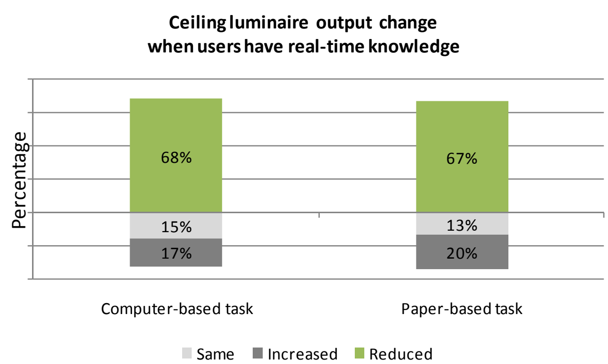

Figure 4.8.4 Percentage of occupants who reduced, or kept the same, or increased ceiling luminaire output with KBMC interface

4.8.3 Task light on/off control

Most occupants followed the KBMC recommendations to turn off task light when undertaking computer-based tasks (p-value<0.01). However, when they conducted paper-based task, they still followed their own preference on whether to use or not use task lights (p-value=0.13).

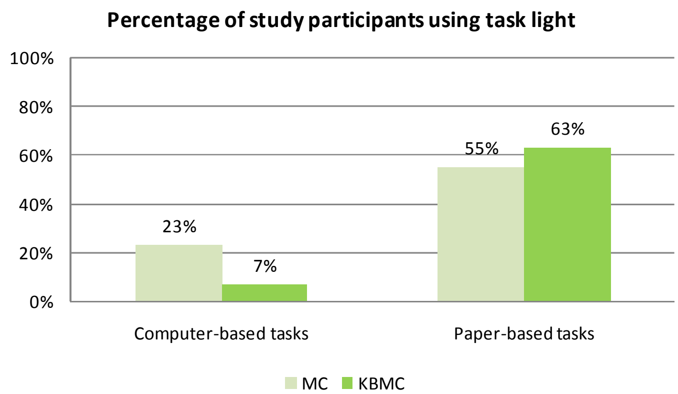

Figure 4.8.5 Percentage of study participants using task light

4.9 Value of real time knowledge

Over 70% of study participants stated that real-time information helped them decide how to operate the blinds, ceiling luminaires and task lights. All four aspects: suitability of light level, recommendations for blinds and lights settings, real-time power consumption, and real-time carbon emission related to electricity usage, were almost equally evaluated by users for the helpfulness. When asked to identify the most important feedback for decision-making, users also gave equal weight to all four aspects.

3.4 Does feedback on light, 'too dim', 'just right', and 'too bright' help you better operate blinds and lights for better light condition?

Absolutely No			Neutral			Absolutely Yes
-3	-2	-1	0	1	2	3
☐	☐	☐	☐	☐	☐	☐

3.5 Do recommendations for setting your lighting conditions help you better operate blinds and lights?

Absolutely No			Neutral			Absolutely Yes
-3	-2	-1	0	1	2	3
☐	☐	☐	☐	☐	☐	☐

3.6 Does real time energy consumption data influence your decisions to operate blinds and lights?

Absolutely No			Neutral			Absolutely Yes
-3	-2	-1	0	1	2	3
☐	☐	☐	☐	☐	☐	☐

3.7 Does real time carbon emission data influence your decisions to operate blinds and lights?

Absolutely No			Neutral			Absolutely Yes
-3	-2	-1	0	1	2	3
☐	☐	☐	☐	☐	☐	☐

Figure 4.9.1 Survey questions regarding helpfulness of the four categories of feedback knowledge

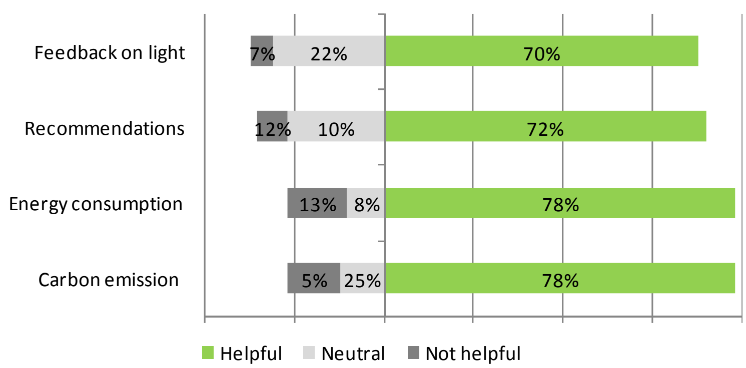

Figure 4.9.2 Percentage of participants stated the helpfulness of real-time knowledge

3.9 Which of the following most influenced your actions to operate lights or blinds?

- ☐ Feedback on light, 'too dim', 'just right', and 'too bright'
- ☐ Recommendations for setting your lighting conditions
- ☐ Real time energy consumption data
- ☐ Real time carbon emission data

Figure 4.9.3 Survey question regarding the most important category of feedback knowledge

Table 4.9.1 Most influential input from KBMC for setting lighting environment

Most influential	%
Feedback on light amount	31.7%
Recommendations for setting	38.3%
Real time energy use	33.3%
Real time carbon emissions	31.7%

Chapter 5 Conclusions

5.1 Background and research question

Individualized environments help meet a variety of demands for office occupants, making it possible to maximize office occupants' satisfaction and reduce energy use. In addition to variations in preferences for environmental conditions such as temperature, air quality and light levels, the quick pace and diverse nature of today's office work make individual environmental control a significant value for meeting various demands, such as computer work, paperwork, teleconferencing, group meetings and more. Individualized environments contribute to savings in energy because of the ability to respond to occupancy status and task requirements. However, building occupants often lack access to controls as well as knowledge and feedback to make the best decision in setting the temperature, ventilation or lighting conditions. Zosia Brown examined post-occupancy studies of green buildings and found gaps between predicted and actual energy and environmental performance, as well as between assumed and actual design comfort and comfort-related behaviour in buildings, due to individual controls (Brown, 2009). "While the availability and use of personal controls was higher in the green building, the quality of personal control in terms of responsiveness, the absense of immediate and relevant feedback, and poor user comprehension may have led to sub-optimal comfort conditions" (Brown and Cole, 2009). In 2000, David Wyon outlined design principles to "bring the user back into the control loop". The user "must understand the way that the building works and the consequences of their actions, so they must be given insight" (Wyon, 2000). The user "must learn to use the control delegated to them". "As learning cannot take place without feedback, they must be given online information. Only when they have both insight and information can they be given influence."

This dissertation is intended to establish both the value of control and of control with knowledge-based feedback. The office lighting environment was chosen for this study for two reasons. First, lighting plays a significant role in office environmental quality and energy use. Office occupants can be given information and knowledge to understand the available options and basic rules of "green" behavior. Second, unlike temperature and ventilation may have a time lag between user settings and measured environmental conditions, lighting systems react instantly to user input. The “no-lag” response of the lighting system controls makes it ideal for examining the value of user control. A controlled human subject experiment was carried out in this dissertation. The experimental conditions allowed for the study of how lighting power demand, subjective perceptions on lighting environment quality, and task performance are impacted by personalized lighting controls along or with real-time information. Real-time information regarding lighting environment operation includes the suitability of light-level based on the task, electricity consumption and equivalent carbon dioxide emissions, as well as expert recommendations for blind position, ceiling luminaire and desk lamp output. 60 participants were invited in this study to work on office tasks in three lighting control sessions in a high performance office with daylight control, dimmable ceiling luminaire and on/off task lights, with statistically significant results.

5.2 Individual lighting controls offer energy saving + higher user satisfaction + no decrement in task performance

When office occupants manually set blind position, ceiling luminaire output and the on/off status for task lights, lighting power demand is significantly (p-value < 0.01) reduced compared to the more conventional fixed ceiling luminaire output levels. Based on literature review of the time office occupant spent on tasks (Maniccia et al., 1999; Hua, 2007; Steelcase, 2001), this study assumes that office users spend 2/3 of their time on computer-based tasks and 1/3 time on paper-based tasks. The operating lighting power density in the fixed light session was 1.68w/sf for this experiment. The operational demand can be reduced by 42% if users manually control the space ambient light together with task light for local illuminance at low energy cost, as well as blind modification. The mean desktop illuminance level met the requirement defined by IESNA for both computer-based tasks and paper-based tasks for the age group of 40 or younger. Individual lighting control enabling a shift to tasks contributes to 42% lighting energy reduction.

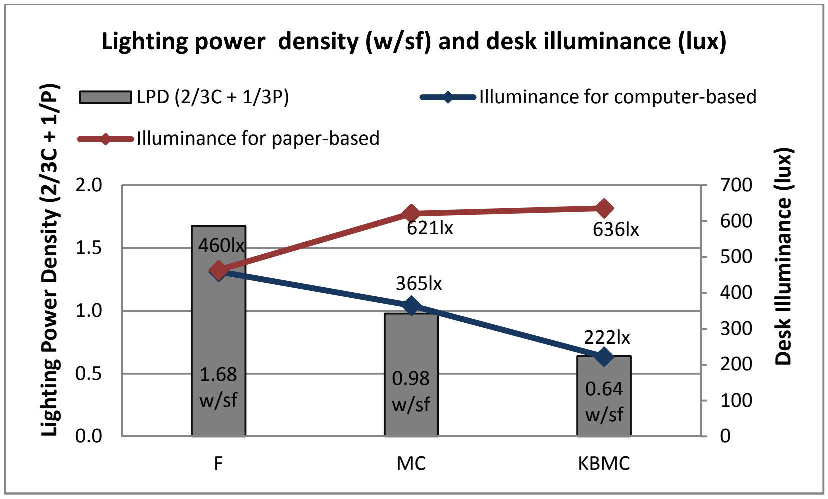

Figure 5.2.1 Lighting power density and desktop illuminance

In addition to high energy use, today's fixed ceiling luminaire output in office environment does not satisfy most occupants. In the fixed ceiling lighting settings, only 53% of occupants were satisfied with the light level on their varying tasks. When occupants are able to adjust blind positions, luminaire and task light output, their satisfaction rates increased to 72% for computer-based task and 80% for paper-based task.

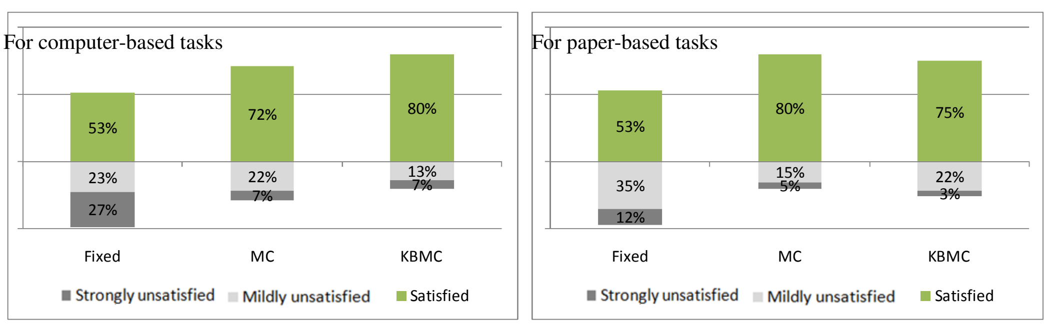

Figure 5.2.2 Participants' satisfaction with light levels

There are three major reasons for the reduced energy demands coincident with improved user satisfaction. Individualized lighting control enables users the opportunity to set environmental condition to meet personal preferences and the requirements of different tasks. When occupants become part of the "control loop", their satisfactory is easier to be achieved compared to automatic control. The separation of ambient and task lighting makes it possible to use lower ambient light levels, that consume and be less electricity for all computer based tasks. When participants work on tasks requiring high illuminance level, task light can increase the desktop illuminance at a low energy cost. Daylight helps eliminate or reduce the use of electrical lights. Glare control that prevents direct light in working are critical as well as users can freely regulate daylight amount.

5.3 Knowledge-based manual control offers more energy saving + no decrement in user satisfaction and task performance

Knowledge-based individual lighting control helps office occupants to set office lighting conditions that consider the suitability of the light level, the potential for energy conservation with related reduction of carbon dioxide emissions, and expert recommendations for blinds, ceiling luminaire and task light settings. Recommendations help occupants understand the right action to achieve comfort while reducing operational costs and environmental impact. The knowledge linking behavior to energy consumption and carbon emission does impact decisions of those committed to reducing energy consumption.

This dissertation revealed that with real-time knowledge, office occupants reduced lighting power demand while maintaining or increasing satisfaction with light levels for both computer-based tasks and paper-based tasks. The four categories of real time knowledge were classified as equally valuable that shall be presented to office occupants together with individual control.

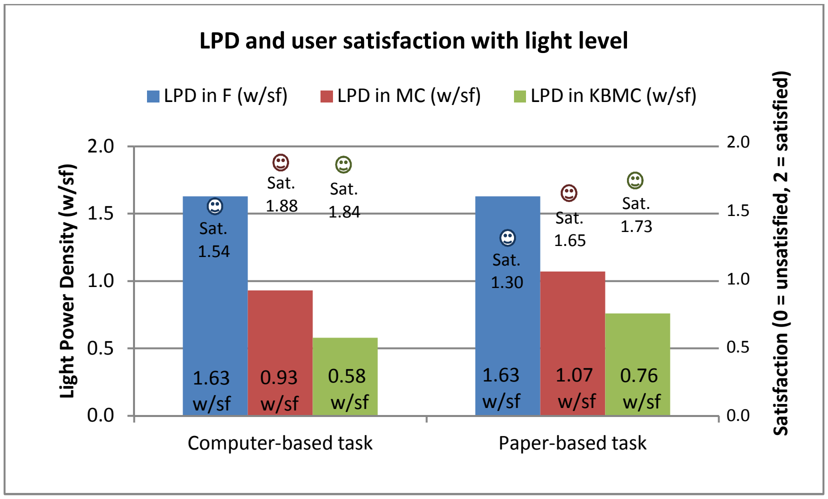

Figure 5.3.1 Lighting power density and user satisfactory

5.4 Potential national energy savings

Based on the 2003 Commercial Building Energy Consumption Survey (CBECS) data (EIA, 2010), the total office building floorspace in the United States is 64.8 billion. The total area of small office building (1,001 sf to 5,000 sf) is 4.8 billion square feet, while the total area of medium office building (5,001 sf to 50,000 sf) is 26.8 billion square feet. The total are of large office building (over 50,001 sf) is 31.2 billion square feet. Table 5.4.1 shows the expertise estimation of percentage of daylight area and open office in daylight area in office buildings in terms of floorspace area.

Table 5.4.1 Assumptions for national energy saving potential

Office building type based on size	Total area* (billion sf)	Percentage of potential daylight area (%)	Assumed percentage of open office in daylight area (%)
Small building (1,001 sf to 5,000 sf)	6.8	70%	50%
Medium (5,001 sf to 50,000 sf)	26.8	70%	50%
Large (over 50,001 sf)	31.2	20%	30%

* Reference: CBECS 2003

Table 5.4.2 Office lighting energy consumption by control options

	Base case	Occupancy sensor	Time scheduling + daylighting responsive
Private office	5.7 kwh/sf/yr	5 kwh/sf/yr	3.7 kwh/sf/yr
Open office	3.52 kwh/sf/yr	2.66 kwh/sf/yr	1.95 kwh/sf/yr

This study reveals that manual control (MC) contributes to 40% energy savings compared to no manual control. KBMC contributes to 60% energy savings. Based on the assumption that Federal Energy Management Program (FEMP, 2010) made for annual lighting energy use for private office and open office (Table 5.4.2), if manual control being applied in office area with daylight, the national energy reduction could reach 69.6 billion kwh/yr, compared to base case. The energy savings equals to 17.4 times of annual net generation of the Hoover dam (eBIDS, 2004). If KBMC is being applied, 92.1 billion kwh/yr electricity can be reduced, which equal to 23 times of annual net generation of the Hoover dam.

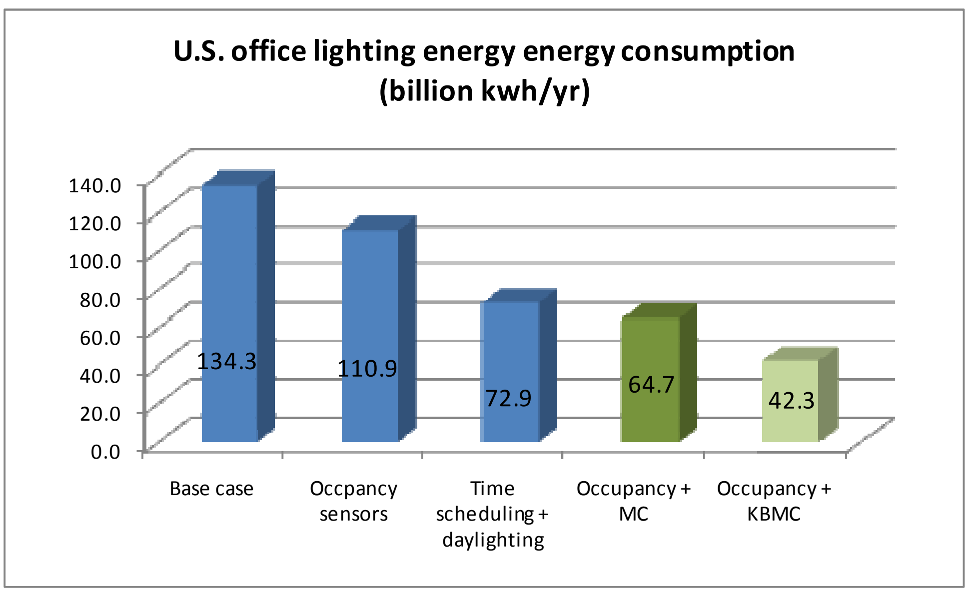

Figure 5.4.1 National energy saving potential of manual control and KBMC of offic lighting

5.5 Contributions

This study provides laboratory data to support that individual control helps achieve lighting energy reduction and improve office worker satisfaction without task performance decrement. The study also provides laboratory evidence that real-time knowledge and feedback help to achieve further energy reduction while sustaining user high user satisfaction and task performance.

✓ *Office occupants need personal environment control to achieve the 80% satisfaction*

In a test environment with fixed ceiling light setting in U.S. offices, only 53% of occupants were satisfied with the light level on the work surface for either computer-based task or paper-based task. When occupants manually operated the blinds, dimed ceiling luminaires and turn task light on/off in the test space, 80% user satisfaction rate could be achieved.

✓ *Manual ambient light, task light and blind control save as much as 40% energy, while increase satisfaction from 50% to 80%.*

Separated ambient and task light with personal glare free daylight control, dimmable ambient light and task lights, are keys for user satisfaction and energy savings. The flexibility of occupants to manipulate blinds and lights settings based on personal preference and task requirement offers 40% energy savings compared to a fixed office lighting design in a daylit office.

✓ *Real-time feedback and expert knowledge for understanding the lighting and daylighting choices further reduce energy by 20%, for a total of 60% over fixed ceiling luminaire output, while maintaining the high level of satisfaction.*

Real-time feedback on environmental conditions, energy consumption with emission consequence, and expert recommendations, help office occupants understand their options for setting blinds and lights. Office users equally ranked the importance of the four categories of the information to be useful in helping them make decisions. Total energy consumption is now reduced by 60% compared to fixed ceiling luminaire settings in a daylit office as user satisfaction rate is still at 80%.

5.6 Limitations and Future research:

5.6.1 Task performance measurement

This laboratory study invited and compensated participants to undertake 3 hours of computer-based and paper based tasks. The participants expected to be tested during this time period, so that most of them were well motivated to succeed. Three sessions of 30 minutes intensive office work is not the same as eight hours of work each day for months that in the true condition in office environments. Participants were interested in short-term achievement on task performance in the study, so that they intended to create a lighting environment to achieve this goal. But long term effects of KBMC on office occupants' decision might not be the same as in short term, being like that different strategies will be applied to run a 5-K or to run 100-m. Field studies in office buildings with randomized subjects in different lighting control groups will help to better explain the impact of lighting control on office occupants task performance

5.6.2 Climate conditions

All experiments were conducted in the winter season in predominant overcast sky conditions in west facing office settings. The limited sunlight and glare conditions may have impacted occupant needs to adjust blinds position. Future research should establish test environment in all four orientations in four seasons in multiple sky conditions including clear, partially cloudy and overcast sky.

5.6.3 Beyond lighting

This is a pilot study of how real-time information helps on office occupants to behavior "green", with lighting system as subject. Future studies can explore the impact of KBMC on thermal system, ventilation system, and even office appliances. For example, in space temperature modulation, KBMC shall tell occupant whether current condition falls in comfortable range based on measure indoor temperature and humidity, season, clo value, and metabolic level etc. In air quality setting, with measured indoor CO_2, VOC, particulate concentration, weather etc, system is able to tell occupant whether to increase or decrease mechanical ventilation rate or open/close window.

Bibliography:

Abrahamse, W., Steg, L., Vlek, C., Rothengatter, T. (2005). A review of intervention studies aimed at household energynext term conservation. *Journal of Environmental Psychology , 25* (3), 273-291.

ABSIC/CBPD. (2004). *7 Guidelines for High Performance Lighting for visual quality, resource conservation & environmental health*. Retrieved from eBIDS: http://cbpd.arc.cmu.edu/ebids/pages/group.aspx?group=3

Ander, G. (2003). *Daylighting Performance and Design.* (2nd, Ed.) Wiley.

ANSI/IESNA. *American National Standard Practice for Office Lighting.*

ANSI/IESNA. (2004). American National Standard Practice for Office Lighting.

Bamberg, S. (2003). How dose environmental concern influence specific environmentally related behaviors? A new answer to an old question. *Journal of Environmental Psychology , 23*, 21-32.

Baron, R.A. Thomley, J. . (1994). A whiff of reality: positive affect as a potential mediator of the effects of pleasant fragrances on task performance and helping. *Environment and Behavior* , pp. 766-784.

Bordass, W., Bromely, K., Leaman, A. . (1993). User and occupant control in buildings. *Proceedings of the International Conference on Building Design, Technology and Occupant Well-Being in Temperate Climate* .

Bordass, W., Bromley, K., Leam, A. (1993). User and occupant control in buildings. *Proceedings of teh International Conference on Building Design* .

Boyce, P. (1981). *Human Factors in Lighting.* Essex, England: Applied Science Publishers LTD.

Boyce, P. R. (2003). *Human factors in lighting.* London: Taylor & Francis.

Boyce, P., Veitch, J. A., Newsham, G. R., Myer, M., Hunter, C., . (2003). *Lighting Quality and Office Work: A Field Simulation Study.* National Research Council of Canada, Institute for Research in Construction.

Boyce, P.R., Eklund, N.H., Simpson, S.N. (2000). Individual lighting control: task performance, mood, and illuminance. *Journal of the Illuminating Engineer Society , Winter*, 131-142.

Boyce, P.R., Veith, J.A., Newsham, G.R., Myer, M., Hunter, C. (2003). *Lighting quality and office work: a field simulation study.* U.S. Department of Energy.

Brown, A. & Cole, R. (2008). Engaging occupants in green building performance: addressing the knowledge gap. *Proceedigns of the ACEEE Summer Study on Energy Efficiency in Buildings.* Asilomar, CA, U.S.: ACEEE.

Brown, Z. & Cole, R.J. (2009). Influence of occupants' knowledge on comfort expectations and behaviour. *Building Research & Information , 37* (3), 227-245.

Brown, Z. (2009, Dec). Occupant comfort and engagement in green buildings: examing the effects of knowledge, feedback and workplace culture. *Ph.D Thesis, University of British Columbia* .

Bülow-Hübe, H. (2001). Energy-efficient window system: effects on energy use and daylight in buildings. *Ph.D Dissertation, Lunds Unversity, Sweden* .

CBPD. (n.d.). *eBIDS - lighting*. Retrieved Jul 2010, from http://cbpd.arc.cmu.edu/ebids/pages/group.aspx?group=3

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences.* Hillsdale, New Jersey: Lawrence Erlbaum Associates, Inc.

Collins, B. (1976). Review of the psychological reaction to windows. *Lighting Research and Technology , 8* (2), 80-88.

Conway, B. (2010). *Office building*. Retrieved Jun 20th. , 2010, from Whole building Design Guide : http://www.wbdg.org/design/office.php

Cooper, J. R., Wiltshire, T. and Hardy, A. C. (1973). Attitude towards the use of heat rejecting/low light transmission glasses in office buildings. *Proc. CIE Conference, Window and their function in architectural design.* Instanbul.

Dashboard, B. (2010). Retrieved Aug 2010, from http://www.demandless.org/building/

Day, R. (2010, Oct.). A discussion in the "Biostatistics Consulting Practicum" class.

Demidenko, E. (2004). *Mixed models: theory and applications.* Hoboken, New Jersery: Wiley.

EIA. (2010, Sep.). *Energy Information Adiministration - Commercial Buildings Energy Consumption Survey*. Retrieved May 2011, from http://www.eia.doe.gov/emeu/cbecs/cbecs2003/officereport/office1.html

EIA. (2010). *Green Building*. Retrieved Aug 2010, from http://www.epa.gov/greenbuilding/pubs/about.htm

Faul, F., Erdfelder, E., Lang A. G., Buchner, A., . (2010, Jun.). *Heinrich-Heine-Universitat - Institut fur experimentelle Psychologie*. Retrieved Jan 2011, from http://www.psycho.uni-duesseldorf.de/abteilungen/aap/gpower3/download-and-register

FEMP. (2010, Apr.). *Federal Energy Management Program: Lighting Control Types*. Retrieved Apr. 2011, from http://www1.eere.energy.gov/femp/technologies/eep_light_controls.html

Fischer, C. (2007). Influencing electricity consumption via consumer feedback- a review of experience. *ECEEE 2007 summer study.* Berlin, Germany.

Foster, M., Oreszczyn, T. (2001). Occupant control of passive system: the use of venetian blinds. *Building and Envrionemnt , 36*, 130-136.

Geller, E. (2002). The challenge of increasing proenvironment behavior. In R. C. Bechtel, *Handbook of Enviornmental Psychology* (pp. 525-540). New York: Wiley.

Group, L. D. (2010). Retrieved Aug. 2010, from http://www.luciddesigngroup.com/research.php

Guillemin, A., Morel, N. (2001). An innovative lighting controller integrated in a self-adaptive building control system. *Energy and Buildings , 33*, 477-487.

Heerwagen, J. (1990). The psychological aspects of windows and window design. *Proceedings of the EDRA 21 Conference*, (pp. 269-280). Washington, DC,.

Heschong, L. (2006). Windows and office worker performance - the sumd call center and desktop studies. In D. Clements-Croome, *Creating the productive workplace* (pp. 277-309). Oxon: Taylor & Francis.

Heschong, L., Wright, R.L., Okura, S. (2002). Daylighting impacts on retail sales performance. *Journal of the Illuminating Engineering Society* , 21-25.

Hua, Y. (2007). Design open-plan workplace for collaboration: an exploration of the impact of workplace spatial settings on space perception and collaboration effectiveness . Ph.D dissertation.

IEA. (2005). *Daylighting Buildings in the 21st Century*. Retrieved Jul 2010, from International Energy Agency - Solar Heating and Cooling Programme: http://www.iea-shc.org/task31/

IEA. (2005, Aug). *Daylighting Buildings in the 21st Century*. Retrieved Apr. 2011, from http://www.iea-shc.org/task31/

IESNA. *IESNA - Office Lighting Guide 2007.*

Inkarojrit, V. (2006). Developing predictive venetian blinds control models using visual comfort predictors. *PLEA.* Geneva, Switzerland.

Inoue, T., Kawase, T., Ibamoto, T., Takakusa, S., Matsuo, Y. (1988). The development of an optimal control system for window shading deices based on investigations in office buildings. *ASHRAE Transactions , 94* (2), 1034-1049.

Jennings, J.D, Rubinstein, F.M, DiBartolomeo, D. (2000). Comparison of control options in private offices in an advanced lighting controls testbed. *Journal - illuminating engineering society* .

Karjalainen, S., Siivola, M., Johnson, M., Nieminen, M. (2007). User problems with individual temperature control in offices. *Building and Environment , 42* (8), 2880-2887.

Kiesler, S. (n.d.). *Sara Kiesl*. Retrieved July 2010, from http://www.cs.cmu.edu/~kiesler/.

Kiesler, S. (2009). *Sara Kiesl*. Retrieved July 2010, from http://www.cs.cmu.edu/~kiesler/.

Langdon, F. J. (1966). *Modern offices: a user survey.* London: HMSO.

Leslie, R.P., Raghavan, R., Howlett, O., Eaton, C. (2005). The potential of simplified concepts for daylight harvesting. *Lighting Research & Technology , 37* (1), 21-40.

Lindsay, C.R.T., Littlefair, P.J. (1993). Occupant use of venetian blinds in offices. Watford: Building Research Establishment.

Loutzenhiser, P.G., Manz, H., Felsmann, C., Strachan, P.A., Maxwell, G.M. (2007). An empirical validation of modeling solar gain through a glazing unit with external and internal shading screens. . *Applied Thermal Engineering , 37* (8-9), 833-843.

Mahdavi, A., Mathew,P., Kumar,S., Hartkopf,V. and Loftness, V. . (1995). Effects of Lighting, Zoning, and Control Strategies on Energy Use in Commercial Buildings. *Journal of the Illuminating Engineering Society of North America* , 25-35.

Maniccia, D., Rutledge, B., Rea, M.S., Morrow, W.,. (1999). Occupant use of manual lighting controls in private offices. *Journal of the Illuminating Engineering Society* , 42-56.

Mankoff, J., Fussell, S. R., Dillahunt, T., etc. (2010). StepGree.org: Increasign Energy Savings Behavior via Social Networks. *Proceedings of the 4th International AAAI Conference on Weblogs and Social Media.*

Manning, P. (1965). *Office design: a study of environment.* Pilkington Research Unit, Univeristy of Liverpool, England.

Mattern, F., Staake, T., Weiss, M. (2010). ICT for green: how computers can help us to conserve energy. *e-Energy '10.* Passau, Germany.

Matthies, E. (2005). How can psychologists improve their outreach towards practitioners? A suggestion for a new, integrative model of environmentally sound everyday practice. *Umweltpsychologie , 9* (1), 62–81.

McAliney, M. (1993). *Arguments for land conservation: documentation and information sources for land resources protection.* Sacramento, CA: Trust for Public Land, Sacramento, CA, .

McKennan, G.T., Parry C.M. (1984). An investigation of task lighting for offices. *Lighting Research and Technology , 16* (4), 171-186.

Newsham, G. (1994). Manual control of window blinds and electric lighting: implications for comfort and energy consumption. *Indoor Environment , 3*, 135-144.

Newsham, G. R., Mancini, S., Veitch, J.A., Marchang, R.G., Lei, W., Charles, K.E., Arsenault, C. D. (2009, Jan). Control strateige for lighting and ventilation in offices: effects on energy and occupants. *Intelligent Building International, 1* , pp. 101-121.

Newsham, G., Arsenault, C., Veith, J., Tosco, A.M., Dual, C. (2005). Task lighting effects on office workers satisfaction and performance, and energy efficiency. *The Journal of the Illuminating Engineering Society of North America , 1* (4), 7-26.

Nicol, J. (2001). Characterizing occupant behavior in buildings: Towards a stochastic model of occupant use of windows, lights, blinds, heater and fans. *Proceedings of th 7th. International IBPSA Conference*, (pp. 1073-1078). Rio de Janeiro, Brazil.

NRC. (n.d.). *IESNA Lighting Design Guide*. Retrieved July 2010, from https://www.nrc-cnrc.gc.ca/eng/ibp/irc/ctus/ctus-n62.html

Peterson, J.E., Shunturov, V., Janda, K., Platt, G., Weinberger, K. (2007). Dormitory residents reduce electricity consumption when exposed to real-time visual feedback and incentives. *International Journal of Sustainability in High Education , 8* (1), 16-33.

Pigg. S., Eilers, M., Reed, J. (1996). Behaviroal aspects of lighting and occupancy sensors in private offices: a case study of university office building. *ACEEE Summer Study on Energy Efficiency in Buildings*, *8*, pp. 161-171.

Prowler, D. (2008, May). *Sun Control and Shading Devices*. Retrieved July 2010, from Whole Building Design Guideline.

Raja., I.A., Nicol, F., McCartney, K.J., Humphreys, M.A. (2001). Thermal comfort: user of controls in naturally ventilatied buildings. *Energy and Buildings* , 235-244.

Rea, M. (1984). Window blind occlusion: a pilot study. *Building and Environment , 19* (2), 133-137.

Reinhart, C.F., Voss, K. (2003). Monitoring manual control of electrical lighting and blinds. *Lighting Research and Technology , 35* (3), 243-260.

Rubin, A.I., Collins, B.L., Tibbott, R.L. (1978). Window blinds as a potintial energy saver - a case study. *NBS Building Science Series 112* . Washinton, DC, U.S.: Department of Commerce, National Bureau of Standards.

Slater, A. (1996). Lighting control in office: how to improve occupant comfort and energy efficiency. *CIBSE National Lighting Conference*, (pp. 178-184). London.

Steelcase. (1999). *Office workers believe quailty of lighting affects productivity and creativity.*

Tiller, D.K., Pasini, I.C., Jaekel, R.R., Newsham, G.R., Iwata, T. (1995). Furniture mounted lighting system performance: lighting energy consumption. *Proceedings of the CIE 23rd Session*, (pp. 296-297). New Delhi, India.

Tzemplikos, A., Athienitis, A.K., . (2002). A methodology for simulation of daylight room illuminance distribution and light dimming for a room with a controlled shading device. *Solar Energy , 72* (4), 271-281.

USGBC. (2010). *U.S. Green Building Council*. Retrieved Aug 2010, from http://www.usgbc.org/DisplayPage.aspx?CMSPageID=124

Veitch, J.A., Newsham, G.R. (1998). Lighting quality and energy-efficiency effects on task performance, mood, health, satisfaction and comfort. *Journal of the Illuminating Engineering Society , 27* (1), 107-139.

Vine, E.L., Lee, E., Clear, R., DiBartolomeo, S., Selkowitz, S. (1998). Office worker response to an automated venetian blind and electric lighting system: a pilot study. *Energy and Buildings* , 205-218.

WBDG. (2009, August). *Provide Comfortable Environments*. Retrieved July 2010, from Whole Building Design Guideline: http://www.wbdg.org/design/provide_comfort.php

Wikipedia. (n.d.). *Mixed model*. Retrieved Aug 2010, from http://en.wikipedia.org/wiki/Mixed_model

Wyon, D. (2000). Individual control at each workplace: the means and the potential benefits. In D. Clements-Croome, *Creating the productive workplace* (p. 192).

Wyon, D. (2000). Individual control at each workplace: the means and the potential benefits. In D. Clements-Croome, *Creating the productive workplace* (pp. 192-206). London, New York: E & FN SPON.

Yaffee, R. A. (n.d.). *Mixed Analysis of Variance Models with SPSS*. Retrieved 2010 йил Dec from Statistical Computing in the New York University: http://www.nyu.edu/its/socsci/Docs/SPSSMixed.ppt

Yamakawa, K., Watabe, K., Inanuma, M., Sakata, K, Takeda, H. (2000). A study on the practical use of a task and ambient lighting system in an office. *Journal of Lighting & Visual Environment , 24* (2), 15-18.

APPENDIX A: Internal Review Board approve and modification

Carnegie Mellon University

Institutional Review Board

Federalwide Assurance No: FWA00004206

IRB Registration No: IRB00000603

Certification of IRB Approval

IRB Protocol Number:	HS09-462
Title:	Office Occupants' Behavior in Space Lighting Operation
Investigator(s):	Yun Gu, David Archer
Department(s):	Architecture
Date:	**October 16, 2009**

Carnegie Mellon University Institutional Review Board (IRB) reviewed the above referenced research protocol in accordance with the requirements of Public Law 99-158 as implemented by 45 CFR 46 and CMU's Federalwide Assurance. The research protocol has been given **APPROVAL by Expedited Review on October 16, 2009. This APPROVAL expires on October 15, 2010** one year from the approval date, unless suspended or terminated earlier by action of the IRB.

All untoward or adverse events occurring in the course of the protocol must be reported to the IRB within three (3) working days. Any additional modifications to this research protocol or advertising materials pertaining to the study must be submitted for review prior to their being enacted. Please refer to the above-referenced protocol number in all correspondence.

Federal regulations require that all records relating to this research protocol be maintained for **at least three (3) years after completion** of the research, and be accessible for inspection and copying by authorized representatives at reasonable times and in a reasonable manner.

The Investigator(s) listed above in conducting this protocol agree(s) to follow the recommendations of the IRB and the Office of the Provost of any conditions to or changes in procedure subsequent to this review. In undertaking the execution of the protocol, the investigator(s) further agree(s) to abide by all CMU research policies including, but not limited to the policies on responsible conduct research and conflict of interest.

The IRB maintains ongoing review of all projects involving humans or human materials, and at continuing intervals, projects will require update until completion. At the end of the current approval, a progress report and current consent form must be submitted to the IRB summarizing progress on the protocol during that period. Please be advised that the progress report requests information pertaining to women and minorities; therefore, this information should be tracked with your participants' data. The Public Health Service (PHS) has guidelines for the inclusion of women and minorities as research participants. These guidelines require that women and minorities be represented in research, and if not, justification as their exclusion. Listed below are the racial categories of participant to be reported as defined by PHS:

- **American Indian or Alaska Native:** A person having origins in any of the original peoples of North, Central, or South America, and who maintains tribal affiliations or community attachment.
- **Asian:** A person having origins in any of the original peoples of the Far East, Southeast Asia, or the Indian subcontinent including, for example, Cambodia, China, India, Japan, Korea, Malaysia, Pakistan, the Philippine Islands, Thailand, and Vietnam.
- **Black or African American:** A person having origins in any of the black racial groups of Africa. Terms such as "Haitian" or "Negro" can be used in addition to "Black or African American."
- **Native Hawaiian or Other Pacific Islander:** A person having origins in any of the original peoples of Hawaii, Guam, Samoa, or other Pacific Islands.
- **White:** A person having origins in any of the original peoples of Europe, the Middle East, or North Africa.

Please call the Research Regulatory Compliance Office at 8-5460 if you should have any questions regarding this certification. Thank you.

David Danks, Ph.D., Chair, IRB

Carnegie Mellon

Research Regulatory Compliance
Warner Hall
Pittsburgh PA 15213
412-268-1901
Irb-review@andrew.cmu.edu

MEMORANDUM

To: Yun Gu, David Archer
From: David Danks
Date: December 4, 2009
Re: HS09-462: Office Occupants' Behavior in Space Lighting Operation

This is to notify you that your modification request submitted on November 23, 2009 to include change in study duration and compensation was approved on December 4, 2009. Please be reminded that if additional changes are made, those changes will need to be reviewed prior to implementation. Please refer to the above referenced protocol number in all correspondence regarding this protocol.

Please call the Research Regulatory Compliance office at 8-1901 if you should have any questions regarding this memo. Thank you.

____
David Danks, Ph.D., Chair

APPENDIX B: Questionnaire

1. Questionnaire for sequence 1

Demographic Questions

0.1 Age:

☐ 18-24 ☐ 25-29 ☐ 30-34 ☐ 35-40

0.2 Gender:

☐ Female ☐ Male

0.3 Your ability in reading English:

Not capable				Very capable
1	2	3	4	5
☐	☐	☐	☐	☐

0.3 Owned highest education:

☐ High school ☐ Community college ☐ Bachelor degree ☐ Graduate degree

0.4 You current occupation:

☐ Student ☐ Office worker ☐ Others (please specify ___________________________)

0.5 Do you wear glasses or contact lens: ☐ Yes ☐ No

0.6 Are you right handed or left handed? ☐ Right handed ☐ Left handed

Below will be filled by the investigator:

0.8 Corrected visual acuity with both eyes: 20/______

0.9 Ishihara color test result: ______/10

Section 1. Questionnaire:

1.1 How satisfied are you with the following aspects of this workplace in the last 1 hour?

	Very unsatisfactory -3	-2	-1	Neutral 0	1	2	Very satisfactory 3
a. noise level	☐	☐	☐	☐	☐	☐	☐
b. odour	☐	☐	☐	☐	☐	☐	☐
c. ventilation	☐	☐	☐	☐	☐	☐	☐
d. temperature	☐	☐	☐	☐	☐	☐	☐
e. window size	☐	☐	☐	☐	☐	☐	☐
f. privacy	☐	☐	☐	☐	☐	☐	☐
g. space size	☐	☐	☐	☐	☐	☐	☐
h. view	☐	☐	☐	☐	☐	☐	☐
i. workplace aesthetics (e.g. colours, carpet, decoration)	☐	☐	☐	☐	☐	☐	☐

1.2 In general, how satisfied are you with the light environment in this workplace?

Very unsatisfactory -3	-2	-1	Neutral 0	1	2	Very satisfactory 3
☐	☐	☐	☐	☐	☐	☐

1.3 How important is it to you to have a window in the working environment?

Not important at all -3	-2	-1	Neutral 0	1	2	Very important 3
☐	☐	☐	☐	☐	☐	☐

1.4 The amount of light at this work area for the tasks you performed in the last 1 hour is:

	Too dim -3	-2	-1	Right amount 0	1	2	Too bright 3
a. in the room in general	☐	☐	☐	☐	☐	☐	☐
b. on desk surface for paper based work	☐	☐	☐	☐	☐	☐	☐
c. at the monitor for computer tasks	☐	☐	☐	☐	☐	☐	☐

1.5 Is daylight adequate in your working area?

No daylight -3	-2	-1	Right amount 0	1	2	Too much daylight 3
☐	☐	☐	☐	☐	☐	☐

1.6 Did you notice reflected light or glare on the computer screen?

☐ Yes, I noticed. If 'yes', reflection was from: ☐ Daylight

☐ Overhead light

☐ Desk light

☐ No, I did not notice.

1.7 Overall, do you agree that the lighting environment enhance your ability to get your task done?

Strongly Disagree -3	-2	-1	Neutral 0	1	2	Strongly Agree 3
☐	☐	☐	☐	☐	☐	☐

Section 2. Questionnaire:

2.1 How satisfied are you with the following aspects of this workplace in the last 1 hour?

	Very unsatisfactory -3	-2	-1	Neutral 0	1	2	Very satisfactory 3
a. noise level	☐	☐	☐	☐	☐	☐	☐
b. odour	☐	☐	☐	☐	☐	☐	☐
c. ventilation	☐	☐	☐	☐	☐	☐	☐
d. temperature	☐	☐	☐	☐	☐	☐	☐

2.2 The amount of light at your work area for the tasks you perform is:

	Too dim -3	-2	-1	Right amount 0	1	2	Too bright 3
a. in the room in general	☐	☐	☐	☐	☐	☐	☐
b. on desk surface for paper based work	☐	☐	☐	☐	☐	☐	☐
c. at the monitor for computer tasks	☐	☐	☐	☐	☐	☐	☐

2.3 Did you notice reflected light or glare on the computer screen?

☐ Yes, I noticed. If 'yes', reflection was from: ☐ Daylight

☐ Overhead light

☐ Desk light

☐ No, I did not notice.

2.4 Does CONTROL of OVERHEAD LIGHT provide better lighting conditions?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

2.5 Does CONTROL of DESK LIGHT provide better lighting conditions?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

2.6 Does CONTROL of BLINDS provide better lighting conditions?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

2.7 Overall, do you agree this lighting environment enhances your ability to get your task done?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

Section 3. Questionnaire:

3.1 How satisfied are you with the following aspects of this workplace in the last 1 hour?

	Very unsatisfactory -3	-2	-1	Neutral 0	1	2	Very satisfactory 3
a. noise level	☐	☐	☐	☐	☐	☐	☐
b. odour	☐	☐	☐	☐	☐	☐	☐
c. ventilation	☐	☐	☐	☐	☐	☐	☐
d. temperature	☐	☐	☐	☐	☐	☐	☐

3.2 The amount of light at your work area for the tasks you perform is:

	Too dim -3	-2	-1	Right amount 0	1	2	Too bright 3
a. in the room in general	☐	☐	☐	☐	☐	☐	☐
b. on desk surface for paper based work	☐	☐	☐	☐	☐	☐	☐
c. at the monitor for computer tasks	☐	☐	☐	☐	☐	☐	☐

3.3 Did you notice reflected light or glare on the computer screen?

☐ Yes, I noticed. If 'yes', reflection was from: ☐ Daylight

☐ Overhead light

☐ Desk light

☐ No, I did not notice.

3.4 Does feedback on light, 'too dim', 'just right', and 'too bright' help you better operate blinds and lights for better light condition?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

3.5 Do recommendations for setting your lighting conditions help you better operate blinds and lights?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

3.6 Does real time energy consumption data influence your decisions to operate blinds and lights?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

3.7 Does real time carbon emission data influence your decisions to operate blinds and lights?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

3.8 Overall, do you agree this lighting environment enhances your ability to get your task done?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

Turn to the back

3.9 Which of the following most influenced your actions to operate lights or blinds?

- ☐ Feedback on light, 'too dim', 'just right', and 'too bright'
- ☐ Recommendations for setting your lighting conditions
- ☐ Real time energy consumption data
- ☐ Real time carbon emission data

Please elaborate:

____

____

____

____

____

____

2. Questionnaire for sequence 2

Demographic Questions

0.1 Age:

☐ 18-24 ☐ 25-29 ☐ 30-34 ☐ 35-40

0.2 Gender:

☐ Female ☐ Male

0.3 Your ability in reading English:

Not capable 1	2	3	4	Very capable 5
☐	☐	☐	☐	☐

0.3 Owned highest education:

☐ High school ☐ Community college ☐ Bachelor degree ☐ Graduate degree

0.4 You current occupation:

☐ Student ☐ Office worker ☐ Others (please specify ________________________)

0.5 Do you wear glasses or contact lens: ☐ Yes ☐ No

0.6 Are you right handed or left handed? ☐ Right handed ☐ Left handed

Below will be filled by the investigator:

0.8 Corrected visual acuity with both eyes: 20/_____

0.9 Ishihara color test result: _____/10

Section 1. Questionnaire:

1.1 How satisfied are you with the following aspects of this workplace in the last 1 hour?

	Very unsatisfactory -3	-2	-1	Neutral 0	1	2	Very satisfactory 3
a. noise level	☐	☐	☐	☐	☐	☐	☐
b. odour	☐	☐	☐	☐	☐	☐	☐
c. ventilation	☐	☐	☐	☐	☐	☐	☐
d. temperature	☐	☐	☐	☐	☐	☐	☐

1.2 The amount of light at your work area for the tasks you perform is:

	Too dim -3	-2	-1	Right amount 0	1	2	Too bright 3
a. in the room in general	☐	☐	☐	☐	☐	☐	☐
b. on desk surface for paper based work	☐	☐	☐	☐	☐	☐	☐
c. at the monitor for computer tasks	☐	☐	☐	☐	☐	☐	☐

1.3 Did you notice reflected light or glare on the computer screen?

☐ Yes, I noticed. If 'yes', reflection was from: ☐ Daylight

☐ Overhead light

☐ Desk light

☐ No, I did not notice.

1.4 Does CONTROL of OVERHEAD LIGHT provide better lighting conditions?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

1.5 Does CONTROL of DESK LIGHT provide better lighting conditions?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

1.6 Does CONTROL of BLINDS provide better lighting conditions?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

1.7 Overall, do you agree this lighting environment enhances your ability to get your task done?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

Section 2. Questionnaire:

2.1 How satisfied are you with the following aspects of this workplace in the last 1 hour?

	Very unsatisfactory -3	-2	-1	Neutral 0	1	2	Very satisfactory 3
a. noise level	☐	☐	☐	☐	☐	☐	☐
b. odour	☐	☐	☐	☐	☐	☐	☐
c. ventilation	☐	☐	☐	☐	☐	☐	☐
d. temperature	☐	☐	☐	☐	☐	☐	☐

2.2 The amount of light at your work area for the tasks you perform is:

	Too dim -3	-2	-1	Right amount 0	1	2	Too bright 3
a. in the room in general	☐	☐	☐	☐	☐	☐	☐
b. on desk surface for paper based work	☐	☐	☐	☐	☐	☐	☐
c. at the monitor for computer tasks	☐	☐	☐	☐	☐	☐	☐

2.3 Did you notice reflected light or glare on the computer screen in last 1 hour?

☐ Yes, I noticed. If 'yes', reflection was from: ☐ Daylight

☐ Overhead light

☐ Desk light

☐ No, I did not notice.

2.4 Does feedback on light, 'too dim', 'just right', and 'too bright' help you better operate blinds and lights for better light condition?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

2.5 Do recommendations for setting your lighting conditions help you better operate blinds and lights?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

2.6 Does real time energy consumption data influence your decisions to operate blinds and lights?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

2.7 Does real time carbon emission data influence your decisions to operate blinds and lights?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

2.8 Overall, do you agree this lighting environment enhances your ability to get your task done?

Absolutely No -3	-2	-1	Neutral 0	1	2	Absolutely Yes 3
☐	☐	☐	☐	☐	☐	☐

Turn to the back

2.9 Which of the following most influenced your actions to operate lights or blinds?

- ☐ Feedback on light, 'too dim', 'just right', and 'too bright'
- ☐ Recommendations for setting your lighting conditions
- ☐ Real time energy consumption data
- ☐ Real time carbon emission data

Please elaborate:

____

____

Section 3. Questionnaire:

3.1 How satisfied are you with the following aspects of this workplace in the last 3 hour?

	Very unsatisfactory -3	-2	-1	Neutral 0	1	2	Very satisfactory 3
a. noise level	☐	☐	☐	☐	☐	☐	☐
b. odour	☐	☐	☐	☐	☐	☐	☐
c. ventilation	☐	☐	☐	☐	☐	☐	☐
d. temperature	☐	☐	☐	☐	☐	☐	☐
e. window size	☐	☐	☐	☐	☐	☐	☐
f. privacy	☐	☐	☐	☐	☐	☐	☐
g. space size	☐	☐	☐	☐	☐	☐	☐
h. view	☐	☐	☐	☐	☐	☐	☐
i. workplace aesthetics (e.g. colours, carpet, decoration)	☐	☐	☐	☐	☐	☐	☐

3.2 In general, how satisfied are you with the light environment in this workplace?

Very unsatisfactory -3	-2	-1	Neutral 0	1	2	Very satisfactory 3
☐	☐	☐	☐	☐	☐	☐

3.3 How important is it to you to have a window in the working environment?

Not important at all -3	-2	-1	Neutral 0	1	2	Very important 3
☐	☐	☐	☐	☐	☐	☐

3.4 The amount of light at this work area for the tasks you performed in the last 1 hour is:

	Too dim -3	-2	-1	Right amount 0	1	2	Too bright 3
a. in the room in general	☐	☐	☐	☐	☐	☐	☐
b. on desk surface for paper based work	☐	☐	☐	☐	☐	☐	☐
c. at the monitor for computer tasks	☐	☐	☐	☐	☐	☐	☐

3.5 Is daylight adequate in your working area?

No daylight -3	-2	-1	Right amount 0	1	2	Too much daylight 3
☐	☐	☐	☐	☐	☐	☐

3.6 Did you notice reflected light or glare on the computer screen?

☐ Yes, I noticed. If 'yes', reflection was from: ☐ Daylight

☐ Overhead light

☐ Desk light

☐ No, I did not notice.

3.7 Overall, do you agree that the lighting environment in last 1 hour enhance your ability to get your task done?

Strongly Disagree -3	-2	-1	Neutral 0	1	2	Strongly Agree 3
☐	☐	☐	☐	☐	☐	☐

APPENDIX C: Demographic

Weather	1. Snow	2. Cloudy	3. Partial cloudy	4. Sunny	5. Rain
Age	1: 18-24	2: 25-29	3: 30-34	4: 35-40	
Gender	1. Female	2. Male			
English	1: Not capable	5: Very capable			
Education	1. High school	2. Community college	3. Bachelor	4. Graduate degree	
Occupation	1. student	2. office worker	3. others		
Glass	0. not wear glass or len	1. wear glass/len			
CVA	1. 20/20	2. 20/25	3. 20/30		
ESL	0. No	1. Yes			

Participants in sequence groups 1:

Weather	Am_Pm	Age	Gender	English	Education	Occupation	Glass	CVA	ESL
3	2	2	2	3	4	1	0	1	1
3	1	1	1	5	3	1	1	1	1
2	2	1	2	4	3	1	1	1	1
2	1	1	2	4	3	1	0	1	1
1	2	3	1	3	4	1	1	1	1
1	1	1	2	4	3	1	1	2	1
1	2	2	2	5	4	1	1	1	1
1	1	2	2	5	3	1	1	1	1
1	1	1	2	5	4	1	1	1	1
1	2	1	2	4	3	1	0	1	1
1	2	2	1	3	3	1	1	1	1
1	1	4	2	4	4	2	0	1	1
1	1	2	2	4	4	1	1	1	1
1	2	2	1	5	4	1	1	1	1
1	1	1	2	5	3	1	1	1	1
1	2	1	1	5	3	3	1	2	0
1	1	3	1	5	4	2	1	1	1
1	2	2	1	3	4	1	1	2	1
1	1	1	2	5	3	1	1	1	1
1	2	2	2	4	4	1	1	2	1
1	1	1	2	5	3	2	0	1	1
1	2	1	2	4	1	1	1	1	1
4	1	1	2	5	1	1	0	1	1
4	2	1	1	5	1	1	0	1	0
4	2	2	2	5	4	1	1	1	1
3	1	1	1	5	4	1	0	1	1
3	2	2	2	3	4	1	0	1	1
1	1	1	1	5	1	1	1	1	1
1	2	1	1	5	3	1	1	1	1
1	2	2	2	5	2	1	1	2	1

Participants in sequence groups 2:

Weather	Am_Pm	Age	Gender	English	Education	Occupation	Glass	CVA	ESL
3	2	3	1	5	4	1	0	1	1
3	1	1	1	4	3	1	0	1	1
2	1	1	1	5	1	1	1	1	0
2	2	2	2	3	3	1	0	1	1
1	2	3	1	5	4	3	1	1	1
1	1	1	2	4	3	1	1	2	1
1	1	1	2	5	4	1	0	1	1
1	2	1	2	5	3	1	0	1	0
1	2	2	2	5	4	1	0	1	1
5	2	2	2	5	4	1	0	1	0
1	2	2	2	5	1	1	0	1	1
1	1	1	1	5	4	1	0	1	1
1	1	1	1	5	1	1	0	1	0
1	2	3	2	5	4	1	1	1	1
1	2	2	2	5	3	1	0	1	1
1	1	1	2	5	3	1	0	1	1
1	2	1	2	5	1	1	0	1	0
1	1	4	1	4	4	2	0	2	1
1	1	1	2	5	3	1	0	1	1
1	2	2	2	3	4	1	1	1	1
1	2	1	2	5	3	1	1	1	1
1	1	2	2	4	3	1	0	2	1
4	2	1	1	5	4	1	1	1	1
4	1	1	2	5	3	1	0	1	0
3	2	1	1	5	1	1	1	1	0
4	1	1	2	5	3	1	1	1	1
2	1	1	2	5	4	1	1	1	1
3	2	4	1	5	4	1	1	2	1
2	2	2	2	4	3	1	1	1	1
1	1	1	1	5	1	1	1	1	1

APPENDIX D: Sensor data sheet

1. Illuminance sensor

Intersil ISL29101 – small, low power, voltage-output ambient light photo detect IC

Specifications:

Range: 0.5lx – 10,000lx

Power supply: 1.8V – 3.3V

Electrical Specifications V_{DD} = 3V, T_A = +25°C, R_{EXT} = 100kΩ, no load at V_{OUT}, green LED light, unless otherwise specified.

PARAMETER	DESCRIPTION	CONDITION	MIN	TYP	MAX	UNIT
E	Range of Input Light Intensity			0.5 to 10k		lux
VDD	Power Supply Range		1.8		3.3	V
I_{DD}	Supply Current	E = 1000 lux		23	35	µA
		E = 100 lux		3.5		µA
		E = 0 lux		0.65		µA
V_{OUT0}	Light-to-Voltage Accuracy	E = 100 lux		165		mV
V_{OUT1}	Light-to-Voltage Accuracy	E = 1000 lux	1.15	1.65	2.13	V
V_{DARK}	Voltage Output in the Absence of Light	E = 0 lux, R_L = 10MΩ		1	25	mV
ΔV_{OUT}	Output Voltage Variation Over Three Light Sources: Fluorescent, Incandescent and Halogen	E = 1000 lux		20		%
PSRR	Power Supply Rejection Ratio	E = 100 lux, V_{DD} = 1.8V to 3.3V		2.5		mV/V
V_{O-MAX}	Maximum Output Compliance Voltage at 95% of Nominal Output			V_{DD} - 0.7V		V
t_R	ISRC and ISNK Rise Time (Note 3)	E = 300 lux from 0 lux		104		µs
		E = 1000 lux from 0 lux		27		µs
t_F	ISRC and ISNK Fall Time (Note 3)	E = 300 lux to 0 lux		562		µs
		E = 1000 lux to 0 lux		233		µs
t_D	ISRC and ISNK Delay Time for Rising Edge (Note 3)	E = 300 lux from 0 lux		504		µs
		E = 1000 lux from 0 lux		209		µs
t_S	ISRC and ISNK Delay Time for Falling Edge (Note 3)	E = 300 lux to 0 lux		30		µs
		E = 1000 lux to 0 lux		18		µs
I_{SC}	Short Circuit Current of Op Amp			±11		mA
SR	Slew Rate of Op Amp			±10		V/ms
V_{OS}	Offset Voltage of Op Amp			±1.2		mV

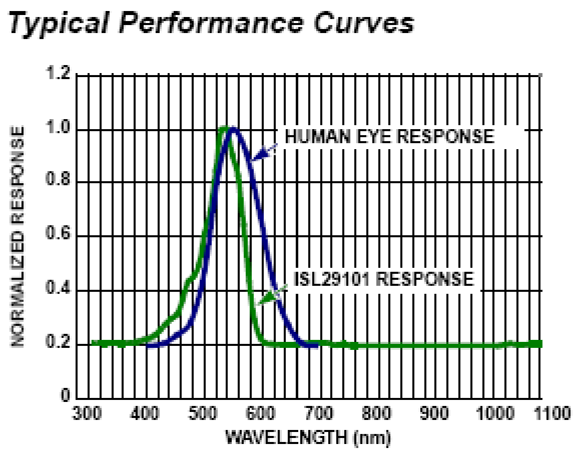

FIGURE 3. SPECTRAL RESPONSE

2. Sound Level Meter

Omega HHSL

Specification:

Accuracy: stated accuracy at 23˚C ± 5˚C, < 75% RH

Range: low: 35 to 90 dB, hi: 75 to 130 dB

Resolution: 0.1 dB

Accuracy: ±1.5 dB (ref 94 dB @ 1 kHZ)

Dynamic range: 55 dB

Frequency range: 31.5 to 8000 Hz

3. Portable air temperature and relative humidity sensor

Name: Air velocity meter 4-in-1 – anemometer, hygrometer, light meter, thermometer

Thermometer specifications:

Range:	0˚C to 50˚C (32˚F - 122˚F)
Resolution:	0.1˚C/˚F
Accuracy:	±1.2˚C (±2.5˚F)

Humidity sensor specifications:

Range:	10 to 95%
Resolution:	0.1%
Accuracy:	<70% RH (±4% RH)
	≥70% RH (±1.2% RH)


TYPE K
Humidity
REC.
44.0
%RH
25.9°C
Power
Hold
Max./Min.
Unit/Zero
°C / °F
Lux/Ft-cd
Function

APPENDIX E: Most important feedback in KBMC

	Light Suitability	Recommendation	Energy Consumption	Carbon Emission	Elaboration
01	√	×	×	×	It is great to control the lighting environment.
02	√	×	×	×	Adjusted the light according to my own preference. The feedback helps me to decide the light levels I wanted. However, I also pay attention to the energy consumption/carbon emission when I operated light or blinds
03	√	×	√	√	Though felt it was not bright enough, the feedback told it's sufficient and the CO2 emissions told I might waste energy equal to 10 trees absorption per day. So I decided to follow the feedback and recommendations to turn the ceiling light lower to 30%. However, I felt daylight is not as comfortable as ceiling light when doing these tasks.
04	×	×	√	×	Prefer a comfortable and energy-saving working environment, which gives sufficient of light needed while saving energy
05	×	×	×	√	Tried to find a comprimised between the lighting that was desired while at the same time checking the carbon emission data to see that it was not too wasteful

06	×	√	×	×	The recommendation is a good start point which make the adjustment of lights easier, especially ceiling light.
07	√	×	×	×	Because the feedback is the same as how I feel about the light condition. The feedback show 'sufficient' when I feel comfortable with the light condition
08	√	×	×	×	Prefer natural light. Usually work under dim light. White lights sometimes make my eyes hurts. So I'd rather turn lights down or use colored lights. E.g. red. Energy consumption and carbon emission do influence my decision. But my personal feeling is the most important when I make decision whether to turn lights on or not.
09	×	√	×	×	Will follow the recommendations first to check whether it gives best lighting environment.
10	√	×	×	×	since the work efficiency is the factor I care most, I prefer to adjust the light to the most comfortable condition
11	×	√	×	×	Based on the instructions, I changed the desk light instead of ceiling light to better support my work on computer. In addition, closing all the user-side blinds helped me focus on my work

12	×	×	√	×	The desk light is always too strong no matter how I adjust. The blinds do not matter much. I think the weather also influence.
13	×	×	×	√	Energy consumption based on pre-knowledge of carbon footprint is vital not just in saving the environment, but gives adequate lighting as needed by the eyes, which otherwise may be always exposed to excessively bright environment.
14	√	×	×	√	It depends from individual to individual. I frankly do not think much about lighting condition as long as I am concentrating on my work. But while doing this experiment, I was greatly influenced by it and I do believe that perfect lighting can help being more productive. The conscious effect to reduce carbon emission play a role while adjusting the lights.
15	×	√	√	√	I assumed the recommendations were based on studies which showed which setting reduced glare and eye strain the most. The energy consumption and carbon emission data allowed me to make my listening decisions so that I would be least wasteful.
16	×	√	×	×	The recommendations for setting lighting conditions prompted me

					for the optimal ceiling light to set which was very useful
17	×	×	×	√	That motivates to work at the right light condition
18	×	×	√	×	In the second task I adjusted the settings according to my preference. The feedback about energy consumption just made me more aware.
19	√	√	×	×	I think everyone prefer to work in a relaxed environment. It is obvious that the lighting condition is one of the most important factor.
20	×	×	×	√	I wanted to reduce CO2 as much as possible while maintaining sufficient lighting to get tasks done. If data was given on how much money is spent on energy consumption, I would have included it in my decision making.
21	√	×	×	×	Feedback on light helped me understand whether the light too bright or too dim which are also affect the carbon emission data
22	×	×	√	×	
23	×	×	×	√	In the condition of environment friendly, to be brightly. Look at carbon emission, then check whether just right to too bright.
24	×	√	√	√	In general, light has little influence on my performance as long as I can see what's on screen and paper. I prefer right

					amount or somewhat dim visual environment.
25	×	√	×	×	Computer work, lift the blinds, turn off ceiling light also according to my own feeling. The carbon emission data also influence my decisions.
26	×	×	√	×	When there is real time energy consumption data, it reminds me to save energy. I think it is good to add that in control panel. It links the energy consumption with user behavior.
27	×	√	√	×	The recommendations make me feel comfortable when I use lights, and then I use the settings. When I saw consumption data, I adjusted the light a little bit dim. However, I think the desk light is enough for reading white page.
28	×	√	×	×	While I liked the feedback on 'too dim', 'just right', and 'too bright', I felt that the more specific instructions were more useful as it gave advice on more that just the direct overheat lighting.
29	×	×	√	×	The data made me aware of the amount of energy I was using. I felt responsible to use only the adequate amount so that less energy is consumed.

30	√	×	×	×	I think a suitable light condition is important for office work, especially intensive office work. Either "too dim" or "too bright" would make me feel tired easily, as well as damaging my visual ability. So I think the feedback on light is the most important factors.
31	√	×	√	√	Right and appropriate decision can be made. Keeping energy consumption in mind, also without affecting your working environment
32	√	×	×	×	I felt I need less light for the computer tasks and more light for the phone book task. Etc….
33	×	√	×	×	I feel like I kind of know when it was too bright, so being told was nice but not as helpful. Because there are a lot of unusual lighting controls in this environment. Specific suggestions were more helpful than overall notifications of sth. I kind of knowing already
34	×	√	×	×	
35	√	×	×	×	It can help me to make a judgment. Because sometimes I am a little confused about the mini adjustment of the lights
36	√	×	×	×	
37	×	×	×	√	With growing fear of global warming just using natural sunlight without using any energy that causes emissions

					motivated me to choose that option. Monitor screen light was sufficient and with no ceiling lights there seemed to be less sufficient doing the task.
38	×	√	×	×	My concentration throughout the experiment is o how to complete it faster and better. Therefore, real tie energy consumption data and real-time carbon emission data are of less concern to me than the other two parameters. Since the recommendations are more specific than the signals such as "too dim", "just right", hence my choice.
39	×	×	×	√	I tried to keep the emissions to a minimum
40	×	√	×	×	Recommendations helped me made a decision for the overall lighting envionment
41	×	√	×	×	Setting light should be an automatic thing. The system should understand my lighting preference over a period of time and must be able to come up with suggestions which are easy for me to see.
42	√	×	×	×	I found feedback was very close to what I felt. So, I believed in that 4 kept lighting levels which were not too bright or too dim.
43	√	×	×	×	As I played w/the interface, the recommendations that

					always turned to first was based on too dime, just right, or too bright. I followed for look at the real time energy consumption date; third to the real time CO2 emission data, and finally verified whether my decisions matched the recommendations.
44	√	√	√	√	I just followed the recommendations to adjust the light and blind. I didn't feel too much difference between these slight variations. Thus, real time energy consumption data and carbon emission data became my only reference.
45	×	√	×	×	I took a look at the recommendations and they seemed like good conditions so I thought I would give it a try. I think the recommendations they gave most information
46	×	√	√	√	Seeing how much energy was consumed made me want to use natural sunlight rather than the lights. The recommendation helped me pick the settings so that the workplace was not too bright. I think working an environment with natural sunlight was more helpful and productive than artificial lights
47	×	√	×	×	Recommendation to switch on the desk light seemed a good idea. As

					there was no need for switching the ceiling light on.
48	×	×	√	×	I tried to keep co2 and energy consumption lower. Tried to set the light conditions to 'just right'. That's how I got my final light conditioning.
49	×	×	√	√	I feels good to same energy & make environment a better place to live in.
50	×	×	√	×	Many time you are not aware the lights are on unnecessarily. If there is some way which can tell me how much energy we are wasting, it helps to be aware and thus save energy.
51	×	√	√	√	The visual display of carbon emission data was very convincing. The recommendations were helpful because otherwise, I probably would have completely lifted the blinds but that might have been too much light.
52	×	×	×	√	The amount of carbon dioxide was a good indication of how some CO2 emission could be avoided by adjusting light intensity
53	×	√	×	×	
54	×	√	×	×	The recommendations for setting lighting conditions were followed by me first. I did not want my eyes to get strained while working. It also happened to be coincidental that

					recommended settings for computer work reduced real time carbon emission data and this made me feel good
55	×	×	√	√	Although the feedback on light for working on the computer screen showed 'too bright', I felt I needed the light to perform the task properly. For my preference, I used the energy consumption data as guide in using the absolutely lowest amount of light for the task.
56	×	√	×	×	Make easier to make decision. Relative easy to approach the less-energy-consumption way. Bette rif there can be an apply button
57	×	×	√	×	There are too much options when we control lights. We do not know what is the best light to improve working efficiency. Suggestions given in the last test might decrease the efficiency of people's working ability.
58	√	×	×	×	The feedback on controlling light enhanced my judgment of the light some better. Not just my preference using the measurement of my eyes. I felt more comfortable.
59	√	×	×	×	
60	×	×	√	√	The real time energy consumption and real time carbon emission were different fro

					different options of lighting so choosing the lower one was made easy by the data, the availability of data made it easier to make a decision.
Count	19	23	20	19	