Addressing variability as an expansion of naturalistic lighting theory for user wellbeing

by

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DEDICATION

First, I would like to thank my wife who has provided tremendous support, and made a lot of personal sacrifices during the course of my studies. I would like to thank my family who has supported me both mentally and financially. I would never be where I am today without their support and guidance.

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ABSTRACT

This study is an exploration into the relationship between lighting and office occupant productivity and wellbeing, attempting to better understand how enhanced naturalistic lighting and lighting control might enable an environment that affects occupants positively. To explore the possibilities of this concept, a morphological research approach has been implemented to ultimately integrate the following three major lighting developments; human affinity to nature; accommodation of physiological, functional, and psychological aspects; and acknowledgement of the inherent need for variability and evolution.

This study consisted mainly of two segments. First, through the review of literature, three key lighting-oriented developments have been identified; human affinity to nature; accommodation of physiological, functional, and psychological aspects; and acknowledgement of the inherent need for variability and evolution. No lighting solution that integrates all these factors has yet been found. Second, the study introduces the concept of enhanced naturalistic lighting and its control schematic, holistically combining all three of these key developments. Future exploration of interior design implications related to enhanced naturalistic lighting and associated control systems will be discussed to clarify how such lighting systems could impact the wellbeing of the users.

CHAPTER 1. INTRODUCTION

Statement of the Problem

Office lighting strategy is currently at a turning point. While many offices today continue to utilize longstanding standards and recommendations for office lighting based on the horizontal illuminance at the work plane, thereby fulfilling basic visual needs for reading and writing tasks (Tenner, 2003), workers in modern offices are engaged in tasks beyond merely reading and writing, such as using personal computers and engaging in collaborative activities have become the major tasks of many office workers. With such a dramatic shift in office tasks, lighting requirements must change accordingly (Tenner, 2003). Providing an optimum lighting environment would assist office workers in handling their respective work tasks, and lighting conditions may be equally essential to the health, motivation, and productivity of an office's occupants (GmbH & Stuttgart, Fraunhofer IAO, 2014).

In general, an office space lighting environment is the combination of artificial lighting and natural sunlight, both vital and valuable to the workspace. While artificial lighting may offer the space a stable and consistent lighting environment, natural sunlight can play a significant role in an office space as well. The physics of the use of natural sunlight has not changed, which is the primary lighting source in office buildings. Artificial lights have, of course, been used to supplement natural sunlight and, even with the development of artificial lighting, the design of buildings has often continued to utilize daylight as an architectural statement and for energy-saving (Edwards & Torcellini, 2002) as well as for illuminance functionality. The physiological, psychological, and functional benefits of natural lighting have often been overlooked. Illumination from cool white fluorescent lights, incandescent lights, and energy-efficient fluorescent lights typically is concentrated in the red to green portion of the color spectrum with the blue portion, important to human beings and found in natural sunlight, is missing (Liberman, 1991). In poorly-illuminated environments our body may not be able to perceive colors, with potential negative physical and mental effects on our bodies. Dr. Ott (Ott Biolight System, Inc. 1997a) has mentioned that human body utilizes light as a nutrient for metabolic processing in a manner similar to that of water or food.

Aside from the lighting itself, a lighting control system within a workspace is also a significant factor that may impact the wellbeing and productivity of office occupants. The workspace lighting environment provided to office occupants doesn't always conform to users' demand. The general overall lighting strategy in office spaces is to use a fixed grid of luminaires designed to provide everyone in the space the same light level, even though it is well known that individuals may have widely different preferences for illuminance levels even for performance of identical tasks. Based on the lighting control strategy provided to designers by the American National Standard Practice for Office Lighting, design of controls has been heavily oriented toward the goal of energy saving, and the personal control available to occupants is limited to on/off switches and dimming controls. Fast forward to today, as technology has advanced within the lighting arena, especially the emergence of Lighting Emitting Diodes(LEDs), great possibilities are presented for lighting to achieve more than just illumination, including features such as changing colors and correlating color temperature. There is strong evidence that personal control over one's own-workspace lighting can have a positive impact on an office occupant's comfort, mood, and satisfaction (Illuminating Engineering Society, 2017). Without an appropriate control system, however, office occupants can benefit from neither the lighting system itself nor the lighting control.

While it may be satisfactory for the traditional lighting profession to focus on adequate quality and quantity of lighting and offer office occupants a singular solution, such a singular lighting solution takes away the ability of a user to personally control the lighting. Contemporary office design concepts are shifting focus to end users, the office workers, and architecture and interior design activities increasingly focus on the needs of office workers and their activities (GmbH & Stuttgart, Fraunhofer IAO, 2014). Lighting within an office environment in this context is particularly important. Natural lighting and artificial lighting each have shortcomings in this context, establishing the relationship among office environment, occupant wellbeing, and productivity as a foundation for research. The central focus of this study was aimed at studying the impact of lighting on office occupants and designing a lighting control approach that would enable them to achieve better performance and increase their wellbeing and productivity.

Study Purpose

This study's purpose was threefold. First, it analyzed current trends in the design of office spaces with a focus on how lighting affects the wellbeing and productivity on the occupants. This involves understanding lighting and its effects from the perspectives of physiology and psychology, in addition to its primary functionality of illumination. Second, it introduced naturalistic lighting concepts in the context of office environment to determine functions and features of a naturalistic lighting system that would be required to shape an office lighting environment that could assist office occupants with their wellbeing and productivity. Third, a control system schematic was initiated, not only to provide means for users to access functions and features that a naturalistic lighting system has to offer, but also to offer the end user more control over the lighting system. Most office lighting arrangements have largely remained based on old standards and recommendations (Tenner, 2003) that are often unsuitable for a more diverse working environment and potentially limiting with respect to the performance and wellbeing of office occupants. While a literature review on lighting reveals its physiological and psychological impacts, there have been relatively few studies that propose or establish how such impact should be utilized as an inclusive system to benefit office occupants. This study was therefore developed and performed to initiate such a lighting concept, and framed a lighting control schematic principally based on the values and benefits of natural sunlight. The study sought not only to provide a way for the users to have better access to the lighting, but further provided a control schematic for use by office occupants. It explored the option of putting the office occupants in the driver's seat of lighting control, to seek understanding of the functional, physiological, and psychological requirements of a lighting control schematic.

Objectives

The objectives of this study include the following:

1. Determine lighting factors that positively contribute to office occupants' productivity and wellbeing in the workplace.
2. Identify elements of naturalistic lighting concepts by analyzing some of the significant traits of natural sunlight, along with appropriate well-proven findings in the existing literature. Generate simulations to illustrate the naturalistic lighting concept.
3. Create a control system schematic for a naturalistic lighting system to offer the end users access to lighting functions and features, as well as offering them more controls over lighting in general.

Research Questions

The primary goal of this study is focused on how lighting could be designed and utilized to better serve the office occupants, not just functionally, but also from the perspectives of physiology and psychology. Developing a control system for lighting is equally, if not more important, in the context of this study. A literature review was a main source for all the information required for such systems, and P.A.Th.Ways. methodology was used to create a naturalistic lighting system and its associated control system.

1. How are lighting, wellbeing, and productivity related to one another in office spaces? [Literature Review]
2. Based on the traits of natural sunlight and existing lighting research findings, what are the major characteristics of naturalistic lighting systems within office environments? [Literature Review]
3. How should optimal control of enhanced naturalistic lighting qualities be provided in a manner that accommodates: a) human's affinity to nature; b) naturalistic lighting concept; c) human's inherent need for variability? [P.A.Th.Way.S.]

Scope of Limitations

This study was conducted to establish potential beneficial relationships between lighting and office occupants, to define a naturalistic lighting concept, and ultimately to design a control schematic for naturalistic lighting systems. This is a circumstantial defense of the theory, with no testing with subjects. This research has focused on developing a theoretical framework for more humanistic lighting whose central theme is for people to appreciate how lighting control could affect their body by providing variability and control.

The study has been based solely on literature related to lighting, lighting control, and lighting variability. Up to this point no field tests has been performed to test the theory.

Although this study has access to a very large body of literature as a foundation to work with, there exist some limitations and shortcomings. First, there have been many different approaches in terms of defining office spaces, (e.g., open office, closed office, conference rooms, collaboration space, etc.). The office configuration feature in this study focused on a closed private office of typical area of about 100 square feet. This relatively smaller scale offers examination of artificial lighting configurations that are easy to observe and control for the study. Second, the lighting scope in this study is generally discussed in a quantitative manner, meaning that light can be translated into numerical data, using units such as lux and kelvin degrees. The fact that lighting is infinitely variable almost precludes exhaustive testing, and if one range was tested for luminosity and Correlated Color Temperature, that is just one of an infinite number of combinations possible for that range. If the study takes a more quantitative approach, it is more likely to achieve a breakthrough in terms of lighting phenomenon, that can then be converted into a more controlled, qualitative scenario. However, most studies must begin with a quantitative assessment, also the focus of this study. Third, neither lighting itself nor lighting control represent sole factors that contribute to the wellbeing and productivity of the office occupants, and there are obviously other variables vital to occupants' wellbeing and productivity within a workplace. Finally, this study's scope was to design a schematic for a naturalistic lighting control system to be demonstrated via computer-generated simulation and diagrams. A detailed and fully fleshed-out control mechanism and interface is beyond the scope of the study.

CHAPTER 2. BACKGROUND

Introduction

This chapter describes the premise and foundation of this study and includes a synopsis describing how an office environment may impact office occupants' productivity, the relationship between occupants' wellbeing and their productivity, and how an office environment may affect the wellbeing of its occupants. These topics establish a strong, connected relationship among office environment, occupants' wellbeing, and their productivity. Finally, control factors are discussed in terms of office environment, and the types of control within an office environment is more specifically laid out and defined.

Office Environment and Productivity

With the development of information and communication technology and a consequently more diverse and flexible working style, office environments have shifted dramatically during the past years few years (De Croon, Sluiter, Kuijer, & Frings-Dresen, 2005). Vos and Van der Voordt (2002) mentioned that the changing nature of the office worker's environment is exemplified by the growing number of organizations that move from conventional offices with fixed workplaces to more open and transparent offices with shared workplaces. A significant amount of research conducted on the impact of office environments on productivity has shown that satisfaction in the working environment is directly related to job satisfaction and productivity (Carlopio, 1996; Danielsson & Bodin, 2008; De Croon et al., 2005; J. Veitch, Charles, Newsham, Marquardt, & Geerts, 2003).

The word 'environment' is not limited to only the physical environment of the office space; it has a broader spectrum, embracing how an organization works and manages its staff; the physical factors include but are not limited to lighting, noise, indoor air quality, spatial planning, economic factors amenities, and social ambience (Clements-Croome, 2006). Barry P. Haynes (2007) systematically categorized these elements within the office environment into two major categories: physical environment and behavioral environment. The physical environment consists of components that relate to the office occupants' ability to physically connect with their office environment, while the behavioral environment consists of components related to how well the office occupiers connect with one another, and the impact an office environment can have on individual behavior. Comfort, ergonomics and office layout would fall into the category of physical environment, while interaction and distraction lie within the category of behavioral environment. Physical and behavioral environment both play a very important role in achieving optimal job satisfaction and productivity.

Physical environment

Lighting

Lighting is one of the key factors in an individual's working environment. Providing the right type of lighting may assist in minimizing glare and fatigue and increasing wellbeing and productivity (Summers, 1989). In general terms, while lighting is fundamentally provided to allow office workers to see their tasks, it may also contribute to the atmosphere created by the surroundings (WG & HJ, 1980). Since lighting researchers have put much attention on visibility, we have a complete understanding of what is needed to make an object visible. Derek Clements-Croome (2006) has summarized four variables that provide the greatest effects on visibility: age of the viewer, task size, task/background contrast, and task illuminance. In general, when objects are larger, have higher contrast, and are observed at higher luminance, they are more easily viewed. Based on the relative visual performance model created by Rea and Ouellette (1991), visual performance can be precisely predicted from these given inputs.

By today's standards, visibility is no longer a concern for the modern office environment. The lighting of today's office environment usually consists of two essential parts, artificial light and natural sunlight. For contemporary office artificial lighting installment, fluorescent lighting systems dominant workplace electric lighting due to their high energy efficiency (Clements-Croome, 2006). Functionally, a florescent lighting system produces a constant luminance output, but when operating on alternating current (AC), there is a degree of luminance modulation within the light (J. A. Veitch & Newsham, 1995). While most people could not perceive this modulation as flicker, evidence shows neural activity can occur in response to the modulation. The low-frequency flicker (modulation) can interfere with visual processing and disrupt eye movement while reading, causing visual fatigue and lowering visual performance efficiency and computer screen-based performance (Küller & Laike, 1998; J. A. Veitch & Newsham, 1995).

Even though artificial lighting can provide a constant lighting environment, people show a consistent preference for natural daylight when it is available, and many office workers believe natural lighting is superior to and more attractive than electric artificial lighting systems (Heerwagen & Heerwagen, 1986). Natural light influences human wellbeing and enables visual contact with the outside world. In an office working environment, people near a window or with window access to daylight within 15 feet had higher satisfaction with the lighting than people without a window. Window views within an office environment appear to assist with the coping process in response to stress both at work and at home (Kaplan, 2001; Leather, Pyrgas, Beale, & Lawrence, 1998). However, daylight is also not perfect. Because the direction of daylight varies throughout the day and intensity of daylight varies throughout the season, thermal control and glare control are things to consider within the office environment. Buildings may utilize insulating windows and shades or blinds to control direct sunlight (Roche, Dewey, & Littlefair, 2000; J. Veitch et al., 2003).

Within the office environment, the lighting system consists mostly of a combination of natural daylight and artificial light, and should as well be a combination of direct light and indirect light. Considerable studies have found that office workers show a preference for a combination of direct light and indirect light over fully direct office lighting (Boyce et al., 2006; Hedge, Sims Jr., & Becker, 1995).

LED lighting systems are also being specified in office environment. Compared to traditional fluorescent lighting systems, LED lighting could achieve the required illuminance and the color temperature while achieving an energy saving of up to 80 percent (Ono et al., 2012). Philips, the Dutch electronics giant, perceives that the trend toward replacing fluorescent and incandescent lights with LEDS to save energy within office environments is growing (Anonymous, 2011).

Acoustic

While many offices today utilize open-plan office designs to achieve increases in teamwork, communication, and productivity, with an increase in interactions, these types of spaces also augment noise in the workplace. Considerable studies have shown that noise is the most frequent complaint among office workers (Maxwell, 2002). This noise can come from all kinds of sources: air conditioning, ringtones, traffic, construction, and other people's voices. Much research shows that the most destructive sound of all is other people's conversations (Steelcase, 2014a). Decrease in productivity, increase in illness and hormone levels, stress, interference with speech, sleep disorders, and impaired cognition are all possible outcomes of too much noise around us (Maxwell, 2002; Steelcase, 2014a).

The positive objective of a good acoustic environment in office spaces has been very well established. Robert and Michael (1975) of Herman Miller summarized and established three guidelines and objectives for a proper acoustic environment in the office space.

> “A) Communications: people should be able to speak with clarity to each other without raising effort in a small group. B) Privacy: The discussion or conversation should not be understood beyond the immediate zone and not be disturbed by conversations outside the zone. To be specific, in a well-modulated installation, people should be able to preserve communication privacy within a radius of 10 to 15 feet from speakers. C) Context: Every space should have an acoustical environment that is natural to the activity of the organization that occupies it” (Propst & Wodka, 1975) .

These three factors should work intimately to achieve a comfortable and productive acoustic environment.

Many office product manufacturers, such as Steelcase, have taken actions to improve the sound environment in their offices. Five types of “Quiet Spaces”, ranging from individual work to team collaborations, have been introduced by that company. These Quiet Spaces offer a huge degree of control of the space. In terms of sound, they provide a quiet and confidential environment for people both inside and outside the group, resulting in a less noisy space (Steelcase, 2006).

Designing a space that completely omits the problem of noise is difficult. Sound within an environment could either be sealed, absorbed, or masked. Each of these techniques has its own advantages and disadvantages, and the design criteria for the sound environment depends on the tasks and tolerance level necessary to achieve an optimal condition (Steelcase, 2006).

Room temperature

The room temperature at office environment affects people's reaction to the environment through aspects like thermal comfort, sick building syndrome (SBS) symptoms, and productivity (O Seppänen, Fisk, & Lei, 2006). Determining the optimum indoor temperature range for a typical working environment has been explored and tested through many studies. If the office temperature had always been in the 70-75 °F (21-24 °C) range, it would reduce 70 percent of the 'hot and cold call-out', and the maintenance cost would be reduced by 20 percent (Federspiel, 1998). Office worker performance shifts only slightly in the temperature range of 70-77 °F (21-25 °C), but begins to decrease when temperature rises above 77 °F (25 °C) (Olli Seppänen, Fisk, & Faulkner, 2006).

With a rise in air temperature, many Sick Building Syndrome symptoms become more obvious and affect a larger portion of building occupants, and this could be a potential factor affecting office worker's productivity. Under cold conditions, vasoconstriction would reduce skin temperature, causing reduction in finger sensitivity and finger movement as well as affecting other aspects of manual dexterity that are important to productivity (Meese, Kok, Lewis, & Wyon, 1982).

Indoor air quality (IAQ)

Heating, ventilation, and air-conditioning (HVAC) systems are designed to provide air at comfortable temperature and humidity levels, and free from harmful concentrations of air pollutants. (Environmental Protection Agency, 1990a). Room temperature could be controlled through air-conditioning systems, while indoor air quality is more reliant on the ventilation system.

Indoor air quality is usually less noticeable to occupants when the air quality is good, but often most people would realize and react when there in a decrease in air quality. Indoor air pollution is caused by both indoor and outdoor factors; indoor sources could be people, their activities, smoking, building and furnishing materials, and electronic equipment; outdoor sources could include urban traffic, industry, etc. (Wyon & Wargocki, 2006). The quality of the indoor environment can dramatically affect the health, comfort, wellbeing and productivity of building occupants (Wargocki, Wyon, & Fanger, 2000a, 2000b). Derek (2006) summarized that poor indoor quality can reduce the performance of office work by 6-10 percent; in addition to such sacrifice in performance, a negative indoor environmental effect is also often accompanied by headaches and concentration issues.

To provide and maintain good indoor air quality, the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) has set standards for acceptable mechanical ventilation and indoor-air quality of a minimum rate of 20 cubic feet per minute (cfm) per person in general office space or 20 cfm for every 1000 square feet of floor space (ASHRAE, 2016). In addition to the ventilation system itself, building managers and office occupants must work together to improve indoor air quality, and there are several areas that need addressing, including: operation and maintenance of the HVAC system, identification and removal of pollution sources, elimination of practices that may restrict air movement, increasing ventilation rates during periods of increased pollution, and always keeping the ventilation standards and building codes affected by those standards up to date (Environmental Protection Agency, 1990b).

Behavioral Environment

The Hawthorne experiments on illumination (Roethlisberger & Dickson, 1939) made researchers realize that the workplace environment consists of more than just physical environment. The Hawthorne studies concluded in two main parts, the *illumination study* and the *back wiring room study* (B. P. Haynes, 2007). The research initially aimed to establish how productive and satisfying working environments could be achieved, and the results from these studies pointed to the impact of the behavioral environment on productivity (Roethlisberger & Dickson, 1939).

Behavioral environment consists of interactions between humans and the surrounding environment, and in office spaces it generally refers to interactions and distractions within the space, including social interaction, work interaction, creative physical environment, overall atmosphere, position relative to colleagues, position relative to equipment, and overall office layout; interruptions, crowding, and noise could also be considered as elements of an office space behavior environment (B. Haynes, 2008).

Considerable research has shown evidence that the behavioral environment will influence and change patterns of behavior in the physical environment (Becker & Steele, 1995; Bitner, 1992). Environmental behavior theorists have conceptualized several perspectives of human interactions including, but not limited to, arousal, behavioral, and environmental stresses.

The arousal approach

Based on the Yerkes-Dodson Law of Arousal, performance can be improved if a person is aroused in some manner (Yerkes & Dodson, 1908), and people could achieve their optimum performance at intermediate levels of arousal. However, if the level of arousal increases too much, performance may decrease. Arousal can be heightened by both pleasant and unpleasant stimuli. A change in arousal level causes people to seek information about their internal state to find out whether there is some kind of threat to their wellbeing. Since some tasks require more arousal than others, arousal could affect the level of performance (Farshchi & Fisher, 2006). Some of the most notable environmental factors affecting arousal are noise, heat, and crowding (Poulton, 1976).

From the arousal standpoint, some levels of environmental distraction may benefit office workers' productivity, and when choosing a working environment, office workers may consider the availability of certain environmental stimuli to heighten their arousal, thereby helping them boost their productivity.

The behavioral constraint approach

The behavioral constraint approach indicates that the loss of perceived control over environmental stimulation can lead to arousal or strain one's capacity for information processing (Farshchi & Fisher, 2006). When perceived control is lost, at first uncomfortable feelings will be experienced and then one may attempt to restore their freedom by removing obstacles (i.e., regaining control). Sommer's (1970) conceptualization of personal space and Brehm's (1966) theory of psychological reactance are frequently used in conduct of behavioral constraint approach research. Sommer (1970) defined personal space as invisible boundaries surrounding an individual; intruders are usually not welcomed when they go beyond such a boundary of personal space (McCann & Sommer, 1970). Based on Brehm's (1966) research, having access to a certain degree of control is an important motivating factor, and people will experience a reaction when the control is eliminated or threatened with elimination. The level of control perceived by or given to people may affect their reaction to the constraints.

In a modern office environment, because of dramatic shifts in office work, office workers tend to feel much less bound by restrictions than in the past. However, because there are many specific spaces particularly suited for certain types of tasks, it is necessary for office occupants to understand the functionality and purpose of these spaces, and this may affect their decisions to select locations where they can work more efficiently.

The stress approach

Salvendy (1997) summarized that stress is an outcome of an unbalanced interaction between a person and his or her environment. Noise and crowding are viewed as stressors in the physical environment, and social factors such as job pressure and family disorder can cause stress as well. Such unbalanced environmental factors may possibly become stressors and affect human behavior, function, and emotion.

Stress will occur if a person's capability cannot meet environmental demands, and/or a person's expectations are greater than supplied by the environment (Salvendy, 1997). Problem solving, social competence, and somatic health are some of the adaptive functioning factors strongly influenced by stress emotions. Environment can also cause stress-related emotions such as anxiety, fear, guilt, anger, sadness-depression, and jealousy (Lazarus & Cohen, 1977).

For optimal performance there should be a fit for demand between office workers and the working environment, it is necessary to understand office workers' choices of working space within the person-environment fit framework. The Person-Environment fit refers to the relationship of compatibility or incompatibility that may exist between a person and the environment. French, Rodgers, and Cobb (1974) mentioned that individuals' attempts to adapt or rearrange a space could be improved by the person-environment fit (French, Rodgers, & Cobb, 1974). With shifts in work types and office workers having additional flexibility in choosing their workspace, they may very well prefer places that best fit their working types.

The ecological approach

Ecological codependences exist between the environment and behavior (Barker, 1968). Based on Barker's research, the physical setting of an environment could provide us suggestions relating to what behavior would or should happen in that specific environment (Farshchi & Fisher, 2006).

The research by Nathan and Doyle (2002) aims to establish the views of office workers who worked in office environments by evaluating office environments in terms of two aspects. 1) The ways organizational cultures communicate through office environments, 2) the territorial nature in which occupiers view their space and give meaning to their workspace (B. P. Haynes, 2007). This research indicates that it is necessary to provide individual territory and privacy as well as open plans for collaborated workplaces. There is also a demand to establish organizational brand and identity throughout a space (Nathan & Doyle, 2002).

Research by Nathan and Doyle (2002) provides evidence of how an environment and behaviors within an environment affect one another. The workplace provides different postures and microenvironments to fit office workers' demands, while in the meantime, office workers must behave in certain ways to fit the culture and the brand the office is trying to achieve.

When designing modern workspaces, it is necessary to include information not only from office occupants, but also from office managers, clients, designers, and other people involved in the workspace to understand the cultures or action structures that govern the behavior of office workers in the workspaces.

Office Productivity

Office productivity in today's modern office has become relatively more complex and difficult to measure than that in a manufacturing economy, as the economy has migrated on to service and knowledge based (Mawson, 2002).

Evidence supports Oseland's (1999) notion that perceived productivity can be used as a surrogate for actual productivity and can also be useful in assessing relative changes in performance. Because there has been a large sample size used in consolidating self-assessment measurement, self-assessment measure for office productivity could be a widely-adopted metric.

Office productivity should consider not only the output of each individual; rather it is best defined as hanging in the balance between the cost of doing business and the value of the output (Pritchard, 1992). The office environment has constantly changed based on people's tasks, and from the very beginning it was a shell that contained workers doing standard processes. Nowadays, office environments may pose many different work patterns existing in private spaces for individual work and open spaces for team discussions. Extensive research has confirmed that an office environment is a complex environment, one in which productivity of its occupants is related to the physical environment as well as the social environment, adding another layer of complexity to the existing framework of office productivity. Lack of a theoretical framework for office productivity has made self-assessment approach the only realistic choice. Self- assessment productivity measurement applies a "people-centered" approach to office evaluation; the method is in alignment with establishing an end-user perspective.

Wellbeing and Productivity

Wellbeing mainly reflects feelings about oneself in relation to the world (Clements-Croome, 2006). Warr (1998) proposed a view of wellbeing comprised of three scales: pleasure to displeasure, comfort to anxiety, and enthusiasm to depression. Many attributes both inside and outside the work environment, such as one's competence, aspirations, and degree of personal control, could affect and characterize one's state of wellbeing, and these attributes can overlap one another.

Research has shown that 75 percent of people do not really enjoy the work we do (Townsend, 1997). The workplace can be a space of conflict and dissatisfaction, with the consequence being a decrease in the level of both wellbeing and productivity. A decrease in productivity and the level of wellbeing could be present in various forms such as absenteeism, arriving late and leaving early, over-long lunch breaks, careless mistakes, overwork, boredom, and frustration with the working environment and management system. Additionally, Warr (1998, 1999) has reviewed studies that reflect an increase in wellbeing-ness level associated with better job performance (P. Warr, 1998; Peter Warr, 1999). It is fair to say the there is a close relationship between wellbeing of office workers and their productivity; these are two interdependent factors.

In office settings, wellbeing of the occupants is the key to productivity. Since the identification of sick building syndrome in the 1980s, it has been well-recognized that a building should not induce health problems. Having pleasant and healthy indoor air quality and elimination of fire or other hazardous threats to occupants are bare minimum requirements for today's office environment. An office space should promote productivity wellbeing. The comfortable level, the right space for the specific task, and the right amount of physical and social interaction within the space would boost the wellbeing levels of the employees. Wellbeing in an office environment may also involve many aspects of organizational culture, from making sure people understand what their job is, to having a sense of purpose, and providing the right space, tools, and resources to be successful. A well-designed office should support its occupants from a holistic approach: mentally, physically and emotionally.

In creating a high-performance workspace, it is necessary to place greater emphasis on the wellbeing aspect of the office environment (Haynes, 2008). Independent of wellbeing outside a workspace, both physical and behavioral environment within a workspace can heavily influence office workers' wellbeing. The previous chapter reviews the physical and behavioral environments of the office space, and understanding how these environments may contribute to the office workers' wellbeing is important as well.

Office Environment and Wellbeing

It may seem that office buildings are static and costly and their cost is straightforward (i.e., dollars per square foot). However, when considering office worker productivity, the metrics in a particular space may vary due to its environment; its value may increase if the office space is healthy and sustainable (Clements-Croome, 2006). In addition to physical needs, humans also have demands related to physiological, psychological, and social needs (Boyden, 1972).

To answer the main question of this section: how to create an office environment that boosts office workers' wellbeing? Clements-Croome (2006), Boyden (1972), and Heerwagen (1998) pointed out the necessary wellbeing aspects for a building design:

1. Social environment
2. Freedom for individual and group work
3. Opportunities to develop self-expression

4. An interesting visual scene

5. Acceptable acoustic conditions

6. Contrast and random changes for the senses to react to

7. Opportunities to exercise or switch over from work to other stimulating activities

8. Good indoor air quality

Social and emotional factors along with a good physical environment would create a healthy environment that boosts the wellbeing of its occupants.

Wellbeing in Modern Office Environments

The definition of wellbeing has changed with increased numbers of types of work and how people work. Wellbeing in office space has shifted from simple ergonomics to sustaining a healthy physical and mental state over time in a supportive material and social environment (Steelcase, 2014b). In modern society, people spend approximately 36 percent of the their time working, more than in any other activity (Steelcase, 2014b). The data from research done by Steelcase (2014b) indicate that, people's health and sense of wellbeing has been decreasing throughout the world. Stress has become a global threat for office workers. Among European workers, 30 percent have recognized themselves as being exposed to stress, with 27 million working days lost due to work-related illness and injury, and 15 billion pounds yearly spent on mental health related presentation in the UK. Stress in the workplace is costing 300 billion dollars, and 60 percent of lost workdays every year attributed to work-related stress. The collective physical condition of office workers is also in decline (Steelcase, 2014b).

The previous chapter discussed the physical environment of the office space, including lighting, acoustics, and indoor air quality, and some of these physical settings could pose direct threat to the sense of wellbeing of office workers. According to the Steelcase

Workplace Survey of over 37,000 North American workers, 95 percent of the participating workers demand quiet and private spaces for confidential conversations and 40 percent say they don't have access to such spaces; 95 percent of workers need quieter places to concentrate, but up to 41 percent of them don't have access; 91 percent of workers need casual spaces to re-energize, but more than half have no place to go within their workplace; office workers sometimes even lack basics such as a good view (50%), access to natural light (40%), good indoor air quality (30%), and physical comfort (37%).

Poor physical condition and low sense of wellbeing among office workers would have a negative impact on workers' performance and overall organizational productivity. The data collected by Steelcase coincide with this point of view, and the data reflects the office wellbeing issues from aspects such as physical, physiological, and psychological needs. The demand from office occupants on the office environment is more evident than ever before, and if they are to fully engage and have a true sense of purpose at work, the office environment would need to provide office workers a sense of optimism, connection with one another, and maintenance of physical and mental health for office workers.

Control

Within an office environment, control could address the problem of individual differences in physical preferences by enabling people to self-select their preferred conditions (J. Veitch, 2006). In terms of lighting in the office space, many lighting researchers and designers tend to believe that people will be more satisfied and be more productive with personal control (Barnes, 1981; Simpson, 1990) not only in terms of having physical control of lighting to produce a more desirable luminous setting, but also by increasing the sense of perceived control (Cohen, Standeven, Bordass, & Leaman, 2001; Moore, Carter, & Slater, 2002, 2004). However, control factors within the environment need to be designed precisely and correctly, since an ineffective control represents a source of annoyance and frustration. American National Standard Practice for Office lighting (2017) has suggested that control leads to beneficial consequences, although there were exceptions. Experiments by Veitch and Gifford (1996) concluded that control of lighting in front of the experimenter and another participant led to poorer and slower performance on a creative task than for people who had no control over the lighting situation. The experience ended with such consequence because in a demanding, stressful work environment, additional controls over the physical condition could add to office workers workload and thereby lead the environment in an undesirable direction (Wineman, 1982). Leaman and Bordass (2001) summarized that, without an understanding of individual controls, either the controls do not work as intended or they will require response from overloaded office workers. Lack of understanding of consequences of control will most likely result in an undesirable working environment.

As stated previously, it is natural for individuals to seek control when they perceive they are losing control over their environment. However, a lack of information about the controls or providing too many controls can lead to undesirable outcomes, such as reduction in productivity and poorer performance. To provide the right type of control, either for an individual or for the overall environment, it is necessary to understand what types of control we can have over our environment; According to Bell (2001), several attempts of summarizing the control types has been made, including behavioral control, cognitive control, and decisional control. In addition to control types on the psychology side, the technical side of the control should not be ignored. In order to differentiate the two types of control, *technical control* will be designated simply as *control* in this study and the term *psychological control* will be represented by the term *regulation*.

Types of Regulation (Psychological Control)

Behavioral regulation

The threatening environmental event could be changed by a behavioral response such as turning off a loud noise or changing the luminance of the lighting environment.

Cognitive regulation

Processing information about threats in such a way that people appraise them as less threatening or better understood.

Decisional regulation

Office workers have multiple options they can use to alter the threatening environment, such as going to a quiet space for a more confidential conversation.

Behavioral regulation can be improved either through regulated administration or stimulation modification. Regulated administration demonstrates control over the threatening event, and stimulus modification shows that threats could be avoided, terminated, or modified. Cognitive regulation can be proven either through appraisal of the threatening event as less threatening or through gaining information about the threating event, such as predictability or consequences (Bell, Greene, Fisher, & Baum, 2001).

Personal regulation is highly praised and appreciated among office workers, with these three basic types of regulation offering office workers different styles and degrees of control over their environment. From the perspective of lighting environment in the workplace, it is indispensable to analyze and review what these controls offer, both from the perspective of individual workers and the working environment as a whole.

Types of Lighting Control (Physical Control)

This section reviews common types of control used for lighting in workspaces. They depend on the characteristics of the space, such as occupant behavior, switching or dimming, and manual or automatic (Illuminating Engineering Society, 2017).

Switching and dimming

Switching generally refers to systems that switch lamps simply on or off or light output changes occur in relatively large steps. Dimming refers to systems where the light output varies either continuously or in very small steps.

Manual control

Traditionally, all office building lighting have tended to be centrally-controlled, with all luminaires switched on early in the morning and off in the evening after the last person has left the building. Such as preset scene controls, some slightly more complex manual lighting control systems make use of lighting presets for either small or large spaces to create specific lighting scenes.

Automated control

Automatic controls include features such as time clocks, occupancy sensors, and daylight harvesting. For instance, time clocks, which lights are turned on and off on a predetermined schedule. Occupancy sensors is another example, it uses infrared, microphonic, or ultrasonic technology to detect whether or not the space is occupied, with lights turning off if the space remains unoccupied for an extended period of time.

These are some of the common types of controls to be deployed in office space; more detailed information can be found at American National Standard Practice for Office Lighting by Illuminating Engineering Society (2017). Many of these controls were implemented for the sole purpose of energy saving. No matter whether manual or automated, control systems tend to weigh more toward energy saving than creating lighting environments that encourage higher productivity and increases in wellbeing. With advances in technology, especially the emergence of LEDs, the number of ways in which lighting can be controlled are also expanding through development of more advanced hardware.

Summary

In summary, this chapter has presented the premise and foundation of the study. This information plays a significant role in understanding the study as a cohesive whole. It has addressed the fact that the relationship among office environment, occupants' wellbeing, and their productivity should set the foundation of this study, and how control factors may influence office occupants in terms of their wellbeing and productivity.

CHAPTER 3. LITERATURE REVIEW

Introduction

This research has been conducted in an effort to understand effective means for utilizing naturalistic lighting design concepts in the modern office environment. The broad context and background for the study relates to issues of light and health, interior lighting design in office environments, and characteristics of natural lighting. In this chapter, the characteristics of natural lighting will be examined and grouped for use in the future design framework. Literature on current natural and artificial lighting conditions within modern offices and the effects of natural and artificial light on human behavior is reviewed, and research questions and objectives are developed from the literature review. The chapter conclusion generates inferences from the literature review that create the design and methodology fundamentals for use in conducting the research.

Natural Sunlight within the Office Environment

The relationship between natural lighting and office workers' sense of wellbeing has been well established. Research indicates that sunlight entering an office is associated with higher job satisfaction (Bell et al., 2001). Benefits resulting from exposure to full spectrum daylight include better health, reduced absenteeism, increased productivity, financial savings, and preference of workers (Edwards & Torcellini, 2002). This part of the research is to review and discuss the natural lighting environment within workspaces; thus, revealing how office workers are affected by presence of natural light.

Physical Health

According to John Ott (1997), eyestrain (one of the biggest health problems encountered in offices) is related to the spectrum of lighting presented in the office environment and the eye’s ability to refocus (Edwards & Torcellini, 2002). The direct negative consequences for eyestrain are near and far-sightedness. Natural lighting is often provided through windows, enabling the eyes to be exposed to the full spectrum of light and to refocus by providing short and long range landscape views (Franta & Anstead, 1994).

Natural lighting could also engender positive employee moods, potentially resulting in higher job satisfaction, work involvement satisfaction, motivation, organization attachment, and lowered absenteeism (Heerwagen, Johnson, Brothers, Little, & Rosenfeld, 1998).

Productivity

Research studies have shown that office productivity can be boosted by increasing light quality. Studies of silk weavers were conducted to establish the relationship between productivity and natural light, and in a modern office environment the relationship between performance and the amount of daylight still exists (Edwards & Torcellini, 2002). Edwards and Torcellini (2002) reviewed several companies and organizations, including Lockheed Martin, VeriFone, and West Bend Mutual Insurance, that have benefitted from use of natural lighting.

A Lockheed Martin designer designed Sunnyvale’s California office with an open office plan and integrated daylight, successfully increasing interaction among engineers working there and leading to a 15 percent boost in contract productivity (Romm & Browning, 1998). VeriFone, Inc. reported a 5 percent boost in productivity and total product output increase of 25-28 percent when they moved in to a new daylight-lit Worldwide Distribution Center (Pape, 1998). West Bend Mutual Insurance’s employees moved to a new building where more employees would have access to windows and greater personal controls over workstations, producing a 16 percent increase in claim-processing productivity (Romm & Browning, 1998).

When natural lighting is presented in the workspace, office workers have a tendency to performance better and increase their productivity. Not only has natural lighting the potential to boost workers' performance, it is also being greatly-valued among office workers in workplaces.

Employee Preferences and Perspectives

Office workers in general have expressed positive reactions and impressions when windows and natural light have become part of their working environment. Window exposure is highly-valued by office workers in the work environment, and many research surveys have shown that employees prefer having a window with a view close to their workspace. Office workers also have indicated that natural lighting is preferable to artificial lighting (Cuttle, 1983; Markus, 1967; Wotton & Barkow, 1983). For designers, properly integrating natural sunlight into office spaces can have great positive impact on office workers (Edwards & Torcellini, 2002).

Artificial Lighting within Office Environments

Primary Light Sources

Currently, there is high demand for artificial lighting in office spaces because it provides a stable and reliable light source that enables us to work even when natural daylight is not available. Since Thomas Alva Edison invented the incandescent lamp and manufactured it on an industrial scale in 1879, the lighting industry continued to develop and produced a wide range of different types of lamps. Under criteria of cost-effectiveness, long service life, and low energy consumption, four main groups of light sources are being produced (Zumtobel, 2013b):

1. Thermal light sources (e.g., incandescent lamps, halogen incandescent lamps)
2. Low-intensity discharge lamps (e.g., fluorescent lamps)
3. High-intensity discharge lamps (e.g., metal halide lamps, mercury discharge lamps)
4. Semiconductor light sources (e.g., LED lamps, OLED lamps)

Fluorescent lighting systems have been widely adopted throughout modern office environment because they are highly energy-efficient and have the capability to produce a constant luminance output (Clements-Croome, 2006). In general, a fluorescent lighting system can light wide areas efficiently, providing the workspace a stable, constant, and reliable ambient environment. In addition, such a system is dimmable, and office workers could benefit from the fluorescent lighting system by adjusting to a level consistent with specific tasks.

While fluorescent lighting has been the dominant lighting solution in the office environment for a very long time, the situation is now changing through development of semiconductor lighting sources such as LEDs. Table 1 shows ZUMTOBEL, for which a lighting manufacturer (2013) compared fluorescent light and LEDs, and the semiconductor light sources outperformed the fluorescent light in almost every aspect.

Table 1. Comparison between gas discharge lamps and semiconductor light sources. Retrieved from "The Lighting Handbook" by ZUMTOBEL, 2013, Zumtobel Group, p.92-93.

	Gas Discharge Lamps	**Semiconductor Light Sources**
	Low-pressure Fluorescent lamps Compact Fluorescent lamps	Individual LEDs LED modules LED lamps
Applications	Private and professional	Private and professional
Light Production	Current flow through conductive gas (contains mercury)	Photons are produced in a solid material
Output	Low to moderate 5 - 80W	Very low to high 0.2W to 100W
Lamp voltage	230v, > 110v	230v, 12/24 v
Luminous Flux	250 – 6150 lm	Up to 5000 lm
Luminous efficiency	50 – 100 lm/W	60 to 140 lm/w
Energy efficiency class	A, B	A
Service life	10,000 to 24,000 hours	25,000 to 50,000 hours
Light color	Warm, intermediate, cool Approx. 2500 – 8000K	Warm, intermediate, cool Approx. 2700 – 6500K
Color rendering	Very good (CRI = 80 – 95)	Very good (CRI = 70 to > 90)

Due to their relatively poor efficiency and short service life, fluorescent lighting systems are phasing out and being replaced by high luminous efficiency and long service life LED systems (Zumtobel, 2013b), and because of the superior characteristics of LED light sources, they will most certainly be the lighting source of the future, at least for workspaces.

Guidelines and Recommendations for Office Lighting

After reviewing the codes for office spaces, Zomtobel (2005) stated that most of the current codes are either in conflict with one another or don't measure up to the findings of the most current research. Since office work types and styles are evolving at a fast pace, the lighting guide must be constantly updated to create correct guidelines. Despite a combination of fast development of lighting technology and office worker demands related to lighting environment, some fundamental lighting guidelines for productive and healthy workplace could be found in summaries based on office research (Clements-Croome, 2006; Zumtobel, 2005) as follows:

Visibility factors:

1. Appropriate horizontal vertical illuminance for tasks and viewers
2. Occupant-controlled systems for glare control
3. High-frequency ballasts in fluorescent lighting systems
4. Maintain ambient lighting levels between 350 – 400 lux
5. Utilization of localized task area lighting
6. Keep vertical surfaces bright, above 200 lux vertically

Wellbeing factors (stimulation):

1. Lighting condition fine-tuned to aid night-shift workers
2. Enable increased lighting exposure for some portions of the day
3. Avoid creating stressor: glare, reflections
4. 80% of the net light-able floor area should be adequately lit by natural sunlight
5. Use lighting designs with both direct and indirect components
6. Learn users' expectation beliefs about lighting
7. All workstations should have a view outside with a maximum distance of seven meters to the nearest windows

Control:

1. Allow users to select their preferred range of illuminance
2. Keep control simple and responsive
3. Provide individual controls
4. Integrate user control and automated control
5. Creating luminance variability but within the effective range

The approaches used in setting these guidelines are certainly neither primarily determined by the illuminance of the space or specific area, nor by the artificial lighting only. The preferred approach to lighting design is based on the principle of lighting for people and their visual comfort and sense of wellbeing, as well as a combination of natural and artificial lighting systems. While designers and building managers are starting to realize the benefits of good quality light and beginning to take actions, current natural and artificial lighting system poses several tricks and problems such as glare, reflection, excessive amount of heat, etc., when improperly integrated.

Recent Studies on Perceived Lighting Quality in Workplaces

The data in this section has been retrieved from "Lighting for Offices and Communication" by ZUMTOBEL, 2013, Zumtobel Group, p.10 – 11. The Zomtobel Group and the Fraunhofer Institute of Labor Planning and Organization (IAO) together conducted this global user study on lighting quality perceived in workspaces, focusing on people's need for adequate lighting. The best feature of this study is that it engaged 2,700 participants from Europe, Asia, Australia, and the USA. This sample size and diverse participant group enables researchers to more effectively improve lighting quality and enhance the working environment.

The study points out a few highlights worth considering: preferred illuminance level, demand for artificial lighting, color temperature preferences, broad approval of direct/indirect lighting, and controllable lighting in office space; a specific breakdown is shown below (Zumtobel, 2013a).

1. Preferred illuminance (Age: 26-35): The study shows that more than 60 percent of the participants prefer illuminance levels of 800 lux and higher, and a significant number of them want the illuminance levels set higher than the 500 lux required by the relevant standards.
2. Demand for artificial lighting: Independent of season, there is a high demand for artificial lighting for more than six hours on a daily basis.
3. Color temperature preferences: Users usually perceive intermediate and relatively warm light as more pleasant than cool color temperatures.
4. Broad approval of direct/indirect lighting: 82 percent of the participants perceived a combination of direct and indirect lighting as an ideal lighting situation, even though only 38 percent of the participants work in such an environment.
5. Controllable lighting: 81 percent of the participants have limited or no options to control the lighting situation at their workspaces.

The study had some interesting results. First, the study indicated that younger office workers (up to the age of 36) appear to need more light than provided by the code requirements. Second, despite the availability of the natural light or time of season, there is a high demand for artificial lighting, possibly due to its constancy, controllability, and stability. The findings related to color temperature in practical terms means that ideally flexible luminaires with variable color temperatures should be used. Also, many office workers were dissatisfied with their working environment, and most of the office environments lack of the integration of direct and indirect lighting; personal lighting control is also missing.

Improper Lighting within Office Environment and Corresponding Solutions

Improper Natural Sunlight

As previously discussed, natural lighting could bring significant benefits to office occupants, but only if the natural light is properly integrated and used. Improper use of daylight can cause negative effects to the environment such as extremely high light levels, excessive glare, and high temperature, possibly leading to a decrease in productivity and an increase in office worker absenteeism (Edwards & Torcellini, 2002).

Glare seems to be the number one issue raised by improper implementation of sunlight. Glare usually happens where there is excessive and uncontrolled brightness, and, while our eyes will generally adapt to brighter levels, details in the darker or shadow areas will often be masked (Summers, 1989). Glare may cause annoyance, discomfort, or loss of visual performance (McCormick, 1976), factors often associated with job dissatisfaction (Ruck, 1989).

Office workers are indeed suffering from the effects of glare. At a time when the employees of the Iowa Association of Municipal Utilities building, the VeriFone building, and the Hughes Corporate Headquarters building were enjoying the benefits that a daylight system brings, during certain times of the day they also suffered from the excessive glare produced by sunlight (Edwards & Torcellini, 2002).

There are two practical methods to control glare that introduced by natural light (Abdou,1997):

1. Arrangement of windows and surrounding interior surfaces to reduce the contrast between these surfaces and the observed sky;

2. Reduction of sky luminance by screening the windows with special films, blinds, or louvers, preferably with adjustable screens to control the maximum light being admitted (Abdou, 1997).

The Iowa Association of Municipal Utilities building management made an active response to the glare issue, including installing semi-opaque fabric six feet away from the windows for two to three months a year (Cale, 2001). On a portion of the east side building, venetian blinds were installed to darken the room for multimedia purposes. Additionally, employees were trained to properly orient their computer monitor screens to minimize glare. That building demonstrated effective ways to overcome some of the undesired glare issues caused by the natural sunlight.

Glazing type is another potential aspect with great thermal implications that may impact the satisfaction of office workers, because the temperature of the interior environment can be raised by the glazing effect. Large window-to-wall areas of regular glass could cause extensive overheating near the windows (Abdou, 1997). A current major solution for overheating issues is use of low-emissivity (low-E) glazing to transmit “cooler” daylight; for a given visible transmittance, low-E glazing blocks a large fraction of incident solar infrared radiation, the main cause of heating issues. Low-E glazing could also help increase the mean radiant temperature of the interior during winter and vice versa (Abdou, 1997).

While natural daylight has potential for bringing significant benefits to office workers, at the same time certain issues such as glare, heating, and excessively high light levels have become undesired byproducts of sun-lighting systems. If shades and blinds are used to avoid these issue, the benefits of sunlight are greatly reduced and artificial lighting systems will become the main light source in an office environment. Compared to natural lighting, an artificial lighting system can be implemented and adjusted to provide sufficient luminosity for different type of tasks, even though such a system is not completely issue-free.

Improper Artificial Lighting

Reflection is another problem in addition to glare with the potential to negatively affect workers' productivity when visual perception interacts with an artificial lighting system.

Many types of office work are required for office workers using screen-based equipment, and screens may reflect lighting sources or high reflectance areas, possibly leading to distraction in receiving information from the screen thereby causing discomfort and discontinuation (Summers, 1989).

A top lighting priority is to reduce reflections for screen-based users. Reducing ambient light levels, shielding luminaires, and repositioning screens relative to the lighting source are some of the effective methods of reflection reduction, as shown in Figure 1.

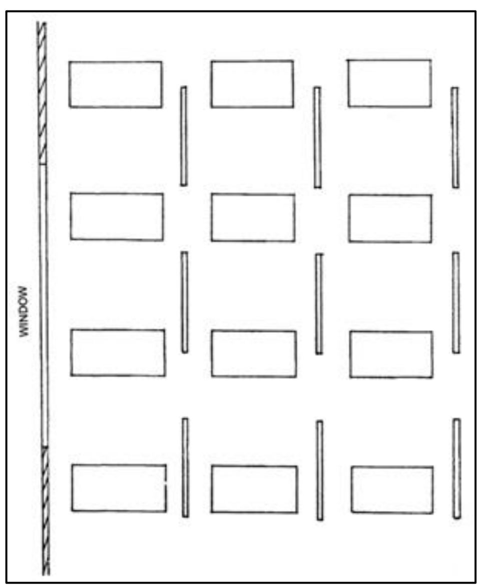

Figure 1. Desks and screens are perpendicular to windows and overhead luminaires. Position desks at right angles to the troublesome light source when windows and fluorescent are not parallel. Retrieved from "Lighting and the Office Environment: A Review" by Summers, Angela June, 1989, Australian Journal and Physiotherapy, 35(1), p.15-24.

Based on reviews of improper lighting studies for both natural lighting and artificial lighting systems, it is clear that these are some of the most pronounced problems caused by these systems. From the perspective of improper lighting, this also proves the importance of lighting environment for office workers, since it can significantly affect office workers' wellbeing, physical health, performance, productivity, and job satisfaction.

With respect to natural lighting, in the office environment section, the effect of lighting was thoroughly discussed, but the reason that natural light provides such tremendous benefits to office workers remains unclear. It would be necessary to understand the fundamentals of natural sunlight and analyze the traits of natural lighting to make full use of that source, and to assist in developing naturalistic lighting when natural light itself becomes unavailable or unreliable.

The Significant Traits of Natural Sunlight in Nature

The spectral power distribution of light emitted by the sun is a full-range spectrum and almost invariant after the sunlight penetrates the earth atmosphere by which a broad range of wavelengths are scattered and absorbed (Henderson, 1977). The definition of the daylight discussed in this research will focus on the light after its interaction with the atmosphere of the earth.

Natural lighting is a readily-available resource from nature and highly unlikely to run out in the predictable future. Long before the appearance of human beings, light was an essential ingredient for the evolution and development of life forms. In the earliest cave era, daylight functioned as an indicator for day and night; as dwellings became more sophisticated, occupants sought ways to create openings and admit light into the living space. (Phillips, 1958) In the development process of human beings and their culture, natural light has always played an indispensable role. An important psychological aspect associated with daylight is meeting a need for contact with the outside living environment (Robbins 1986).

Spectrum

The daylight that people experience on a daily basis can be categorized as a form of electromagnetic radiation. The wavelength of electromagnetic radiation can range from miles to inches to millionths of an inch to billionths of an inch. (Ott, 2000) The wavelength of light is described in nanometers (nm). Humans can detect visible light in wavelengths ranging from 380 nm to 780 nm, and this range of wavelengths is called the visible spectrum. A human eye can detect less than 1 percent of the total electromagnetic spectrum. Slightly beyond each end of the visible spectrum, there are ultraviolet and infrared waves, referred to as background radiation (Ott, 2000). Ultraviolet wavelengths within the earth atmosphere range from 280 – 400, shorter than the visible spectrum. Infrared radiation has longer wavelengths than visible light, ranging from 780 to 3000*10^6. From visible spectrum to ultraviolet to infrared, these components form the complete natural light spectrum in our world.

Variation in Natural Sunlight

As previously mentioned, the spectrum from the sun is partly scattered and absorbed by the atmosphere, with the spectral distribution of daylight varying considerably depending on latitude, time of the day, season of the year, and weather conditions (Judd, MacAdam, & Wyszecki, 1964; Lee & Herna´ndez-Andre´s, 2005a, 2005b).

With changes in sky and weather patterns, the wavelength distribution during the day shifts. Wavelengths of light will be directly reflected in the color appearance of the light, related to color temperature. Color temperature is a measurement in degrees Kelvin that indicates the hue of a specific type of light source. The lower the color temperature of the light source, the redder the source will be and, inversely, the higher the color temperature of the source, the bluer it will be. Table 2 below provides a direct representation of how the daylight color changes throughout the day.

Table 2. Depend on different time of the day; the color temperature of the light also changes. (Bim, 2013)

Degrees Kelvin	Type of Light Source
2000-3000K	Sun: at sunrise or sunset
5000-5400K	Sun: Direct at noon
5500-6500K	Daylight (sun+sky)
5500-6500K	Sun: through clouds/haze
6000-7500K	Sky: overcast
7000-8000K	Outdoor shade areas
8000-10000K	Sky: Partly Cloudy

The atmosphere also produces changes in illuminance intensity and color through the filtering effects of smoke, dust, water vapors, and clouds (Granzier & Valsecchi, 2014). Research by Begemann, Van Den Beld, and Tenner (1997) has collected and demonstrated vertical illuminance and color temperature on the window of an office setting during the year 1993 and, over a 24-hour day cycle, there was an overall change in the intensity of the illuminance from the very bright midday to the darkest starlit night.

Values and Benefits of Natural Sunlight

The anecdotal evidence of benefits that come from contact with natural lighting is clear and rich. For example, despite how luxurious or poor one's house may be, most would let a certain amount of sunlight shine into the house; window seats are also preferred over non-window seats by many. Other indirect measures can be derived by examining wellbeing and changes in productivity of office occupants (Edwards & Torcellini, 2002). On a broader scale, natural lighting has significant effects on aspects such as metabolic activities, sex lives, and life spans of all living things (Ott, 2000). Many have pointed to the importance of natural light. Dr. Ott (Ott Biolight System, Inc. 1997a) for example, states that the body utilizes light in ways similar to water or food as a nutrient for metabolic processes. Essential biological functions in the brain are stimulated by natural light and divided into colors that are vital to our health. In poorly lit environments, the inability to perceive the colors from the light can affect our bodies both mentally and physically. Dr. Liberman has mentioned that natural lighting plays a role in maintaining health, such as the nervous system and and the endocrine system are directly stimulated and regulated by light (Liberman, 1991).

Biological

Several research projects have investigated people's biological reactions and attitudes with respect to natural light. According to Hathaway, et al. (1992), natural lighting presents the highest levels of light needed for biological functions, and wavelengths ranging from 290 to 770 nanometers are of the greatest important to human beings.

As mentioned previously, a human eye typically will respond to a wavelength range from about 390 nm to 700 nm, although the wavelength range with the greatest importance to human beings is wider than that of the visible spectrum. Beyond bluish light (400 nm), there is ultraviolet light (UV) with three classifications: near, mid, and far. Near UV rays, ranging from 300 – 400 nm, are responsible for tanning response in humans; mid UV rays range from 200 to 300 nm and activate the synthesis of Vitamin D and the absorption of Calcium in the human body (World Health Organization. & International Programme on Chemical Safety., 1994). Vitamin D is an important factor in the calcium absorption process, with absence of Vitamin D leading to insufficient calcium absorption and resulting abnormal growth and development of bones (Liberman, 1991).

Coming back down from UV light, the visible portion of light also has great impact on many function of human beings, such as circadian rhythms and secretion of melatonin.

Physiological

Circadian rhythm

Circadian rhythm is a human body's physiological process affected by the wavelength of light (Ott Biolight System, Inc. 1997a) and is perhaps the most significant physiological process affected by light.

Circadian rhythm is largely controlled through our visual system. Light falling on the retina and transmitted to the hypothalamus controls our circadian rhythms (Samuels, 1990). Such rhythms, through which we experience continuous rhythms of various physiological and behavioral functions with an inherent period of about 24 hours, entrained by millions of years' exposure to the natural daylight (Withrow, 1959). have been known to exist in humans for several decades. Circadian rhythms are largely influenced by the suprachiasmatic nucleus (SCN) in the brain that receives input about environment conditions. SCN functions as the master clock of the body. Human and other mammalian SCN's most important type of environmental input appears to be light and darkness transmitted from the eyes' retina via the retinohyphthalamic tract. Light to dark cycles of the solar day have the greatest impact on circadian rhythms compared to other environment conditions such as temperature, sound, etc. (Moore-Ede, 1982), and are also key for the human body to precisely synchronize to a 24-hour day. When the timing signal or light exposure is absent, the circadian rhythm would generally express the intrinsic circadian period of clock with a non-24-hour cycle (Dijk & Lockley, 2002). To maintain such a normal circadian cycle, exposure to relevant environmental time cues such as a solar light-dark cycle is extremely important (Sack et al., 2007).

The light perceived through the visual system has a great effect on secretion of the hormone melatonin. The secretion of melatonin will happen when there is absence of light, such as when there is inadequate artificial lighting or daylighting in an interior environment (Wurtman, 1975). A person's activity and energy level is determined the melatonin level in his or her body. High melatonin levels lead to drowsiness, while low melatonin levels relates to an alert state of consciousness (Ott Biolight Systems, 1997).

Circadian rhythm and secretion of melatonin could also be affected from a non-visual standpoint. Recent research has identified non-rod, non-cone photoreceptors in the ganglion cells of the retina (Berson, Dunn, & Takao, 2002; Hattar, Liao, Takao, Berson, & Yau, 2002). Photopigment melanopsin are found in these nonvisual circadian photoreceptors that are particularly sensitive to blue wavelength lighting. These cells send signals to the SCN, the master clock of the brain, indicating that blue light potentially has great impact on circadian rhythm entrainment and suppression of melatonin production.

Blue light

Along with the discovery of melanopsin retinal ganglion cells, because these receptors are uniquely sensitive to blue light, the attention of the researchers has been drawn to blue light. The major findings related to blue light have been directed to its suppression of melatonin secretion, since it exhibits the most powerful suppression effect on melatonin secretion among all wavelengths (Holzman, 2010). Blue light inhibits the increase of melatonin secretion during nighttime and promotes its decrease in the morning (Morita & Tokura, 1998). Due to its strong effect on the secretion of melatonin, blue light is now regarded as the most important wavelength for entraining the circadian rhythm. Other effects have been found as well, such as acute performance improvement both at night and during the day, boosted alertness, and improvement on memory tasks. Blue light also can cause people to have quicker auditory reaction times and fewer lapses of attention than other wavelengths, and this may be due to a lower level of melatonin secreted in the brain.

The dominant lighting system adopted in the majority of office spaces is fluorescent lighting that lacks a blue portion of light. Because of human biological reactions to blue light, it could potentially benefit office workers by reducing sleepiness and boosting attention, alertness, and the sense of wellbeing.

Up to this point, a link between natural light and human responses has been developed and established. Human physiological and biological processes affected by light explain how and why office workers are usually more satisfied with a natural lighting environment. From a psychological perspective, natural light also affects office workers in an indispensable way. As researchers and manufactures have begun to realize the importance of natural light, a new field of lighting research, Human Centric Lighting (HCL), has emerged in recent years. Human Centric Light is a broad lighting concept that covers a wide range of environments, from residential to retail, from healthcare facilities to workplaces. TRILUX, a lighting solution company, defines HCL as adapting lighting to the specific needs of users to achieve maximum quality of light and lighting.

Conventional Naturalistic Lighting

Nature, Natural, and Naturalistic

To assess the degree of natural character present in the natural lighting in nature is to distinguish between ‘nature’, ‘naturalness’, and ‘naturalistic’. Practitioner Diane Lucas (1996) cites the following application of these criteria:

"'Natural' is of nature; 'naturalness' is the expression of the natural; 'naturalistic' is contrived to exhibit characteristics of nature – that is, it is of the cultural but expressing a relationship with the natural. Naturalistic elements/patterns/processes are built to have a character that has a relationship with nature".

"Naturalistic character cannot substitute for natural character. To change an unbuilt place to a built by introducing naturalistic elements – e.g. a building of camouflage design character, or a design responding to natural visual characteristics such as form, color, line and texture – no matter how successful the development is in mimicking or respecting nature, it still involves a reduction in natural character in replacing naturalness with naturalistic".

The definition provides the fundamental definitions of naturalistic elements and the major differences among the terms nature, naturalness, and naturalistic. As the definition infers, "naturalistic" often does not equal "natural", even though naturalistic elements will always have certain traits from nature; however, they could be differentiated from nature either slightly or dramatically.

The Approach to Naturalistic Lighting – Biophilic Design

As mentioned in the previous section, the term "naturalistic" is contrived to exhibit characteristics of nature. While naturalistic elements/patterns/processes are built to have a character that has a relationship with nature, a naturalistic character cannot substitute for a natural character. In other words, naturalistic elements will always have a few or many traits drawn from the nature, but will not replace nature in any way.

The term naturalistic lighting may serve as one of the derivatives of biophilic design, a deliberate attempt to translate an understanding of inherent human affinity to affiliate with natural systems and processes (Kellert & Wilson, 1993; Wilson, 1984) into the design of the built environment (Kellert, 2008). Because the evolutionary context for the development of the human mind and body has mainly been dominated by critical sensory features in the environment, such as light, sound, odor, wind, weather, water, vegetation, animals, and landscapes, it became human beings' natural inclination to affiliate with natural systems and processes, especially life and life-like features of the nonhuman environment (Kellert, 2008).

Kellert (2008) pointed out that during the past 5,000 years of human civilization, representing only a small fraction of human history, there has been no substitute for the benefits of adaptively responding to a largely natural environment, human health, maturation, and productivity is still in close association with natural systems and processes. Human demand for a natural environment is still considered an important necessity to achieve a healthy life style both mentally and physically.

With respect to light, natural lighting is being identified as one of the biophilic design attributes and is often identified as an important and preferred feature by most people in any built environment. The use of natural daylight could improve morale, comfort, health, and productivity (Kellert, 2008) and a growing body of literature supports the role of contact with natural light in human health and productivity. In the literature review, a comprehensive review of how natural lighting within buildings may impact office occupants' functioning, health and wellbeing is presented.

Biophilic design, essentially the backbone of naturalistic lighting, can be regarded as the missing link in prevailing approaches to providing a more healthy and productive office environment. From a biophilic design approach, naturalistic lighting represents an attempt to bring some of the vital and significant characteristics of natural sunlight into workspaces where traditional artificial lighting is the dominating light source.

The next chapter reviews a large body of literature regarding both visual and non-visual effects of lighting from several perspectives such as intensity, color temperature, timing, duration, and exposure pattern. The knowledge accumulated in this section provides a good idea of how the human body reacts to different lighting scenarios.

Human Centric Lighting

Lighting in workplaces can, in addition to providing sufficient illuminance to support visual tasks, can also have huge impacts on office workers' alertness, mood, cognition, circadian circle, and health. From another perspective, the lighting environment to which office workers are exposed have both image-forming and non-image-forming effects.

In terms of today's lighting in workplace environment, problems related to visual comfort and performance have been very well addressed. Most office workers are provided with a lighting system that enables them to see clearly and minimizes visual comfort hazards such as flare, reflections, and even fatigue. However, the non-visual effects of lighting are generally not given much consideration nor implementation (K. C. Smolders & Beersma, 2014). This may result in creating lighting environments that do not fully support the non-visual functions of the office workers, such as a decrease in alertness, a change in mood, and circadian cycle disruption. It is very important and necessary to address the non-visual aspects of light in workspaces.

HCL may provide a lighting solution for improving the non-visual aspects of light for office workers. As opposed to just taking intensity into the equation, spectrum, timing, duration, and pattern of the light may also be considered in creating a lighting environment for optimum human functioning (K. C. Smolders & Beersma, 2014).

Among current developments in Solid State Lighting (SSL), a well-known example LED lights, can provide lighting over any spectrum and a wide range of intensities at any time. SSL provides flexibility with respect to the possibilities of achieving the Human Centric Lighting concept and to provide lighting systems that support both visual and non-visual functioning for office workers. With SSL, many factors such as intensity, spectrum, timing, duration, and exposure pattern can now be truly considered with respect to the equation of HCL.

Intensity

The effects of lighting intensity have been comprehensively studied in many research studies. In addition to the effects of sufficient/insufficient lighting for conducting visual tasks, light intensity also has an effect on employees' perception of the workplace. Studies show that a space with a higher intensity level may be perceived as more lively, less tense, more formal, and more pleasant (Davis & Ginthner, 1990; Vogels & Bronckers, 2009). However, it is difficult to establish an optimum lighting intensity standard, because intensity preferences may vary from person to person and as a function of personal characteristics, time, and context (Logadóttir & Christoffersen, 2008; K. C. H. J. Smolders, 2013).

Some findings can be generalized from the massive number of research studies regarding light intensity. During daytime, when illuminance of 1000 to 2500 lux is introduced during work hours for some time periods, alertness and sense of vitality are enhanced, and symptoms of depressiveness and sleepiness are reduced (Partonen & Lonnqvist, 2000; Phipps-Nelson, Redman, Dijk, & Rajaratnam, 2003; K. C. H. J. Smolders, 2013). These research findings suggest that bright light exposure during daytime for office workers may significantly support their mental wellbeing.

Light exposure at night also increases sense alertness and arousal both subjectively and objectively. According to some research studies, exposure to more intense light during biological night can reduce the level of sleepiness, result in faster responses during attention tasks, increase heart rate and core body temperature, modulate brain activity, and, of course, suppress the secretion of melatonin (K. C. Smolders & Beersma, 2014). However, other studies have indicated that exposure to bright light during nighttime, in addition to melatonin secretion, may shift the timing of melatonin onset after being exposed to the light, thus affecting an individual's melatonin rhythm and circadian cycle (Zeitzer, Dijk, Kronauer, Brown, & Czeisler, 2000). Melatonin suppression during nighttime may pose threats to office workers' health in the long term (K. C. Smolders & Beersma, 2014). While improvement in alertness and performance achieved by increasing light exposure during nighttime is important, designers should also be aware of the potentially disturbing effect on office workers' circadian circle and health condition in the long term.

Spectrum

Spectrum, a very important aspect of the rendition of the environment, can largely affect how office workers perceive the atmosphere of a space, because the spectral composition of the light can influence the color appearance of objects in the workspace and may also influence performance that requires color detection and discrimination as well. Vogels and Broncker (2009) reveal that low correlated color temperature (CCT), such as yellow and orange, is often perceived as warmer, more relaxed, and less tense, while blue-enriched light is often perceived as brighter when compared to the low CCT at the same illuminance (Wei et al., 2013). However, the situation remains somewhat similar to that of light intensity, where some studies reveal substantial inter-individual differences in CCT level presences (Logadóttir & Christoffersen, 2008).

Spectrum also affects individuals in a non-visual way. The review of literature has shown that mid-Ultraviolet (200-300 nm) helps the body to synthesize vitamin D for better calcium absorption; blue-enriched light suppresses melatonin secretion and improves alertness and performance.

Research throughout the years has demonstrated the beneficial effects of blue or blue-enriched light both in well-controlled lab environments and everyday workplace situations. In controlled laboratory settings, exposure to monochromatic blue light compared to red light has been found to increase subjective alertness during early morning, and dim blue light compared to green or violet light also induces stronger activity modulations in brain areas associated with arousal and cognition (Revell, Arendt, Fogg, & Skene, 2006; G. Vandewalle et al., 2007; Gilles Vandewalle et al., 2007). Within an everyday workspace scenario, office workers also benefitted from exposure to blue-enriched white light, by increases in alertness, mood, sleep quality, and self–reported performance compared to the lower CCT lighting commonly used in office settings (Viola, James, Schlangen, & Dijk, 2008). One point worth mentioning from Vetter and colleagues' (2011) experimental result is that the timing of office workers' rest-activity pattern during days off may be affected by exposure to a high CCT during the workday (Vetter, Juda, Lang, Wojtysiak, & Roenneberg, 2011), although it is currently unknown whether this would have a negative impact on employees' long term health and wellbeing (K. C. Smolders & Beersma, 2014). The research regarding the effects of blue-enriched lighting on people's alertness, behavior, and health is not fully developed, and incorporating blue lighting and adjusting its timing and duration in office spaces should be carefully considered because it may alter some of the employees' other physiological aspects.

Timing

Artificial lighting has dramatically extended people's engagement with light, enabling us to provide enough light to engage in visually-related tasks on a 24-hour cycle. Similar to how light affects our perception, feelings, and physiology over various intensities and spectra, during different times of the day perceptions, reactions, and light preferences might also differ.

Taking circadian rhythm as an example, the timing of light exposure has a direct effect on the size and direction of the phase-shift effect of light on the human circadian rhythm. Phase delay can result from light exposure in the evening and early night, while phase advance could result from light exposure in the early morning (Khalsa, Jewett, Cajochen, & Czeisler, 2003; Rüger et al., 2013)

Rüger and colleagues (2006) investigated the effects of bright light exposure on individuals' sense of alertness and physiological arousal during both day and night. In agreement with the results found by Smolders and colleages (2012), which revealed the effect of bright light exposure on sustained alertness and sense of arousal were significant only in the morning and not in the afternoon.

In addition to the time-dependent effects of light on office workers' sense of alerness and physiological arousal, office workers' lighting preferences may also vary throughout the day, and office workers did not prefer constant light settings in terms of intensity and CCT during the workday (Begemann, Van Den Beld, & Tenner, 1997; Newsham, Aries, Mancini, & Faye, 2008). Despite individual preferences, the results of these studies indicated that employees generally preferred a higher illuminance level in the morning at the start of their working day.

When designing lighting scenarios to support office workers' wellbeing and performance, it is important to take into account the time at which office workers will be present in the workplace.Variation in lighting throughout the day can also play a vital part because office workers' preferences are time-dependent as well.

Duration

Studies have shown that human circadian rhythm (phase-shift) can also be affected by the duration of light exposure. Repeated exposure to intermittent bright light at night or in the early morning can cause phase-shifts and delay or advance the circadian rhythm (Gronfier, Wright, Kronauer, Jewett, & Czeisler, 2004; Rimmer, et al., 2000).

Several other studies have shown that the duration of light exposure can moderate the acute effects of light. For example, effects of bright light on subjective alertness and vitality were not dependent on the duration of exposure, but effects on participants' response times on a sustained attention task occurred after a delay (K. C. H. J. Smolders & de Kort, 2014; K. C. H. J. Smolders, de Kort, & Cluitmans, 2012). As discussed previously, blue light has a great impact on melatonin secretion, and in addition to the melatonin secretion and subjective alertness caused by the blue light, there are delayed effects such as change in core body temperature and heart rate as well (Cajochen, et al., 2005).

Another review of literature by Vandewalle, Maquet and Dijk (2009) reported duration-dependent dynamics in brain activity caused by light; initial activation in subcortical structures requires several minutes and that in various other cortical areas requires approximately 20 minutes of exposure. The activities require 20 minutes to become established and some are maintained for about 20 minutes after the end of light exposure. The research shows indications that when activation is intended, continuous or repeated exposure is required.

While insights provided by current research with respect to duration of light exposure may be inconclusive, both these studies and the review indicate that duration of light exposure is a very important factor in achieving and controlling many effects activated by light.

Exposure pattern

Impact on individuals' affective and cognitive function by dynamic light exposure patterns is a current topic of research interest. A dynamic light exposure pattern refers to a change in illuminance and CCT necessary to achieve an activating effect among office workers. However, the findings in this regard of several studies on improvement in subjective vitality, fatigue, performance, and sense of alertness were either subtle or none at all. For example, when participants were exposed to a variable lighting regime with gradual changes in illuminance level (500 – 1800 lux at 6000 Kelvin) in the morning and afternoon, and compared to exposure to a constant office light at 500 lux with a 4000 Kelvin CCT, no significant activating effects of the dynamic light exposure on performance or physiological arousal were observed (Hoffmann et al., 2008). De Kort and Smolders (2010) also found during a field study no activating effect of exposure to artificial lighting with gradual variations in illuminance level and CCT on individuals' mental wellbeing, health, and performance. However, during the field study, employees reported being more satisfied with the dynamic lighting compared to the fixed lighting set up.

Several studies have investigated the effect of dynamic lighting within a more specific time frame – early morning. These studies showed that exposure to artificial dawn light compared to darkness prior to awakening may reduce sleep inertia and improve individual wellbeing and cognitive functioning (Gabel et al., 2013; Werken et al., 2010).

Contrast

Another variable worth mentioning which has significant influence on occupant wellbeing and productivity is luminance contrast. Contrast is the combination of light and dark areas that the human visual system must discern in order for the object to visualized. However, contrast primarily is an interaction between lighting and the lit surfaces and objects, which can be affected by source/task/eye geometry, disability glare, shadows and the surface characteristics of the object being viewed (Illuminating Engineering Society, 2017). Therefore, this factor is beyond the scope and is not central to this particular discussion.

HCL has provided a vision beyond luminosity and correlated color temperature by bringing timing, duration, and exposure pattern into the equation. Research done in these new categories has revealed tremendous insights and established many new connections between humans and lighting. Even though some of the insights regarding these new categories of lighting are relatively new and inconclusive, new doors have been opened regarding how we could manipulate the lighting to favor office occupants.

Definition of Conventional Naturalistic Lighting

Before defining conventional naturalistic lighting, it is worth noting once again how the term “naturalistic” differs from “nature.” While the term naturalistic will always present some characteristics of nature, it will never be the equivalent of nature. The conventional naturalistic lighting is evaluated and measured in three aspects: 1) physiological aspect; 2) functional aspect; and 3) psychological aspect, and the characteristics ascribed to the naturalistic lighting definition will be closely associated with these aspects in order to provide an overall lighting solution that support users’ function, health and wellbeing.

Naturalistic lighting

The fundamental goal of naturalistic lighting is to provide users a healthier lighting environment. Artificial lighting not only makes human activity no longer limited by the setting of the sun, but simultaneously creates a society out of sync with local time. The artificial lighting people work and live under during the daytime does not match the dynamic quality and intensity that sunlight offers. In other words, artificial light can make days blur into nights and cast people into circadian darkness. A mismatch between a human's internal clock and local time disrupts their circadian system, possibly causing many long-term health and behavioral problems, such as fatigue, cancer, obesity, diabetes, depression, and sleep disorders (Ott, 2000).

Naturalistic lighting mimics the natural sunlight rhythm by providing an increasingly dynamic lighting environment in terms of CCT and intensity. Under exposure by naturalistic lighting, a user's body will tune in to rhythms found in nature. This baseline characteristic of naturalistic lighting permits users to once again have their bodies in sync with local time to achieve a healthier state.

Functional lighting

In today's lighting environment, while problems related to visual comfort and performance have been very well addressed, only the visual forming effects of lighting have been addressed, and the non-visual forming effects of lighting have generally not been given much consideration nor implementation (K. C. Smolders & Beersma, 2014). Human bodies have different reactions to lighting that depend on the intensity, spectrum, timing, duration, and pattern of the light, and while the research in this area may not be conclusive, it is abundant. For example, lower CCT and intensity is perceived as providing a warmer, more relaxed, and less tense environment (Wei et al., 2013) that could help people sleep and rest, while blue or blue-enriched lighting was found to increase subjective alertness compared to the effects of red light (Revell et al., 2006; G. Vandewalle et al., 2007; Gilles Vandewalle et al., 2007).

SSLs such as LEDs offers the flexibility of adjusting the light within a dynamic CCT and intensity range and thereby opens up possibilities for naturalistic lighting to create different lighting scenarios to fit users' very specific functional demands.

Dynamic lighting

One of the most significant traits of natural sunlight is its inconsistency and unpredictability in certain scenarios. Variations in location, seasons, and weather patterns, can affect the rhythm of natural sunlight, with the result that it will not always perform on a consistent level. For example, the change of CCT and intensity in sunlight on a clear day is dramatically different from that on an overcast day (Begemann et al., 1997), and such a dramatic change in CCT and intensity in natural sunlight may work as a form of stimulation to heighten users' arousal, regardless of whether or not it is pleasant or unpleasant. Based on the Yerkes-Donson Law of Arousal, a person's performance can be improved if that person is aroused in some manner (Yerkes & Dodson, 1908).

By letting naturalistic lighting mimic the patterns of changing weather or season, or even change in an unpredictable way, lighting no longer works only as a source of illumination, but also as a source of stimulation to heighten users' arousal. Dynamic lighting may provide users some level of environmental distraction, and they may consider the availability of certain environmental stimuli to heighten arousal, thereby supporting their functioning, health, and wellbeing.

The characteristics of naturalistic lighting is mainly measured from three aspects: physiological, functional, and psychological.

Physiological: By mimicking the pattern of natural sunlight, naturalistic lighting can take people out of circadian darkness and offer an opportunity for them to be in sync with the local time, thereby becoming healthier.

Functional: Naturalistic lighting can provide different lighting scenarios to fit users' vastly different functional demands.

Psychological: Naturalistic lighting can also be unpredictable, thereby functioning as a source of stimulation to heighten users' arousal, possibly assisting in their functioning, health, and wellbeing.

Conventional naturalistic lighting mimics certain qualities of natural sunlight. This is often characterized by incorporation of changes in luminance and correlated color temperature occurring during a typical 24-hour cycle. However, these *naturalistic* characteristics are often employed in a rather unnatural manner, by standardizing their effects during every cycle. The next section horizontally compared three lighting fixtures that utilized the conventional naturalistic lighting concept, which offered a closer look at how these lighting systems addressed user wellbeing from the physiological, functional, and psychological aspects.

The Existing Implementations of Naturalistic Lighting

Existing naturalistic lighting system

Based on abundant research, several companies have already attempted to make healthier artificial lighting fixtures using a biophilic design approach, and some of the existing lighting systems fall under the concept of naturalistic lighting. For example, there is the Sunn light that continuously changes color to match the rhythm of the sun throughout the day and can also function as an alarm, (can help change body clock to a different time zone, etc.). The Ario Lamp is another example that mimics the sun to support sleep, energy, and the body's natural clock. Also, the Color Select lighting solution provided by USAI lighting that can mimic the rhythm of sunlight and also provide manual control for intensity and color temperature, allowing the user to adjust these characteristics to match his or her personal preferences.

All of these lighting systems function in similar ways, with the major differences being the features they offer and how they can be managed or controlled. Some feature physical control mechanisms to control the lighting, while others utilize smart phone apps to manage the lighting system. To get the full picture of what these naturalistic lighting systems have to offer, a horizontal comparison will provide a detailed breakdown of their features and functions. The comparison will be based on the following categories:

1. Color temperature range: Color temperature perceived from natural daylight could range anywhere between 2700 K and 6000 K, so it's important that the light fixture provide any color within that range.
2. Luminance range: The light fixture should be powerful enough for make the human body react to it.
3. Dimming: There should be ability to adjust light levels based on time of day or user preferences.
4. Location based: The ability to stimulate the rhythm of the sun consistent with the user's location.

5. Weather (season-based): The ability to stimulate the rhythm of the sun based on the weather or season.
6. Manual override: The ability to let users set brightness and color temperature according to their preference.
7. Smartphone Application support: Control the lighting through a mobile application via a wireless connection.
8. User-tailored: The ability to learn users' habits over the course of time.
9. Reset function: The reset function here is not a hardware reset, but a reset to the scenario where the light fixture continues to mimic the rhythm of the sun after a user has made certain changes to the light settings.

Table 3. A horizontal Comparison of the Sunn Lighting, USAI BeveLED, and the Ario Lamp.

	Sunn Light	**USAI BeveLED 2.1 CS Color Select**	**The Ario Lamp**
CCT range	2700 – 6500 K	2200 - 6000K	1800 – 6500K
Luminance range	1-3300 Lm	675 – 1975 Lm	1 – 2400 Lm
Dimming	0 - 100%	10 – 100%	0 - 100%
Location based	Yes	N/A	Yes
Weather, season based	Yes	N/A	N/A
Manual override	*Limited	Yes	Yes
App support	Yes	N/A	Yes
User tailored	N/A	N/A	Yes
Reset function	**Unclear	N/A	*Unclear

*Limited: The Sunn light offers users the opportunity to adjust the light to a different time of day, meaning that the color temperature and brightness are changed simultaneously to match the brightness and CCT of the day. No individual control for brightness or CCT is provided.
**Unclear: Both Sunn lighting and the Ario Lamp are successfully funded Kickstarter projects available for pre-order, but neither has yet been on the market and tested by the general consumers, so it is unknown how to reset the lighting after making dramatic changes.

This horizontal comparison of these three lighting systems provides a good idea about both what they offer and what they don't offer. From a purely technical perspective, all three lighting systems provide a good level of brightness, and the CCT range is broad enough to adequately cover the daylight spectrum. One thing worth mentioning is that BeveLED 2.1 CS Color Select from USAI has the lowest luminosity output because it is meant to be installed in arrays, although the luminance range provided in the chart above represents only one BeveLED 2.1 CS Color Select lighting fixture. One the other hand, The Sunn Light and The Ario Lamp are single standalone light fixtures meant for home or small workplace use, so the maximum luminance outputs of these two fixtures are significantly higher.

All three naturalistic lighting solutions provide the right type of hardware to achieve the minimum requirements for naturalistic lighting. What really makes these lighting solutions different from one another is how their control software is implemented. Besides mimicking daylight, BeveLED 2.1 CS Color Select from USAI offers only an independent manual control for brightness and color temperature. The Sunn Light and The Ario Lamp offer a few more features, such as mimicking the rhythm of the sun based on the real-time location and weather, providing remote control through a mobile application, and the Ario Lamp can even learn users' preferences over time and behave differently based on user behavior.

These three approaches to naturalistic lighting provide significant insights on how the concept of naturalistic lighting can be implemented into existing technology, and how such lighting systems could have an impact on a human's functioning, health, and wellbeing. By considering the additional features such lights have to offer, it is not hard to draw the conclusion that, in addition to taking a building's occupants out of the circadian darkness, there are many other things lighting could do, such as adjust to different time zones, function as a sleep assistant, etc. These lighting solutions are good examples of how naturalistic lighting concepts could be executed, and merely mimicking the rhythm of the sun has become a fundamentally basic approach to naturalistic light. To make the concept more suitable for workplace scenarios, an effective lighting control system is the key to creating a better environment that supports the functioning, health, and wellbeing of office occupants. Such control systems could be designed based on the research accumulated in this paper, along with utilizing existing naturalistic lighting control systems created by lighting pioneers, such as the Sunn Light and the Ario Lamp. The existing lighting control system can serve as a basic framework that, combined with research work more closely related to office environments, can generate a naturalistic lighting control system that supports the wellbeing of office workers physiologically, functionally, and psychologically.

Control system of existing naturalistic lighting systems

The previous section concluded that the existing automated control systems of naturalistic lighting behave fundamentally the same (i.e., they mimic the rhythm of natural sunlight) and their non-automated control features are what really made them distinct from one another by adding flexibility and functionality. For example, the BeveLED 2.1 Color Select from USAI users' capability to directly manually override the color temperature and intensity and the Ario Lamp has custom lighting presets that serve a specific purpose. Based on the literature review, these are related to the benefits of natural sunlight, naturalistic lighting, as well as control and regulation. To analyze the control systems of these naturalistic lighting systems, their non-automated control features should be able to provide naturalistic lighting, functional lighting, and dynamic lighting. The following discussion is a brief definition of these terms in the context of the workplace.

Naturalistic Lighting: The light system should be able to support users' wellbeing (i.e., it should provide a setting that mimics the rhythm of natural sunlight to help synchronization of users' circadian clocks).

Functional Lighting: The light system should offer multiple lighting presets to fit users' specific demands (e.g., to be more alert, or to advance or delay the circadian clock).

Dynamic Lighting: The light system should offer the full range of manual control or certain non-functional lighting presets so that users not only would have control of the overall lighting environment, but could also benefit from lighting that works as a source of stimulation. Users will also be able to reset lighting to its default state to prevent unnecessary stress or wellbeing hazards.

The control systems of the BeveLED 2.1 Color Select, the Ario Lamp, and the Sunn light will be analyzed based on the three guidelines as discussed above (Table 4).

Table 4. Horizontal comparison of the control systems of different naturalistic lighting systems.

	Sunn Light	**USAI BeveLED 2.1 CS Color Select**	**The Ario Lamp**
Naturalistic Lighting	Mimic the rhythm of the sun based on the location and seasons	Mimic the rhythm of the sun	Mimic the rhythm of the sun
Functional Lighting	Reduce jet lag; Adjust lighting to certain time of day.	N/A	Reduce jet lag; Sunrise alarm; Bedtime reminder.
Dynamic Lighting	Limited manual control without non-functional lighting presets and no reset functionality built in.	Full manual control on CCT and intensity	Full manual control without non-functional lighting presets and no reset functionality built in.

All three lighting systems offer naturalistic lighting to support users' health and wellbeing, another fundamental aspect of naturalistic lighting. In terms of functional lighting, USAI's BeveLED 2.1 CS Color Select offers the fewest features and does not provide any functional lighting presets to users. The Sunn Light and the Ario Lamp offer several limited lighting presets, which hope to satisfy users' different demands. Dynamic lighting is the aspect that has been addressed the least; USAI's BeveLED 2.1 CS Color Select offers full manual control on CCT and intensity, but provides no non-functional lighting presets or reset functionalities. The other two lighting systems both offer a certain degree of manual control, but neither offers non-functional lighting presets nor reset functionalities.

From the analysis of the three lighting systems, it is fair to say that the existing naturalistic lighting fixtures are good attempts of naturalistic lighting theory, a major evolution of lighting design. However, they stop short of fully facilitating the physiological, functional, and psychological aspects of office occupants. While all these naturalistic lighting fixtures have somewhat addressed the physiological, functional, and psychological aspects of the conventional naturalistic lighting, it is unfortunate that a major characteristic of the natural sunlight has not been considered, that of being natural (i.e., random and unpredictable). Data accumulation and analysis may provide a general pattern as to how natural sunlight varies throughout the day based on location and season, and directly applying preset patterns to the existing lighting fixtures represents a good first step, but it falls short when a user begins to realize that this type of naturalistic lighting performs just as stably, unnoticeably, and predictably as traditional office lighting. When office occupants have been working for an extended period of time, lighting can be an element that stimulates them and rejuvenates their system, so it should offer a kind of control mechanism that provides the user a type of control making it almost impossible for it to be redundant, boring, and predictable. For the purpose of this paper, the introduction of more natural variability into lighting will be referred to as enhanced naturalistic lighting.

Summary

With developments of technology and variations in shifts and working types, office occupants are demanding more from their workspaces to support their working styles. Office workers generally express positive reactions, both physiologically and psychologically, toward dynamic full-spectrum lighting, and the research literature provides a clear and thorough explanation about how people react physically and mentally to different lighting situations. Today's technology is able to provide solid hardware to bring the concept of naturalistic lighting to life, and in addition to lighting hardware development, advances in human centered lighting has also made significant progress. The main deficiency is in lighting control systems, with none of the existing control systems for naturalistic lighting simultaneously addressing the functional, physiological and psychological aspects. They may offer the users a higher degree of control, but still not enough for a lighting system to perform at full potential. To date, there have been three key developments with respect to light. One is addressing human affinity for nature, leading to naturalistic lighting. The second is the accommodation of physiological, functional, and psychological aspects. Last is acknowledging the inherent need for variability and evolution. Since these three issues have not been fully integrated, the focus of this study will be how best to introduce and configure control features to optimize lighting facilitation with respect to physiological, psychological, and functional aspects.

CHAPTER 4. METHDOLOGY

Introduction

The scope of the preliminary project is to find an optimum way to integrate the three key development aspects described previously. To create an overall control system schematic for the enhanced naturalistic lighting system in office spaces, this study uses a morphological approach to list design considerations for each part of the control system and attempt to rationally select the most appealing ones. In this way, rather than solving the design problem intuitively, decisions are made after exploring options in a very feasible, transparent, and logical way. In terms of office occupants and their working time frames, this study focuses on a single office worker who works during typical working hours (i.e., from 9 a.m. to 5 p.m.) and has little access to natural sunlight during working hours.

The methods of research employed in this study and description of the process by which the control system is put together is presented below, including research questions, research design, and ways through which the components of a naturalistic lighting control system can be analyzed, selected, formed and simulated.

The methods chosen were selected as a means for addressing the following research question:

> How should optimal control of enhanced naturalistic lighting qualities be provided in a manner that accommodates: a) human's affinity to nature; b) naturalistic lighting concept; c) human's inherent need for variation?

Defining Office Environment

While this discussion is intended to be broadly applicable to interior design, for purposes of consistency this study will emphasize office applications, recognizing that there is likely to be variations in office types. To define the environment this study focused on, the key interior variations include but are not limited to the following:

1. Layout
2. Lighting Configuration
3. Color Scheme
4. Material
5. Sound quality
6. Air quality
7. Ergonomics
8. Circulation

For the purposes of this study, layout, lighting configuration, and color scheme were the main focus when defining the office environment.

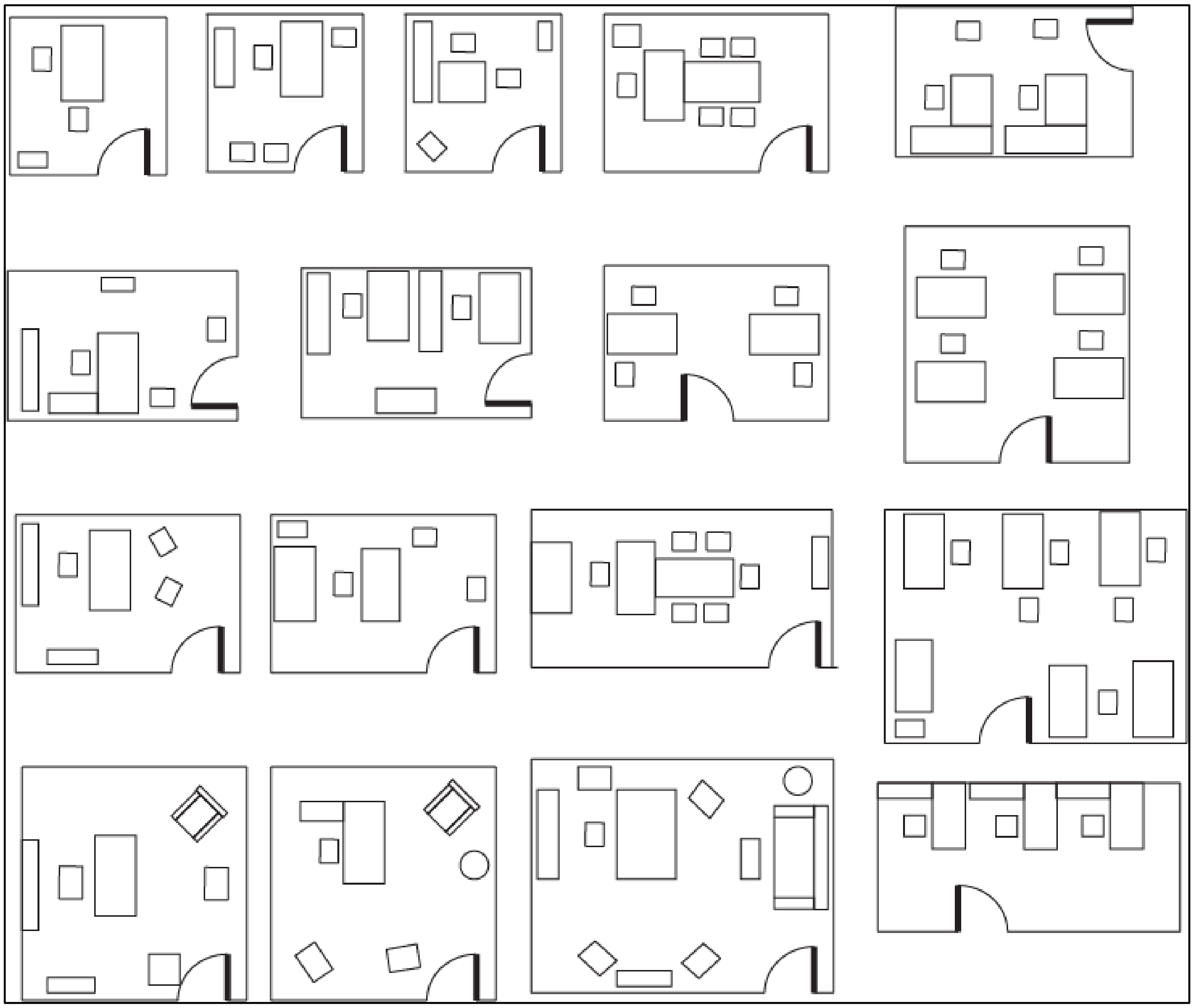

Figure 2. Sketches of private offices and semi-private offices. Retrieved from “Time Saver Standards of Building Types by Chiara and Callender 1990, p.788

For the purposes of this study, the private office arrangement selected is shown in Figure 3, representing a 100 square feet private office setup mainly designed for the use by a single individual.

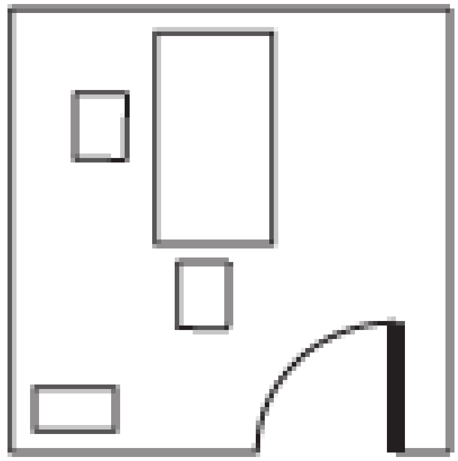

Figure 3. A sketch of a private office for the use of a single individual. Retrieved from “Time Saver Standards of Building Types by Chiara and Callender 1990, p.788.

Closed Office Lighting Configuration

According to a recent global user study conducted by Zomtobel Group and the Fraunhofer Institute of Labour Planning and Organisation (IAO) on lighting quality perceived in workplaces, 82 percent of that study’s participants perceived a combination of direct and indirect lighting to be an ideal lighting situation (Zumtobel, 2013b). Since the closed office environment used in this study will also be using a combination of direct and indirect lighting, the indirect lighting could provide a comfortable and uniform level of ambient lighting within the space, while direct lighting fixtures such as table lamps or floor lamps could fulfill the need for customized light levels.

For this office, measuring approximately 10’x10’, IES recommends an illuminance target ranging from 400 to 750 lux (Illuminating Engineering Society, 2017).

Private Office Color Scheme

It is widely known and agreed that colors can influence emotions and serve as tools for helping employees manage their stresses and moods (Ward, 1995). This research is mainly focused on the lighting environment and how light renders within the private office space, so the overall color theme of the space will be focused on simplicity, using natural, light, and earth colors that can help reflect both the daylight and artificial light coming into the office area. The rendition of the light would therefore be more pronounced. Figure 4, a computer-generated image, depicts the basic and necessary elements of the closed office configuration based on the layouts selected for this research.

Figure 4. A photo simulation of the basic closed office setup to demonstrate the layout, openings, colors scheme, and lighting configurations. 1. Overall lighting that renders an evenly lit space; 2. Accent lighting, creates visual interest or a focal point; 3. Furniture based task lighting.

P.A.Th.Way.S.

According to Eidson (1986), "design theory provides the language and connections necessary to link knowledge and ideas about design concepts with the practice of designing." P.A.Th.Way.S., a systematic method that thoroughly integrates theory into the design process, can be represented in five steps (Malven, 2006).

1. Problem Definition (P.)
2. Analysis of design requirements (A.)
3. Theory exploration (Th.)
4. General ways of solving problems using theory to translate link goals and solutions (Way.)
5. Final Solution (S.)

Jones (1992) once mentioned that the public tends to think of design as a primarily intuitive process, suggesting that there is a missing link between design requirements and solution concepts. The P.A.Th.Way.S. method is essentially a methodology that makes the design process more deliberate and rational. In the five steps of the P.A.Th.Way.S. methodology. *Theory* is defined as a set of evidence-based statements or principles devised to explain a group of facts or phenomena (Malven, 2006). In other words, theory exploration provides a bridge between analysis of requirements and concepts for solving those requirements.

For the purposes of this study, the P.A.Th.Way.S. method is a suitable methodology for the design of the enhanced naturalistic lighting control system. The review of literature has revealed the following design problem: how best to introduce and configure control features so as to optimize lighting facilitation of physiological, psychological, and functional aspects, with respect to which current existing control systems are insufficient. While design requirements can be extracted from analysis of current existing naturalistic lighting control systems, the review of literature also provides information and support for the solution concepts. The P.A.Th.Way.S. method should provide theoretical building blocks for each part of the control system and ensure that the design problem is not solved intuitively; but through decisions made after exploring options in a very feasible, transparent, and logical way.

Naturalistic Lighting

Problem definition

The core underlying idea of using lighting to assist users' physiologically aspect is to support of their physical wellbeing. Office workers who work within an office environment without access to natural sunlight may experience circadian cycle disruptions, possibly causing long-term health issues such as fatigue, cancer, obesity, diabetes, depression, and sleep disorder.

Analysis of design requirements

A.1 Office workers would be provided with a lighting environment that supports their physical wellbeing.

A.2 Lighting users would be able to manipulate lighting variables to achieve optimized lighting configurations with respect to factors like time of day, geographical location, and weather pattern.

Theory exploration

A.1.1 According to John Ott (1997), circadian rhythm is a human body's physiological process that can be altered by modifying the wavelengths of light perceived through the human visual system.

A.1.2 Automatic Control Theory: Automatic control of lighting variables to mimic natural sunlight would result in positive contributions to the physical wellbeing of office users.

A.2.1 Personal control: Both physical and perceived control leads to beneficial consequences, and people will be more satisfied and productive (Barnes, 1981; Simpson, 1990).

Solution concepts

A.1.1.1: The control system should automatically control lighting variables (intensity, CCT) to mimic natural sunlight throughout the year based on weather, season, and geographical location of the natural environment and synchronize them with the users' time of day.

A.2.1.1: Users could partially manually override the automated control system to synchronize with a specific time of day. With a press of a button, the lighting would revert back to synchronization with the actual time of day.

A.2.1.2: Users would be completely in charge of the control system, and when a user adjusts a knob to achieve a particular level, a digital readout of the benefits/effects of the current light setting is provided.

A.2.1.3: Users could partially intervene with the automated control system and set the location, season, and weather pattern for the lighting system to synchronize with. With a press of a button, the lighting would go back to synchronization with the actual time of day and real-time location.

A.2.1.4: A reset button should be provided to enable the lighting to revert to synchronization with the actual time of day, a geographical location, or a lighting configuration pre-defined by users.

Final solution

To create a lighting environment that supports the physical wellbeing of the office occupants, the following control system components of the enhanced naturalistic lighting would be necessary:

1. An automated control system that controls lighting variables to mimic natural sunlight throughout the year based on the weather, the season, and geographical location, and to synchronize it with the users' time of day.
2. Users could partially intervene with the automated control system and manually override the lighting to synchronize with a specific time of day.
3. Users could partially intervene with the automated control system and manually override the lighting to synchronize with different locations, weather patterns, and seasons.
4. A reset button would be provided to revert the lighting back to synchronization with the actual time of day, geographical location, and lighting configuration pre-defined by users.

Functional Lighting

Problem definition

With the development of technology and fast-paced changes in society, there have been dramatic shifts in office tasks. While working with a personal computer and achieving office collaboration have become the major tasks of an office worker (Tenner, 2003), most modern offices still utilize standards and recommendations for office lighting based on the horizontal luminance at the work plane that fulfills basic needs for reading and writing tasks

(Tenner, 2003). Office occupants are then faced with the problems of not having dynamic lighting settings to support their dynamic activities within such office environments.

Analysis of design requirements

A.1 The office worker's dynamic office activities should be supported by a versatile lighting environment.

The following are some examples of specific requirement regarding user activities:

1. A lighting configuration that could assist the users in being more efficient and productive.
2. A lighting configuration that could assist the user in resting/ rejuvenating more efficiently.

A.2 Lighting systems that users can use to manipulate lighting variables and achieve optimized dynamic lighting configurations.

Theory exploration

A.1.1 Dynamic Control Theory: Offer the office occupants the control of a dynamic range of lighting presets that could support their dynamic activities, increase their productivity, and increase their sense of wellbeing.

A.2.1 Personal Control: Physical and perceived control lead to beneficial consequences, and people will be more satisfied and productive (Barnes, 1981; Simpson, 1990).

Solution concepts

A.1.1.1: Increase the luminance (1000 lux to 2500 lux) for periods of time during working hours to reduce sleepiness and increase alertness and sense of vitality.

A.1.1.2: Shift the light to a highly-correlated color temperature, such as blue-enriched light for periods of time during work hours, to increase subjective alertness and performance.

A.1.1.3: At the start of the working day (morning), introduce higher luminance (1000 – 2500 lux), as well as blue-enriched light.

A.1.1.4: Decrease luminance (to under 500 lux) during working hours for periods of time.

A.1.1.5: Shift the lighting to a low CCT such as yellow and orange during the work hours for a period of time.

A.2.1.1: Users could partially intervene with the lighting preset to fine-tune the light settings, perhaps by adjusting the luminance and CCT to a more preferred level and setting the durations of the presets.

A.1.2.2: A reset button should be provided to enable the lighting to revert to synchronization with the actual time of day, the geographical location, or a lighting configuration pre-defined by users.

Final solution

Functional lighting offers users the ability to switch among different lighting scenarios to support their dynamic activities within the office environment. The following are presets users could choose from.

1. Active/energize: Shift the lighting to a higher correlated color temperature, such as blue or blue-enriched light, and increase the luminance.
2. Reading/relax: Shift the lighting to a lower correlated color temperature, such as orange and yellow, and decrease the luminance.

3. Users could partially intervene with the control system to fine-tune the presets (CCT, luminance, and duration) based on users' preferences. The control system could learn users' behaviors over a period of time and become able to automatically tune to the light setting preferred by the user.
4. Users are offered full manual control, able to create their own presets.
5. A reset button could be provided to enable the lighting to revert to synchronization with the actual time of day, the geographical location, or a lighting configuration pre-defined by users.

Dynamic Lighting

Problem definition

Dynamic lighting addresses the psychological aspect of the users. The review of literature revealed that office occupants are generally more satisfied when exposed to natural sunlight that is more dynamic than the relatively stable and non-changing fluorescent lighting found in most office spaces. In addition, if people work on one task for an extended period of time, it tends to disable them, leading to a decrease in productivity and possibly endanger their wellbeing. Office occupants are faced with the problem of not having an option to create a preferable dynamic lighting environment to heighten their arousal.

Analysis of design requirements

A.1 An office lighting system should provide options through which occupants can create a lighting environment that's constantly changing (dynamic lighting) to arouse users to achieve better performance.

A.2 Lighting users should be able to manipulate lighting variables to achieve an optimized dynamic lighting configuration.

Theory exploration

Natural variability: constantly arouse the lighting users by manipulating the illuminance, correlated color temperature, light color, duration, speed of change, and rhythm of change in a natural, random, and unpredictable way.

A.1.1 According to Yerkes-Donson's Law of Arousal (Yerkes & Dodson, 1908), a person's performance can be improved if that person is aroused in some manner.

A.2.1 Personal control: Physical and perceived control leads to beneficial consequences, and people will be more satisfied and productive (Barnes, 1981; Simpson, 1990).

Solution concepts

A.1.1.1. The enhanced naturalistic lighting control system when activated is capable of naturally varying the lighting environment based on nature, meaning that the lighting control system can render a lighting environment based on a basic natural sunlight pattern, but will never be able to fully mimic the rhythm based on real time brightness and CCT value (natural variability).

A.1.1.2. The control system will no longer follow the rhythm of natural sunlight, but will randomly select and manipulate the full range of luminance and CCT values to create a completely random and unpredictable dynamic lighting environment (natural variability).

A.2.1.1. Users could partially intervene with the preset lighting configurations to manipulate the duration of change, rhythm of change, and other lighting variables (synthetic natural variability).

A.2.1.2. Users would have complete control of the lighting intensity and CCT.

A.2.1.3. A reset button is provided to enable the lighting to revert to synchronization with the actual time of day, geographical location, or a lighting configuration pre-defined by users.

Final solution

The core idea of dynamic lighting is to heighten users' arousal and rejuvenate them by creating a dynamic lighting environment and increasing users' perceived control. The following are elements necessary to achieve this goal:

1. The enhanced naturalistic lighting control system when activated is capable of naturally varying the lighting environment based on nature, meaning it can render a lighting environment based on the basic natural sunlight pattern, but never fully mimicking the rhythm based on real-time brightness and CCT values.
2. The control system no longer must follow the rhythm of natural sunlight, and can randomly manipulate the full range of luminance and CCT values to create a completely random and unpredictable dynamic lighting environment.
3. Users could partially intervene with the preset lighting configurations to manipulate the duration of change, the rhythm of change, and all other lighting variables.
4. Users would have complete control of the lighting intensity and CCT.
5. A reset button would be provided to enable the lighting to revert to synchronization with the actual time of day, the geographical location, or a lighting configuration pre-defined by users.

CHAPTER 5. RESULTS AND ANALYSIS

This chapter presents the results extracted from the P.A.Th.Ways. methodology, and summarizes all the functions and characteristic of the enhanced naturalistic lighting control system. Ultimately, three types of lighting control were combined to create a holistic and complete naturally-variable lighting control system.

Control Schematic for Enhanced Naturalistic Lighting

The data extracted from the P.A.Th.Ways methodology include lighting solution concepts that emphasized on physiological aspect, functional aspect, and psychological aspect. This section of the chapter highlights the significant findings of the P.A.Th.Ways, and explains how these solution concepts can be integrated into the enhanced naturalistic lighting control system.

Baseline Controls of Enhanced Naturalistic Lighting

The fundamental controls of enhanced naturalistic lighting address the most basic aspects of the three lighting scenarios.

Naturalistic lighting

1. An automated control system that controls lighting variables to mimic natural sunlight throughout the year based on the weather, season, and geolocation, and synchronize it with the actual time of day.

Functional lighting

1. Active/energetic: Shift the lighting to a higher correlated color temperature, such as blue or blue-enriched light, and increase the illuminance (1000 – 2500 lux).
2. Reading/relax: Shift the lighting to a lower correlated color temperature, such as orange and yellow, and decrease the illuminance (to 500 lux).

Dynamic lighting

1. The enhanced naturalistic lighting control system is capable of naturally varying the lighting environment based on nature when activated, meaning that the lighting control system can render a lighting environment based on the basic natural sunlight pattern, while never having to fully mimic the rhythm based on real-time brightness and CCT values.
2. The control system no longer follows the rhythm of natural sunlight, and randomly selects from the full range of luminance and CCT values, creating a completely random and unpredictable dynamic lighting environment.
3. Users could partially intervene with the preset lighting configurations, and manipulate the duration of change, rhythm of change, and all other lighting variables.

These are the fundamental baseline functions of the enhanced naturalistic lighting, which addresses the physiological aspect, functional aspect, as well as the psychological aspect of the users. It is worth noting that the naturalistic lighting addresses the aspect of physiology, function, and psychology as a whole. For instance, dynamic lighting offers the users a higher degree or total control of the lighting control system that puts the users into the driver seat of lighting design. This feature can also be applied to naturalistic lighting and functional lighting, and form the control system baseline holistically.

Natural Variability

Natural variability is one of the vital components of the enhanced naturalistic lighting system. Under the concept of enhanced naturalistic lighting, natural variability means that the lighting control system is capable of naturally varying the lighting environment based on nature (i.e., the illuminance, correlated color temperature, duration, speed of change, rhythm of change, etc.) to make the lighting environment vary rather unpredictably.

The idea of natural variability is to constantly arouse the lighting users. The previous review of literature has disclosed that performance can be improved if users are aroused in some manner. Due to the unpredictable and random nature of natural variability, lighting users cannot predict how the lighting environment is going to change when natural variability is activated, and this unpredictable aspect of natural variability offers users an option to use lighting as an external stimulus to potentially achieve better performance and improve their state of wellbeing in workspaces. The enhanced naturalistic lighting visualization section has shown some examples of lighting scenarios for certain moments or under certain settings.

While natural variability is a very good starting point for mimicking nature, if the mimic process is more or less the same every day, it’s not really naturalistic. Natural variability based on nature takes characteristics from natural sunlight and forms its own algorithm. The nature of natural variability is to be natural, random, and unpredictable. Natural variability no longer follows the overall rhythm of natural sunlight; and if the rhythm of natural sunlight allows the users to somewhat predict how the lighting changes in terms of correlated color temperature and luminosity throughout the day, natural variability strips this last layer of clue away and lets lighting performs in a completely random and unpredictable way when activated.

Synthetic Natural Variability

While natural variability hopes to offer the right amount of lighting stimulation for the office occupants, there are also possibilities that the lighting environment provided through natural variability may not work out the way the user expected. Users may find themselves in the position of demanding more controls to really make natural variability perform according to their preferences; and synthetic natural variability allows users to make some modifications to certain aspects of natural variability. Natural variability is expressed through three fundamental factors: duration of change, rhythm of change, and lighting variables; and users could manipulate these factors to change natural variability performance.

User-Oriented Control

Similar to synthetic natural variability, with respect to the fundamental controls of enhanced naturalistic lighting, users are given certain degrees of freedom to manipulate the entire enhanced naturalistic lighting control system. Each lighting scenario offers different degrees of freedom to the users to manipulate the lighting environment, and user-oriented controls in each lighting scenario can be conflicting or overlapping. This section will show how these user oriented controls can be sorted and arranged into one package to serve the office occupants in the most efficient way.

First of all, users can partially intervene with the control system to adjust the lighting variables as follows:

1. Users could partially intervene with the automated control system and manually override the naturalistic lighting to synchronize with a specific time of day.
2. Users could partially intervene with the automated control system and manually override the naturalistic lighting to synchronize with different locations, weather patterns, and seasons.
3. Users could partially intervene with the control system to fine-tune the functional lighting presets (CCT, illuminance, and duration)

4. Users could partially intervene with the dynamic lighting preset to fine-tune the light settings, such as adjusting the illuminance and CCT to more preferred levels, and setting the duration of the presets.

Second, users are offered full manual control over the naturalist lighting system, whether to temporarily manipulate the intensity and the CCT or to build a lighting preset based on their personal preferences.

1. Users are offered full manual control, and would be able to create their own lighting presets.
2. Users would have the full access to set the illuminance, CCT range, and duration of change, rhythm of change to create their own dynamic lighting environment.
3. Users would have full access to set the illuminance and CCT values to create a lighting environment based on their preferences.

Third, along with the manual override, a reset button is always available for users to revert the lighting back to a pre-defined setting.

4. With a press of a button, the lighting will revert to synchronization with the actual time of day and real-time location despite the current light setting.

Reset and Refresh Mechanisms

In addition to the existing controls users have to achieve enhanced naturalistic lighting, the two additional control mechanisms needed to make the system more accessible and user-friendly are: 1) A reset system, and 2) a refresh system. As described previously in the design process of the enhanced naturalistic lighting control system, a reset mechanism is needed to assist users in reverting to a pre-defined/default light setting when desired or required, providing a quick and efficient way to avoid stimulation overload when there is simply too much arousal for lighting users.

The refresh mechanism is more focused on the functionality of natural variability and synthetic natural variability that provides a new type of interaction between users and the lighting control system. Through the refresh mechanism, rather than manipulating the control system variables, users can simply tell the lighting control system to make a change to the current lighting condition. From a user's perspective, it is hard to ensure that all the lighting scenarios preferred by a user are generated under natural variability or synthetic natural variability, and when they aren't, users have the option to activate the refresh mechanism that will tell the lighting control system to replace the current lighting scenario with a new one. The refresh mechanism can be constantly triggered until the lighting scenario offer by the lighting control system meets the user's desires or requirements.

Self-Learning

Finally, the self-learning mechanism, through which each and every time a user interacts with the control system and manipulates the synthetic natural variability variables, the control system will learn from users' behavior and improve itself over time. The more users that interact with the lighting control system, the better the lighting control system understands the user behavior. The lighting control system will thus tailor itself to be more personalized and user specific.

Lighting Control Schematic

In order to better understand how the expanded naturalistic lighting control functions, a lighting schematic has been created for this study to better explain how every element of the lighting system functions holistically. Figure 5 demonstrates an overview of the control schematic for the lighting, which consist of six major components. 1) Power and switches; 2) Reset mechanism; 3) User-oriented control; 4) Lighting control baseline; 5) Natural variability; 6) Wellbeing meters. Each of these element is explained in a detailed, enlarged schematic.

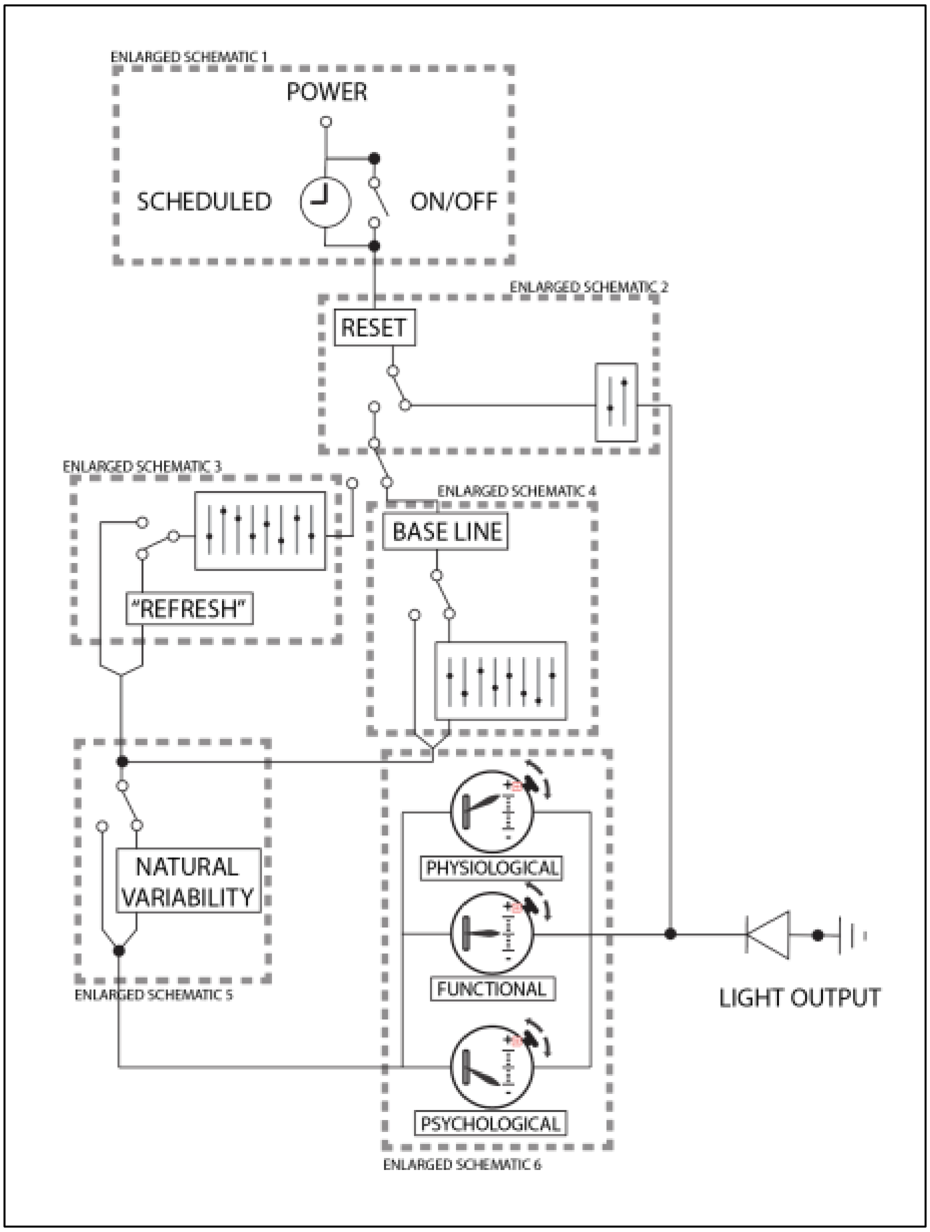

Figure 5. Overall lighting control schematic: overview of the expanded naturalistic lighting control schematic.

Enlarged schematic 1: power and switches

Figure 6 demonstrates that the lighting can be triggered manually through an on/off switch, or through a time scheduled system, such as lights turn on/off during certain time of the day, or certain time of the year, etc.

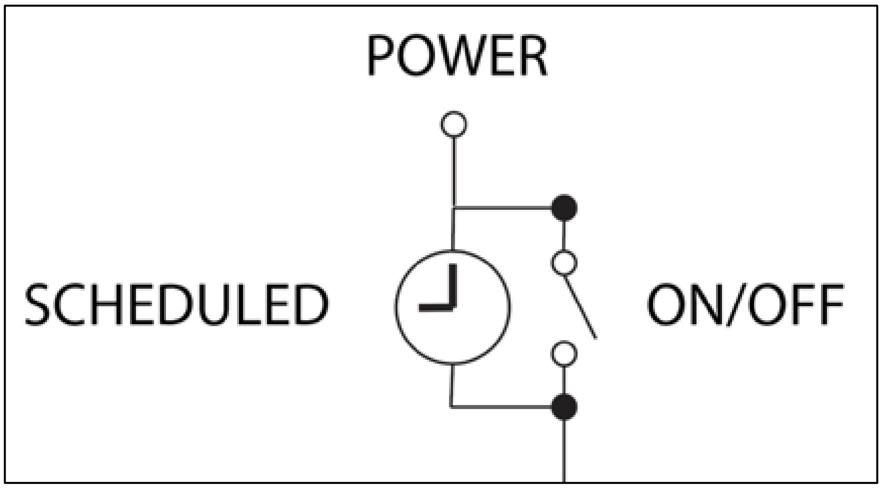

Figure 6. Power and switches schematic: lighting can be activated by a pre-scheduled timer or overridden by a manual on/off switch.

Enlarged schematic 2: reset mechanism

Reset mechanism is a fail-safe addition to the lighting control system in case the user experiences stimulation overload from the lighting, the lighting control system, or other environmental factors. Upon activation of the reset, the lighting reverts to a preset state, emphasizing only luminance and correlated color temperature. Figure 7 illustrates the general concept of the reset function. Lighting users have two options, lighting can be reset to a pre-defined baseline setting (baseline is explained in enlarged schematic 4); or to a pre-defined fixed setting, where users set a fixed luminance and CCT for the reset mechanism. The function of the reset mechanism is to return the system to a conventional functional lighting environment until the user chooses to resume control of some or all enhanced aspects of the system.

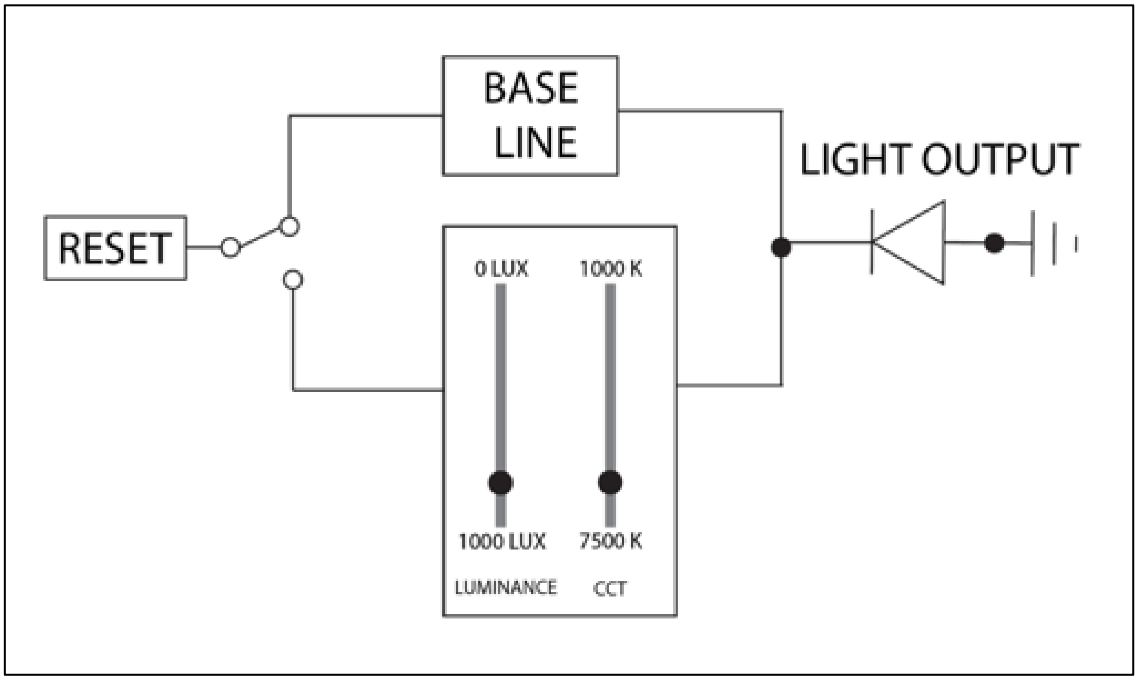

Figure 7. Reset mechanism schematic: through the activation of the reset function, users have the option of either continuing manual control of lighting characteristics or reverting lighting to pre-defined baseline luminance and CCT settings.

Enlarged schematic 3: user-oriented control

User-oriented control consists of two parts. One includes the parameters (Figure 8) users can manipulate manually to create the lighting environment based on their preferences. The second is the refresh mechanism. Instead of manually manipulating every parameter, the refresh function lets the computer auto-generate a lighting environment for the users based on several or all the parameters within the user-oriented control.

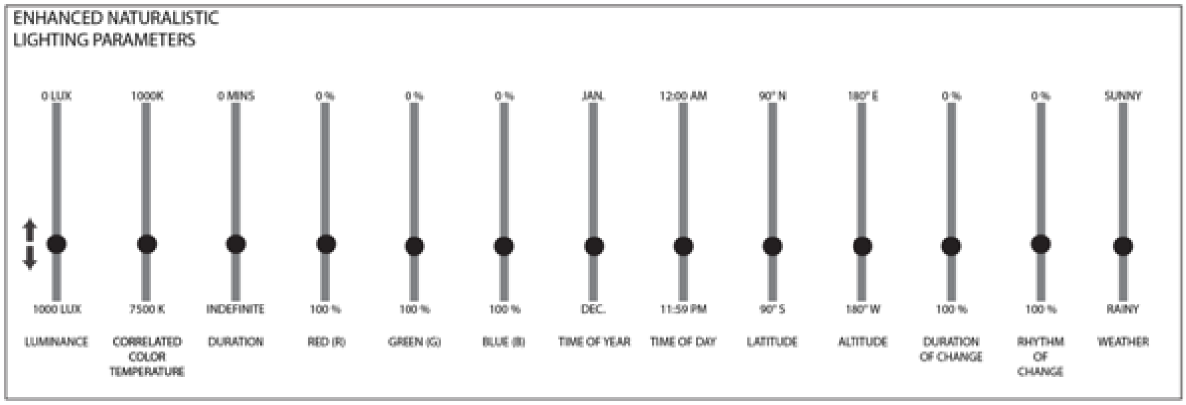

Figure 8. User-oriented control schematic: a compilation of parameters users can elect to utilize and control.

Enlarged schematic 4: lighting control baseline

The lighting control baseline contains the fundamentals of: enhanced naturalistic lighting system, naturalistic lighting, functional lighting, and dynamic lighting (Figure 9). Within the functional lighting, there are two sub-functional settings: active/energize, and relax/reading. Within the baseline, users can exercise a degree of control. For instance, users can change time of year, time of day, and geographical location within the naturalistic lighting. What's worth noting is the provision for limiting the range or spread within certain parameters; those contain a brightly marked section used as a warning to keeping the lighting function effective and make sure the lighting is affecting the user in the positive direction.

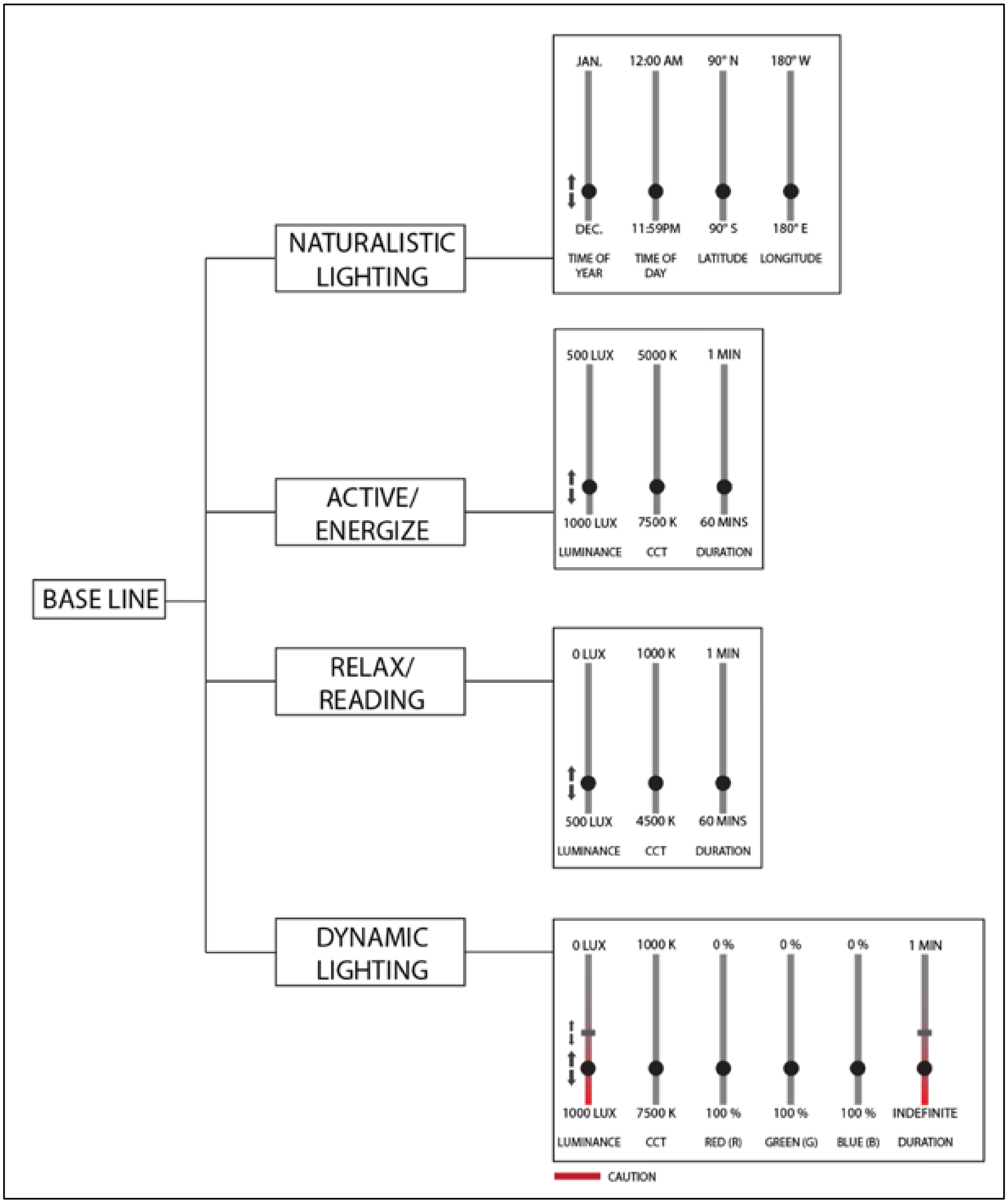

Figure 9. Lighting control baseline schematic: the baseline functionality of the expanded naturalistic lighting system. Where applicable, a secondary slider can be inserted to give users an opportunity to temporarily limit the range of adjustability.

Enlarged schematic 5: natural variability

As presented previously, natural variability (Figure 10) would use light as a source of stimulation to heighten users' arousal, it would be capable of naturally varying the lighting environment based on the nature, to make the lighting environment vary rather randomly and unpredictably. Natural variability can be activated whether users choose the baseline lighting or fully manual controlled lighting. For a more detailed visual explanation of natural variability, refer to Figures 27-29.

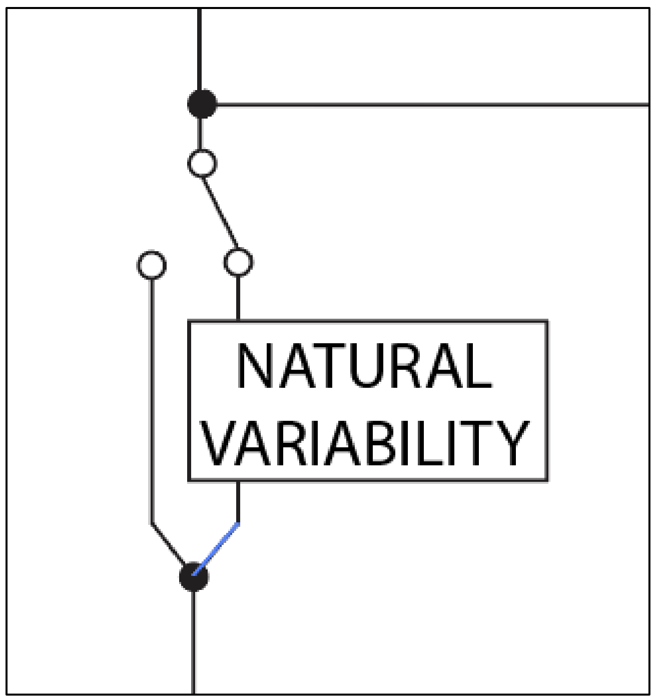

Figure 10. Natural variability schematic.

Enlarged schematic 6: wellbeing meter

The last but not the last layer of filter of the lighting schematic is the wellbeing meter (Figure 11), which measures the aspects of physiological, functional, and psychological. Each meter would offer users a direct read out of how positive or negative the current light setting in term of the three wellbeing aspects. User is also granted a layer of control as this stage. On the right should of each meter (Figure 12), a slider is being provided. Users would be able to set a threshold to the meter to prevent light causing significant negative impact on certain wellbeing aspects. If the light setting triggers certain meter to go below the threshold, the reset function will be triggered to prevent user from negative lighting impact.

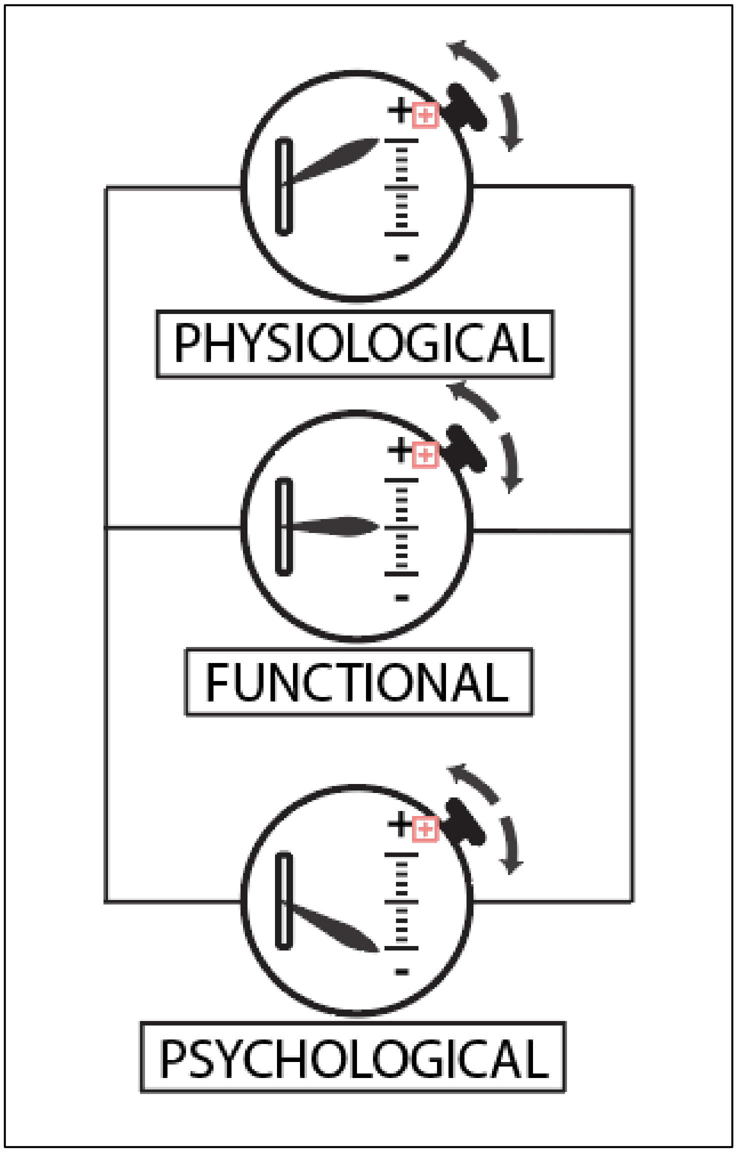

Figure 11. Wellbeing meter: the wellbeing meter can provide users, and the system with feedback on how the current lighting configuration might impact their performance and wellbeing.

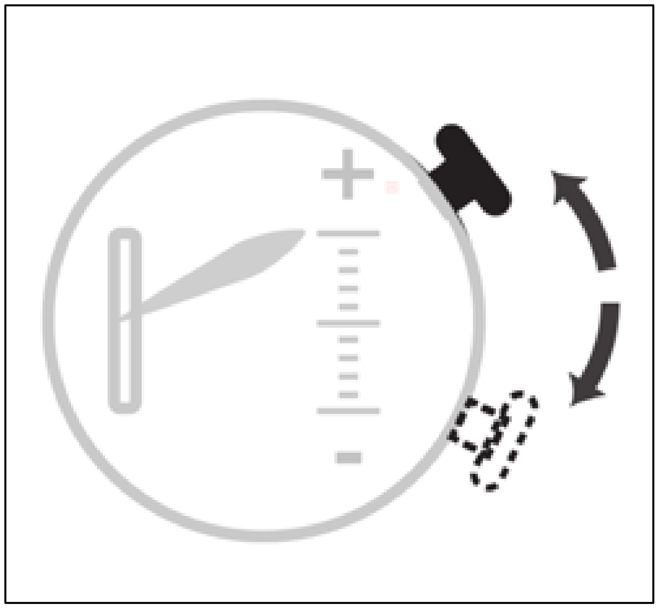

Figure 12. Enlarged wellbeing meter: as users gain more experience, a slider on each meter can give the user control of overall system performance by setting new thresholds to maximize the beneficial effects of lighting on performance and wellbeing.

Enhanced Naturalistic Lighting Visualization

Based on the three major aspects of enhanced naturalistic lighting system, naturalistic lighting, functional lighting, and dynamic lighting, simulations of different lighting scenes showcased in this section are intended to further explain the definition of the enhanced naturalistic lighting concept as well as providing direct visual illustrations of how the system performs under various control settings. In this section, in addition to the three major aspects of enhanced naturalistic lighting, natural sunlight and a combination of natural sunlight and enhanced naturalistic lighting is also simulated for comparison purposes.

Natural Sunlight

A total of six scenes have been simulated to represent the natural sunlight environment and the closed office environment is illuminated by natural sunlight only. The simulated scenes are morning, clear, cloudy, overcast, sunset, and evening. Each of these scenes portrayed the closed office with a different look (i.e., depending on the different times of day and weather patterns) the illuminance and correlated color temperature within the office was different. Figure 13 shows a compilation of the lighting environment of closed office space for different time frames and weather patterns. To provide an even clearer demonstration of how dynamic the natural sunlight is, the same portion of all the simulations has been cropped out (Figure 14) and stacked together for vertical comparison (Figure 15).

Figure 13. A sample compilation of all the natural sunlight simulation based various of scenarios.

The left side of Figure 6 shows that the unshaded area is being cropped out. On the right side, the figure shows the simulation after being cropped out. This portion of the simulation shows a good combination of all the lighting sources, as well as demonstrating the natural sunlight distribution horizontally within the closed office space.

Figure 14. The left of the image shows the portion being cropped out, and the right of the image is an enlarged picture of the cropped-out portion.

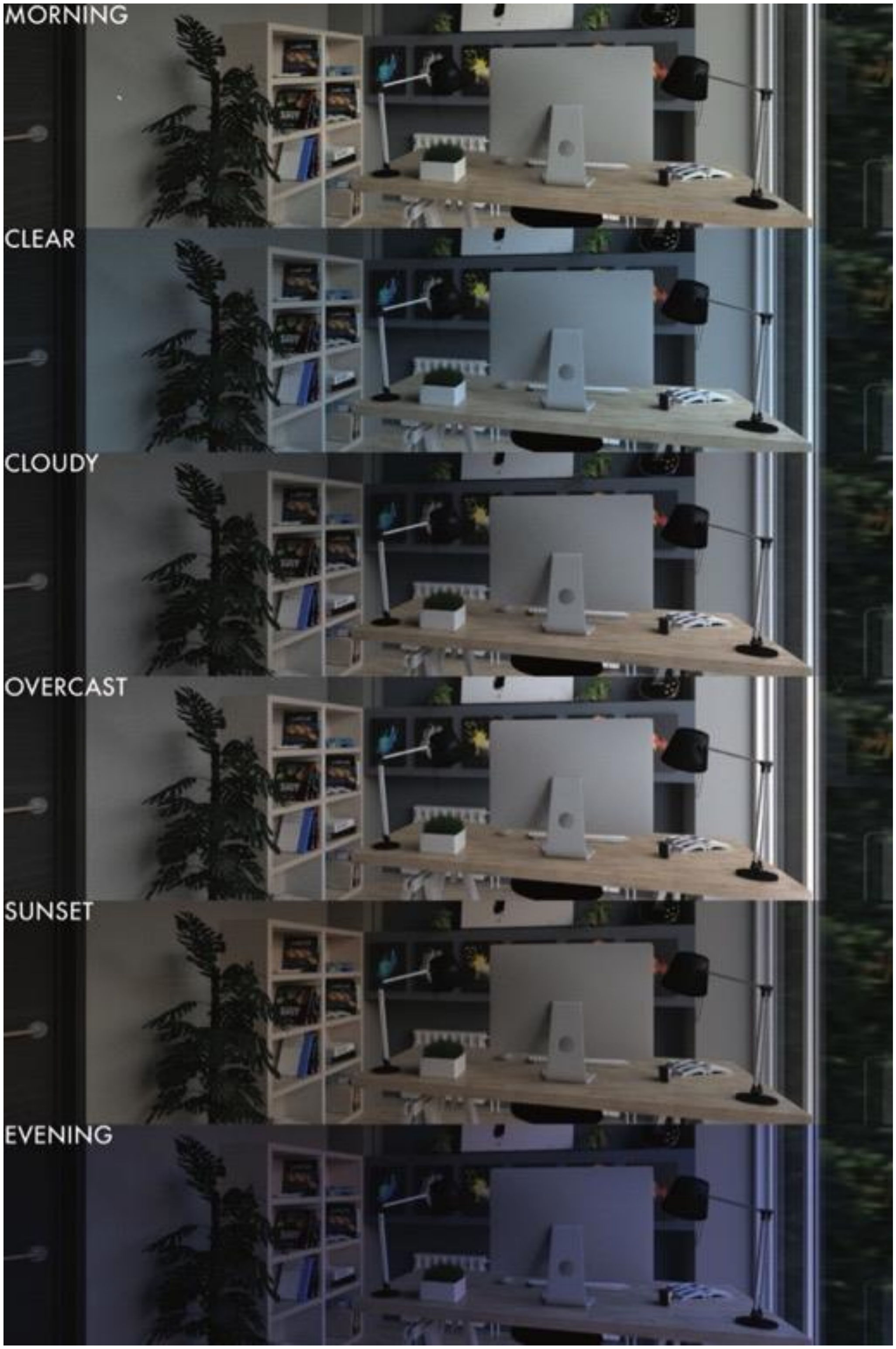

Figure 15. A stacked comparison to demonstrate how natural sunlight renders the closed office space for different times of day and weather patterns.

Naturalistic Lighting

The primary goal of naturalistic lighting is to mimic the natural sunlight rhythm to provide an increasingly dynamic lighting environment in terms of CCT and intensity, with the intent of helping users' bodies tune into the rhythms found in nature, thereby creating a healthier lighting environment to boost office occupants' wellbeing. Figure 16 is a compilation of how CCT and illuminance vary when enhanced naturalistic lighting mimics real-time natural sunlight and weather. Similar to the comparison shown in the natural sunlight section, Figure 17 shows stacked vertical comparisons of the closed office space under enhanced naturalistic lighting environment.

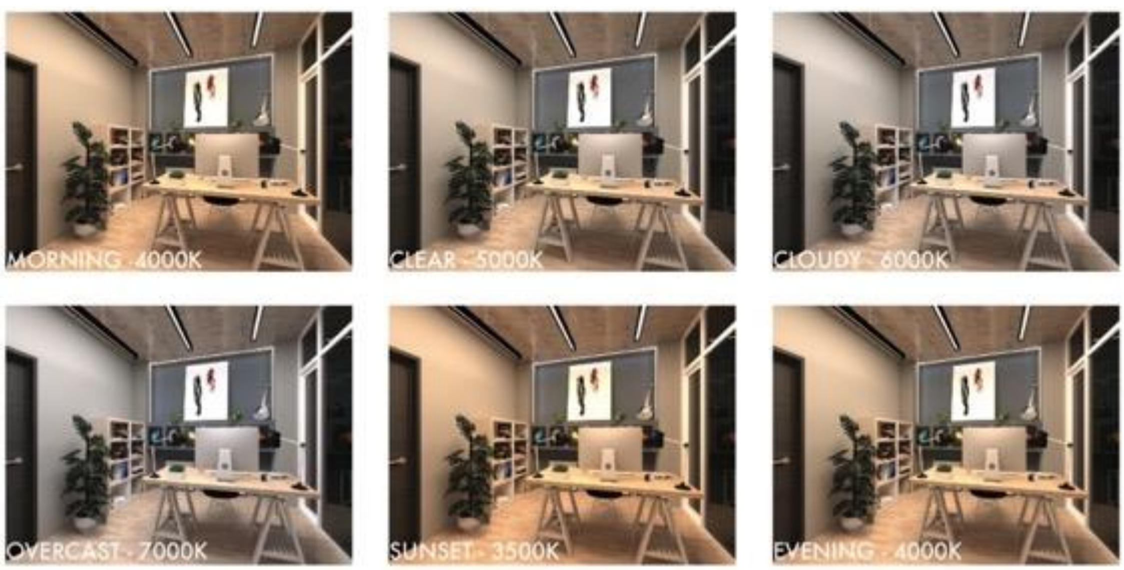

Figure 16. Sample compilation of how CCT and illuminance vary when enhanced naturalistic lighting mimics real-time natural sunlight and weather.

Figure 17. A stacked comparison to demonstrate lighting variations within a closed office space when the enhanced naturalistic lighting system mimics rea- time natural sunlight and weather patterns. Notice that the color shifts correspond to a change of CCT.

Functional Lighting

Functional lighting under the function tab provides essentially four different lighting presets to satisfy users' very specific function demands. Figure 18 shows how *concentrate* mode and *reading* mode is being performed within the closed office space. Again, to fully illustrate functional lighting, the office space is lit entirely by the enhanced naturalistic lighting system and no natural sunlight is being introduced into the space.

Figure 18. The concentrate mode (left) and the reading mode (right). Notice that the concentrate mode task lighting has a cooler tone than that of the reading mode.

Figure 19. A stacked comparison of the concentrate mode (top) and the reading mode (bottom). Notice that the concentration mode task lighting has a cooler tone than that of the reading mode.

Dynamic Lighting

Dynamic lighting can be defined from two perspectives. The enhanced naturalistic lighting system can render a dynamic lighting environment within a closed office space. Office occupants will perceive the changes in lighting environment as a form of stimulation, and, therefore, be aroused. The enhanced naturalistic lighting control system offers occupants a higher degree of control through which users can interact and manipulate the lighting environment. Figure 20 shows a compilation of three examples of the dynamic lighting environment within the closed office space created by the enhanced naturalistic lighting system. In Figure 21, a stacked vertical comparison of the three dynamic lighting scenes is shown to provide a more comprehensive comparison.

Figure 20. A dynamic lighting scenario stimulation. Note the differences among the three scenarios in terms of brightness and colors of all three lighting sources within the space.

In addition to the illustrations and comparisons shown above, a few features of dynamic lighting is worth mentioning: 1) Scene 1, Scene 2, and Scene 3 can be thought of as a sequence of lighting scenarios cycling through a user-defined time frame; 2) Scene 1, Scene 2, and Scene 3 can also perform as standalone presets based on user demand; 3) Users are in complete control in terms of fine-tuning the illuminance and CCT levels under any light settings; 4) Users can also manipulate the illuminance and CCT levels to create new lighting environments according to their personal demands and preferences. Based on the definition of dynamic lighting, the lighting at this stage works more as a source of stimulation to arouse the occupants rather than to fulfill the purpose of illuminance.

Figure 21. A stacked vertical comparison of the three dynamic lighting scenes. Note the differences among three scenarios in terms of brightness and colors of all three lighting sources within the space.

Mixed Scenes

In addition to demonstrating all the lighting control features, it is also necessary to demonstrate how the enhanced naturalistic lighting system performs when combined with natural sunlight. All the previous simulations are either for natural sunlight or enhanced naturalistic lighting only. To portray a more realistic lighting scenario, a few mixed scenes that combine the artificial lighting and natural sunlight were also generated for comparison purposes (Figure 22).

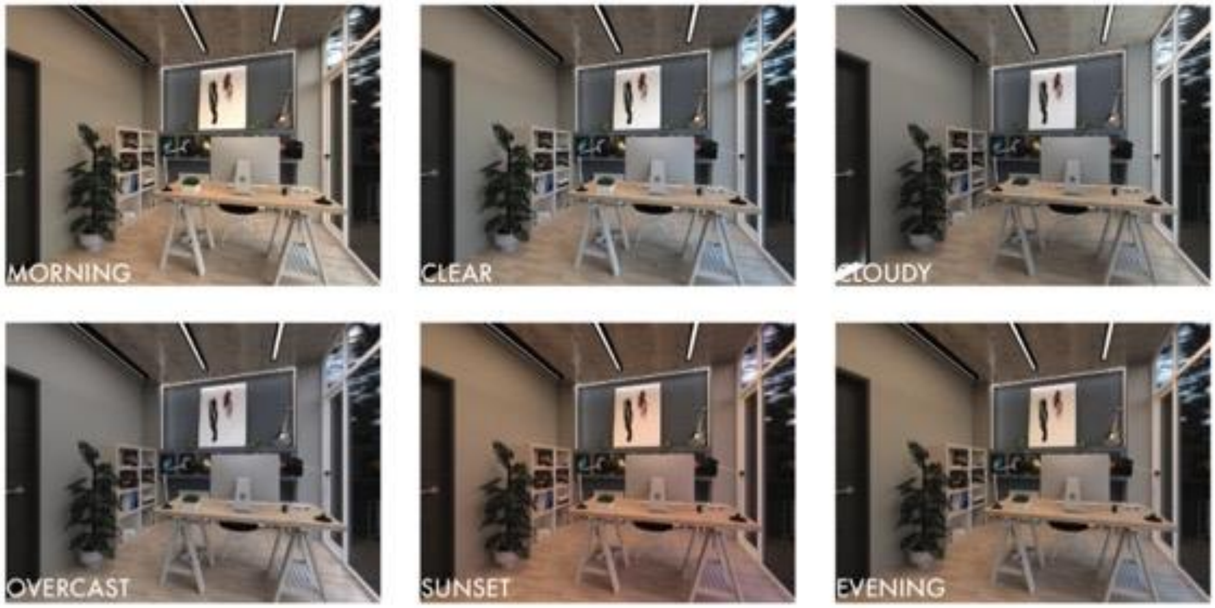

Figure 22. A compilation of all the simulated scenes combining enhanced naturalistic lighting and natural sunlight.

The previous figures depict some simulated scenes to illustrate how naturalistic lighting, functional lighting, and dynamic lighting perform in the enhanced naturalistic lighting control system. These simulations showcased the three major components of such a system and how they can perform as standalone features, as well as how enhanced naturalistic lighting system works with natural sunlight within a closed office space. While these simulations provide solid visual representations of the three major aspects of the enhanced naturalistic lighting system, it is also important to understand how enhanced naturalistic lighting components work seamlessly within the control system and how they compare with more traditional office lighting systems.

Figure 23. A compilation of all the simulated scenes combining enhanced naturalistic lighting and natural sunlight.

In the next section, addition comparisons and illustrations will be provided to explain how the enhanced naturalistic lighting control system works with three enhanced naturalistic lighting aspects to help office occupants create an office environment that could increase both their wellbeing and their productivity.

Comparison of Enhanced Naturalistic Lighting with Traditional Office Lighting

Office lighting strategy and technology have slowly evolved over the years. As discussed in the literature section, before the wide employment of LED light sources, there were largely only two major types of lighting sources, incandescent and fluorescent, that had been used in office settings. This section compares simulations of closed office environments using enhanced naturalistic lighting, incandescent lighting, and fluorescent lighting.

According to American National Standard Practice for Office Lighting, work by people between the age of 25 to 65 is recommended to be performed under an illuminance value range from 400 to 750 lux for small-scale typical daily life/worker related visual tasks (Illuminating Engineering Society, 2017). However, there are no specific recommendations for office settings with respect to correlated color temperature (CCT). For the comparison given here, the CCT values are based on the nature of each light source. The correlated color temperature of incandescent light sources ranges between 2700 K and 3200 K at full voltage; 3000 K, 3500 K, and 4100 K are the most common color temperatures for fluorescent light sources. It should be mentioned that the CCT value of the incandescent light source and fluorescent light sources are fixed and not tunable in general, while enhanced naturalistic lighting that use LEDs as light sources permit tuning of CCT values from 2700 K to 6500 K (Illuminating Engineering Society, 2017).

Figures 24 and 25 demonstrate how incandescent light sources and fluorescent light sources render closed office spaces.

Figure 24. A simulation demonstrating a closed office illuminated by incandescent light source with an illuminance of 750 lux and a CCT of 3200K.

Figure 25. The closed office illuminated by a fluorescent light source with an illuminance of 750 lux and a CCT of 4100K.

Before continuing the comparison among these different light sources, it should be noted that, because the CCT values of these light source are fixed, the environment illuminated by incandescent light sources and fluorescent lighting sources are relatively stable and constant in terms of correlated color temperature when compared with enhanced naturalistic lighting.

The enhanced naturalistic lighting system uses LEDs as light sources, so the correlated color temperature is tunable and can range from 2700 K to 6500 K. Figure 26 demonstrates the enhanced naturalistic lighting system in its naturalistic lighting mode that mimics the rhythm of natural sunlight, so its CCT and illuminance changes throughout the day. For the purposes of this comparison, the illuminance of the enhanced naturalistic lighting system has been set to 750 lux to match the illuminance used for the incandescent and fluorescent lighting simulations.

To make the comparison between enhanced naturalistic lighting and other light sources more evident and clearer, the simulations shown in this comparison use artificial light only, with natural sunlight completely eliminated. In this comparison, the enhanced naturalistic lighting (physiological mode) can be tuned to different correlated color temperatures to make the closed office lighting environment more dynamic than the one illuminated by either an incandescent light source or a fluorescent light source. On a larger scale, the enhanced naturalistic lighting system can not only provide users with a more dynamic light environment, but can also offer users more dynamic control of the lighting environment, providing users with great flexibility in term of lighting control.

Figure 26. The closed office is illuminated by enhanced naturalistic lighting with illuminance fixed at 750 lux and the CCT ranging from 3500K to 7000K depending on the time of day or weather pattern.

Natural Variability

As mentioned previously, natural variability can change illuminance, correlated color temperature, duration, speed of change, rhythm of change, etc., of the lighting environment rather unpredictably. To perceive a better picture of natural variability, diagrams can provide an efficient and effective way to describe the concept. Figure 27 demonstrates how natural sunlight varies throughout the day to establish a baseline for the rest diagrams and to assist the audience in achieving a better understanding of variation under natural sunlight.

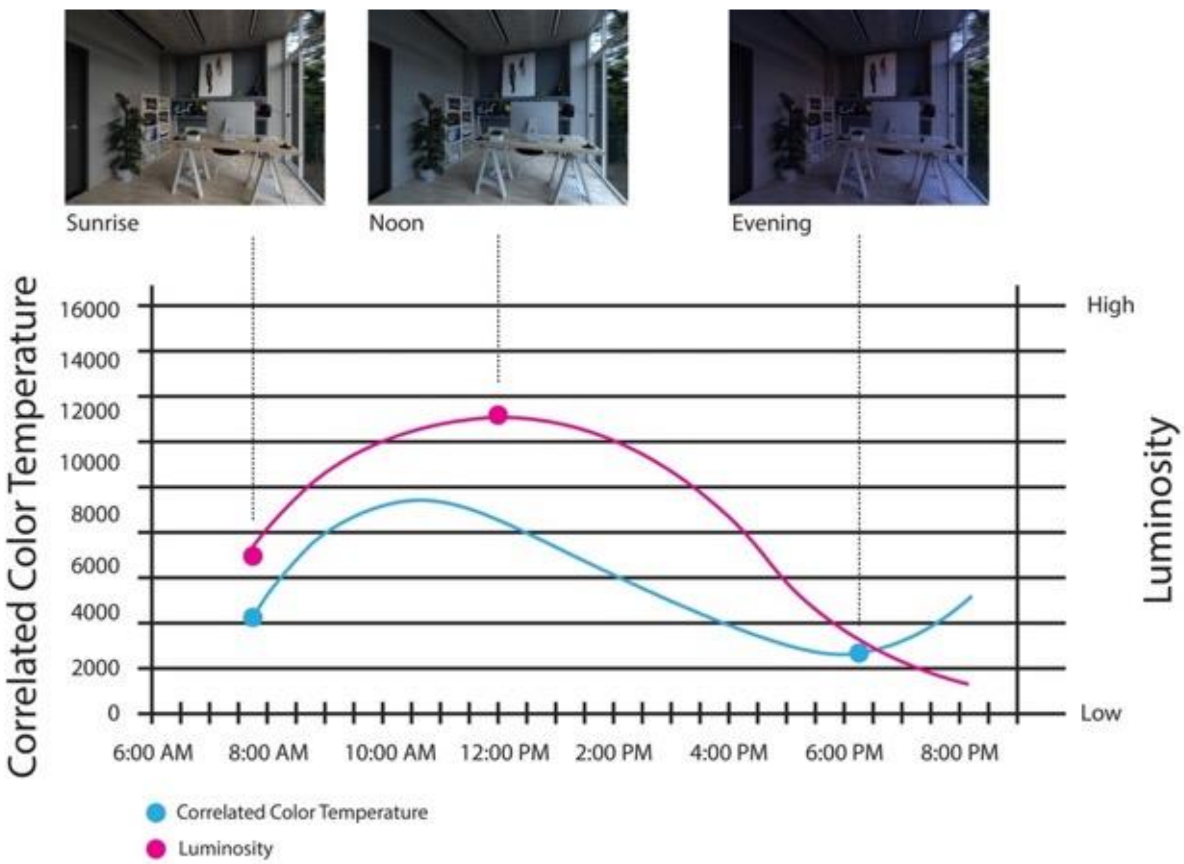

Figure 27. A diagrammatic illustration of how correlated color temperature and luminosity change throughout a normal day (Bim, 2013).

Figure 27 offers an example of how correlated color temperature and luminosity of the natural sunlight changes throughout a typical day. The core value of this diagram is that it illustrates a trend or rhythm related to how natural sunlight varies throughout the day. The graph of luminosity and correlated color temperature may shift either slightly or dramatically depending on the weather pattern, season, and geographical location. If this rhythm is properly followed and the correlated color temperature and luminosity value adjusted to accommodate office spaces, the result is naturalistic lighting that could assist an office occupant to synchronize their circadian rhythm with nature. Natural variability functions go beyond just mimicking the natural sunlight, and Figure 28 illustrates one arbitrarily-chosen example of how natural variability performs.

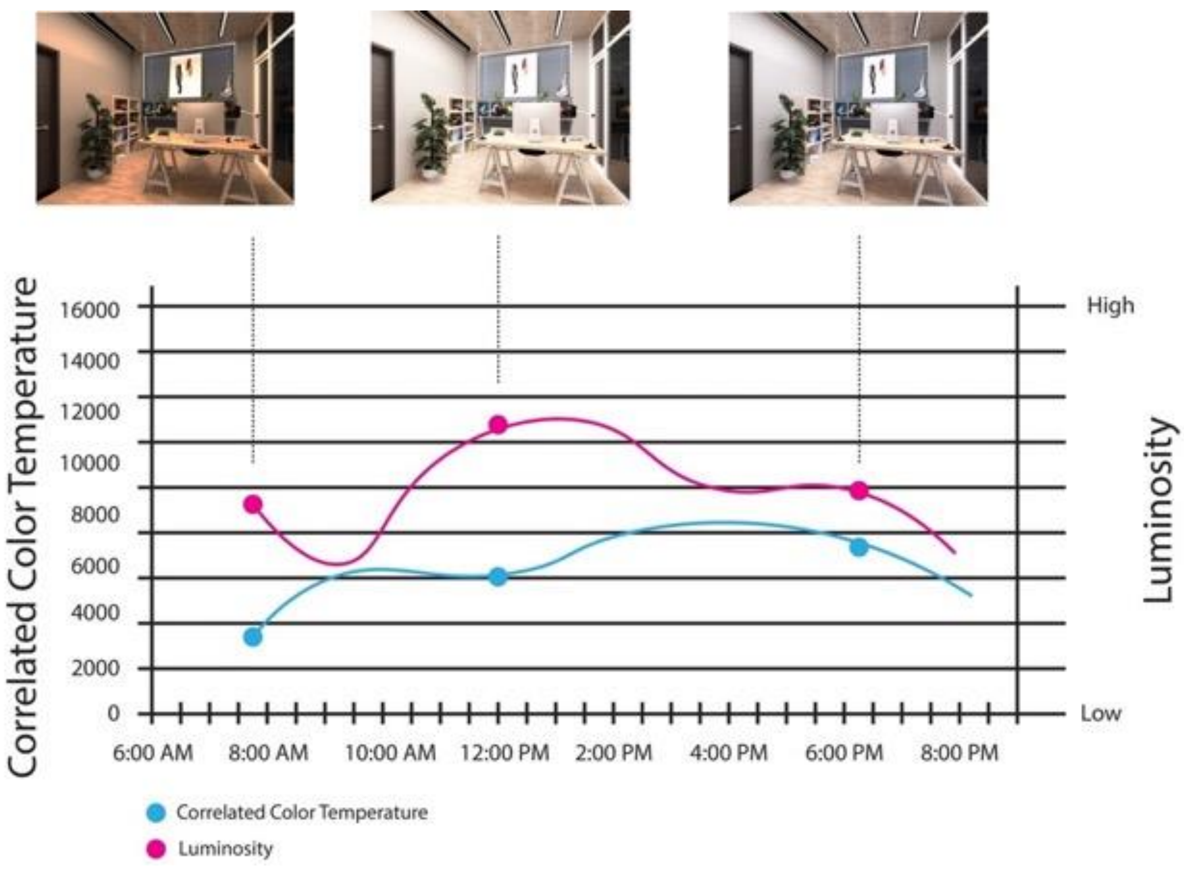

Figure 28. Diagram showing one (among many possibilities) arbitrarily chosen example of how correlated color temperature and luminosity changes when natural variability is activated.

Figure 28 shows that changes in correlated color temperature and luminosity under natural variability are rather unpredictable and can (as in this scenario) be quite dramatic. CCT and luminosity are separate variables, meaning they do not change correspondingly (i.e., a change in luminosity will not necessarily cause a change in CCT) making natural variability even more unpredictable and random.

Synthetic Natural Variability

Synthetic natural variability offers more control than natural variability alone by allowing users to make modifications to certain aspects of natural variability such as duration of change, rhythm of change, and lighting variables. Natural variability can perform more effectively with respect to users' preferences when users decide to change these variables.

Duration of change

Duration of change refers to how fast the lighting changes from one scenario to another. Depending on users' preferences, the transition between lighting scenarios could happen instantly or more smoothly over a certain period of time. Figure 29 illustrates a lighting scenario in which all transitions between lighting scenarios occur instantly.

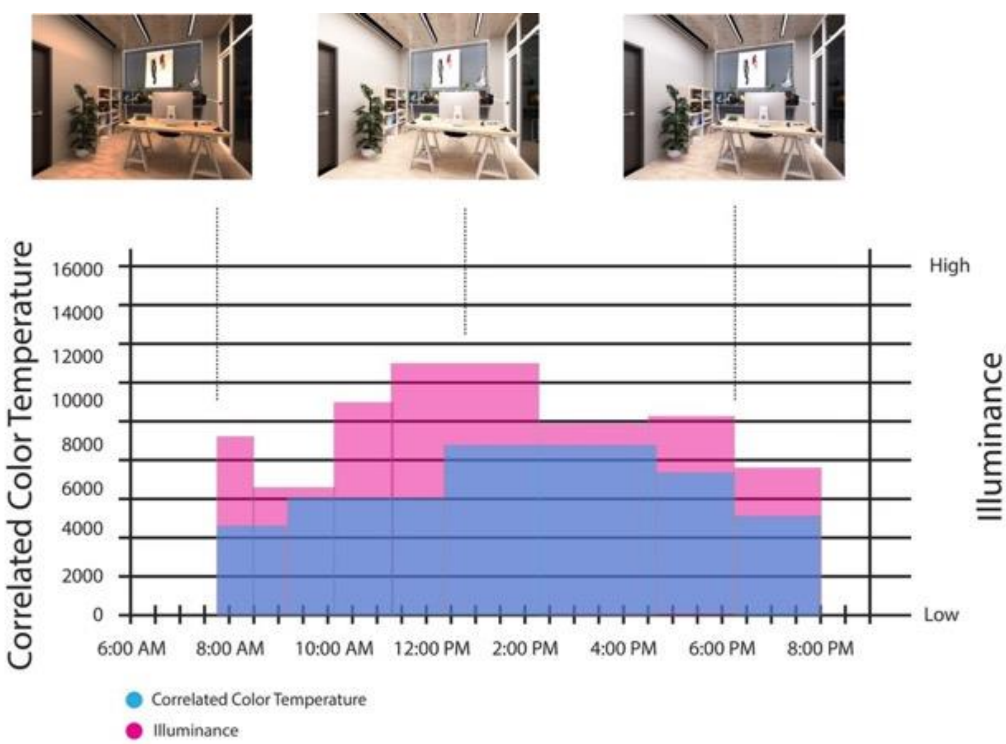

Figure 29. Diagrammatic view of one (of many variable) arbitrarily chosen example illustrating instantaneous transitions between lighting scenarios.

Rhythm of change

Rhythm of change refers to frequency of lighting changes. In the previous example (Figure 21), the lighting constantly changed in the time between sunrise and sunset. Because of the long timeframe and relatively high value of change duration, the change in lighting is very subtle, and arguably less stimulating. If users have ability to control the rhythm of change, they can control the dramatic aspect and intensity of the lighting environment. Figure 30 illustrates the same natural variability lighting option but with a much tighter time frame. Instead of occurring over approximately 12 hours, the new lighting rhythms executes the same dynamic lighting behavior within 30 minutes.

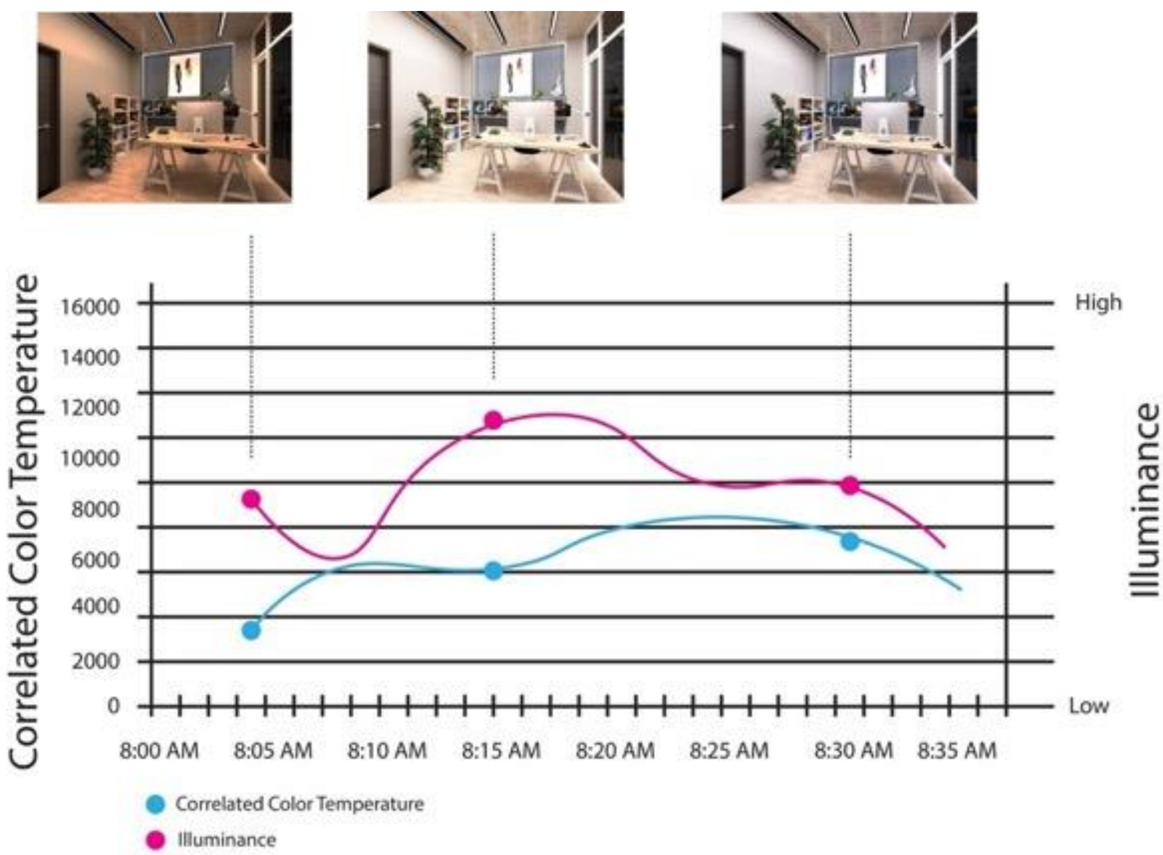

Figure 30. Diagrammatic view of one (of many variable) arbitrarily chosen example to illustrate how natural variability performs within a 30-minute time frame.

Lighting variables

In the natural-variability section, the lighting variables were assumed to be limited to correlated color temperature and illuminance only, but synthetic natural variability brings an additional lighting variable, color, into the equation. Unlike correlated color temperature, presented as different shades of white light (i.e., a mixture of colors in the visible spectrum). Colors are presented in different wavelengths, with each wavelength corresponding to a particular color. Bringing the color variable into synthetic natural variability not only enhances the dynamic aspects of the enhanced naturalistic lighting system, but also offers users another control dimension. With the color variable added, there are a total of three lighting variables, illuminance, correlated color temperature, and color, for users to manipulate under conditions of synthetic natural variability.

By manipulating these factors, natural variability may still continue to perform naturally (i.e., unpredictably). On one hand, users' interventions can serve as guidelines indicating how natural variability should function to fulfill users' desires and requirements. On the other hand, users' modifications to natural variability do not eliminate its key characteristic of varying the lighting in a natural and unpredictable way.

Summary

In summary, the P.A.Th.Ways afforded an opportunity to explore many lighting solutions that addressed users' physiological aspect, function aspect, and psychological aspect, as well as for choosing the most relevant, and useful solution concepts in a very transparent and logical way. The baseline control, natural variability, user-oriented control, reset, and "refresh" mechanism together complete the list of all necessary elements needed in the enhanced naturalistic lighting control system. In order to better communicate the control schematic for the enhanced naturalistic lighting, lighting schematic diagrams and visual illustrations are provided in the next sections to show how the enhanced naturalistic lighting control system functions and performs in a closed office environment.

CHAPTER 6. DISCUSSION

Overview

The evidence compiled in this study shows that lighting can greatly impact office occupants' wellbeing and productivity, but there has never been a holistic definition for this type of lighting, nor a lighting control system that would allow users to gain full access to these benefits. This study was performed to create a lighting control system for office occupants to use in unlocking the potential benefits that such lighting could provide. This study gave definition to the concept of enhanced naturalistic lighting, and created the schematic of a control system based on this concept, thereby providing a strong link between users and the advantageous features that a lighting system has to offer.

This chapter aims to discuss the enhanced naturalistic lighting control system in a way that promotes a relevant discussion regarding the study's contents and context. As a fundamentally creative component, there is considerable room for subjective comment. This chapter, by discussing implications for design practice, overall conclusions of the study, and recommendations for future research, aims to trigger a discussion on relevant design aspects and applications that speak to designed workspaces, office occupants, and the enhanced naturalistic lighting concept.

Implication for Future Design

Control Mechanism and Interface

As mentioned previously in describing the scope of this study, the control system design for enhanced naturalistic lighting has been created on a schematic level, so the control system schematic developed by this study heavily emphasized the functionalities of the system, and how these functions relate to the physiological, functional, and psychological sides of users. What does an actual control system look like? How do users interact with it? There are many functions offered within the enhanced naturalistic lighting control system, so it may not seem practical to integrate the entire control system based solely on physical panels, buttons, and knobs. This approach could easily overwhelm lighting users and result in stimulation overload, possibly leading to potential negative consequences. From a different standpoint, the rise of personal digital voice assistants, smartphones, and smartphone-integrated control has certainly opened up many new avenues for controlling lighting systems. Implementing a lighting control system into a certain space would require flawless integration into the overall lighting design, ranging from a graphical control interface to an easy-to-use lighting control system, not merely something as simple as a compilation of functions. Such a move would enhance physiological, functional, and psychological aspects of the user, and (ideally) enhance the overall experience.

Spatial Arrangement

The arrangement of spaces is critical to both the functionality and experience of a workplace and its spatial arrangements also can dramatically affect the lighting strategy. The principal office space in this study was a 100-square foot private office setup mainly designed for use by a single individual. Compared to large open office plans, the relatively small footprint of such a private office space offers an artificial lighting situation that is easily to observe and control for the study. There is a humane aspect to the lighting control schematic of this study, and lighting designers must be aware of the spatial arrangement of such a space. This implies specific knowledge of lighting strategy and functions of the control system, and should have emphases that relate to user activities, functionalities, and experience with the space. While the control schematic can function as a tool box for lighting control system, a lighting designer needs to repackage the lighting control system depending on the desired functionality and experience with the space to achieve maximum benefits in terms of users' physiological, functional, and psychological aspects.

Lighting and Its Surroundings

During the course of this study is was clear that natural variability is not just about light but about senses in general. The relationships between lighting and its users are rather indirect, because there are few times that lighting users directly interact with the light source. Instead, the light perceived through users' visual systems is most often indirect or reflected light and the indirect lighting perceived by users may be significantly altered by the surrounding environment. The question raised during the study is how the surrounding environment may affect the users perceived lighting environment. How does air quality affect light travel through the space? How do the colors and surface materials reflect lighting differently?

Additionally, within an office environment many tasks are computer-based and computer screens can also be considered as light sources largely producing blue light. The light emitted by a computer screen can add an extra component to the existing lighting system, possibly increasing the complexity of the lighting design from a human perspective. Could there be a design that utilizes computer screen lights as sources that affect the physiological, functional, and psychological aspects of enhanced naturalistic lighting?

Atmosphere

The lighting conditions and scenario focus of this study all can be quantified and translate into numeric data, because correlated color temperature is represented in units of degrees Kelvin, illuminance is measured in lux, and the color of light can be described in wavelengths measured in nanometers. Above and beyond such numerical data, lighting also can play a significant role when considering the atmosphere of a space. Direct light, indirect light, diffused light, and accent light all have their own unique characteristics in terms of creating different atmospheres. While there are certain expectations and standards for atmospheric quality in workplaces, with the introduction of enhanced naturalistic lighting systems has opened up many possibilities for what workplace lighting conditions could be. Could the lighting atmosphere expectation/standard within workplaces be redefined when lighting design is really in the control of users?

Conclusion

The study began as an investigation into relationships among office productivity, wellbeing, and lighting, and to better understand how we as designers could introduce and configure control features to optimize lighting facilitation of physiological, functional, and psychological aspects. Through the review of literature, three key developments have been developed in lighting: human affinity to nature; accommodation of physiological, functional, and psychological aspects; and acknowledgement of the inherent need for variability and evolution. For the purposes of this study, some way to fully integrate these three issues is needed. A morphological approach was used to list each design consideration and integrate the three issues in a transparent and logical way. By creating a control system schematic for the enhanced naturalistic lighting system, we were able to establish a link among the three issues developed early in the study that could potentially inform future lighting design decisions.

To understand how lighting could assist a user in a designed environment, we must approach the issue with a human perspective. A naturally-variable lighting control system schematic is fundamentally a study of human behavior and its relationship with nature. By understanding how lighting could impact physiological, functional, and psychological behavior, it could become possible to apply that information to future design in hope of improvement in user wellbeing and performance in the workplace.

Recommendations for Future Research

This study has undertaken a general overview of *naturalistic* lighting practices with an eye to how benefits of the approach can be expanded and enhanced. In this regard, the paper will conclude with several recommendations for future research directions:

1. Utilize quantitative research methods in the methodology in hopes of obtaining real data to validate the theory established in this study.
2. Research the mechanical details of the control system schematic, and design a well-balanced enhanced naturalistic lighting control system a user could use in everyday working life.
3. Implement the enhanced naturalistic lighting control schematic for different workplace layouts to seek to understand how the functionalities of lighting can shift based on users' demand.
4. Investigate how elements of a surrounding environment, such as surface color, air quality, and sound level, could potential influence the lighting environment we perceive from our visual system.
5. Design and perform a research study to compare different lighting scenarios based on the quality of light (i.e., the atmosphere created by lighting).

The subject appears to offer design researchers rich opportunities for valuable inquiry.

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APPENDIX A. NOMENCLATURE

Conventional Naturalistic Lighting	A lighting system that mimics certain qualities of natural sunlight. Principally, cyclical changes in luminance and correlated color temperature during a "typical" 24-hour cycle. However, generally in a somewhat standardized, and regularized way.
Enhanced Naturalistic Lighting	An expansion of the naturalistic lighting concept that emphasizes the inherent variability of natural lighting, through the inclusion of inherent variability, and a degree of unpredictability, into the lighting system, along with rich opportunities for control of lighting attributes.
Natural sunlight	Natural sunlight is a combination of direct sunlight, diffused light from the sky, and light reflected from the ground (or nearby buildings and trees)
Incandescent	Incandescent and other filament-based lamps have traditionally been used in office areas where down lighting and adjustable accent luminaires are needed. As of 2012, use of incandescent light sources diminished because they no longer met minimum energy efficiency standards according to the Energy Independence Security Act of 2007 (EISA 2007).
Fluorescent	Most office applications use florescent lamps in linear, U-shaped, or compact configurations. All these lamp types use tri-phosphor coating technology to achieve good to excellent color rendition indexes
LED	Light Emitting Diodes (LEDs) are solid-state electronic devices for generating light. In recent years, architecture for lighting applications for these devices has seen rapid growth as improvements in luminous efficacy and chromaticity have made them into viable alternatives for many applications.
Illuminance	Illuminance is the amount of light falling on a surface measured in lux.
Luminance	The amounts of light coming from the surface or a point, measured in candles per square meter (cd/m2).

CCT	Correlated Color Temperature (CCT) refers to the color temperature of light merging from the lighting source in itself and is the absolute temperature of a black body whose chromaticity most nearly resembles that of the light source. It is expressed using the Kelvin temperature scale, i.e., in degrees Kelvin
Direct lighting	Direct lighting de-emphasizes the ceiling locations in the luminaires themselves. Horizontal planes, such as work surfaces and floors are emphasized.
Indirect lighting	Indirect lighting illuminates the ceiling, in turn reflecting the light down onto work planes, walls, and floors. Such light is very much diffused and nearly shadow free.
Accent lighting	Accent lighting provides visual interest and a focal point. It also may help add clarity to an overall composition and help with wayfinding in large spaces.
Furniture-based task lighting	Localized furniture-based task lighting that should not cause problems with glare or other issues.

APPENDIX B. NATURAL SUNLIGHT SIMULATIONS

Morning

Clear

Cloudy

Overcast

Sunset

APPENDIX C. NATURALISTIC LIGHTING SIMULATIONS

Morning – 4000 Kelvin

Clear – 5000K Kelvin

Cloudy – 6000 Kelvin

Overcast – 7000 Kelvin

Sunset – 3500 Kelvin

Evening – 4000K

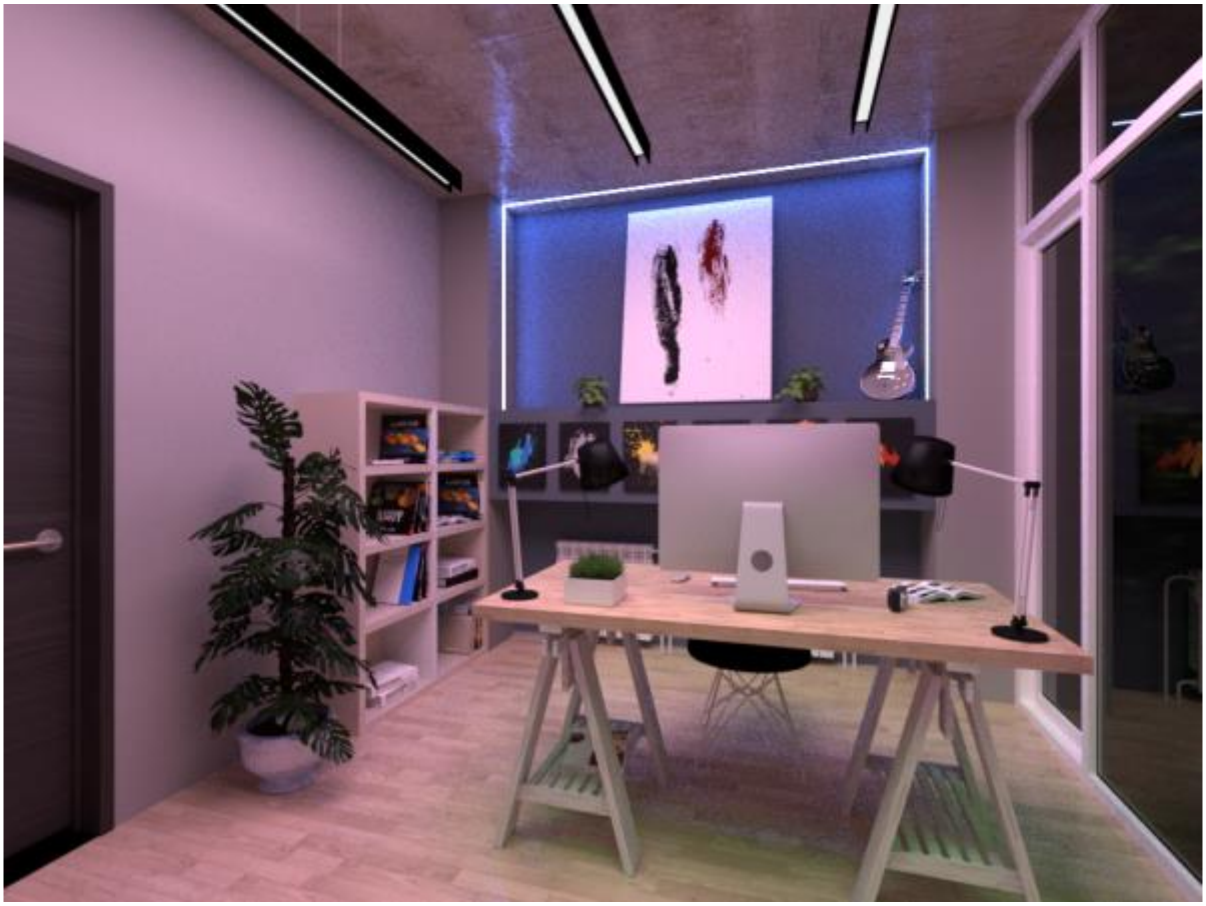
APPENDIX D. FUNCTIONAL LIGHTING SIMULATIONS

Relax

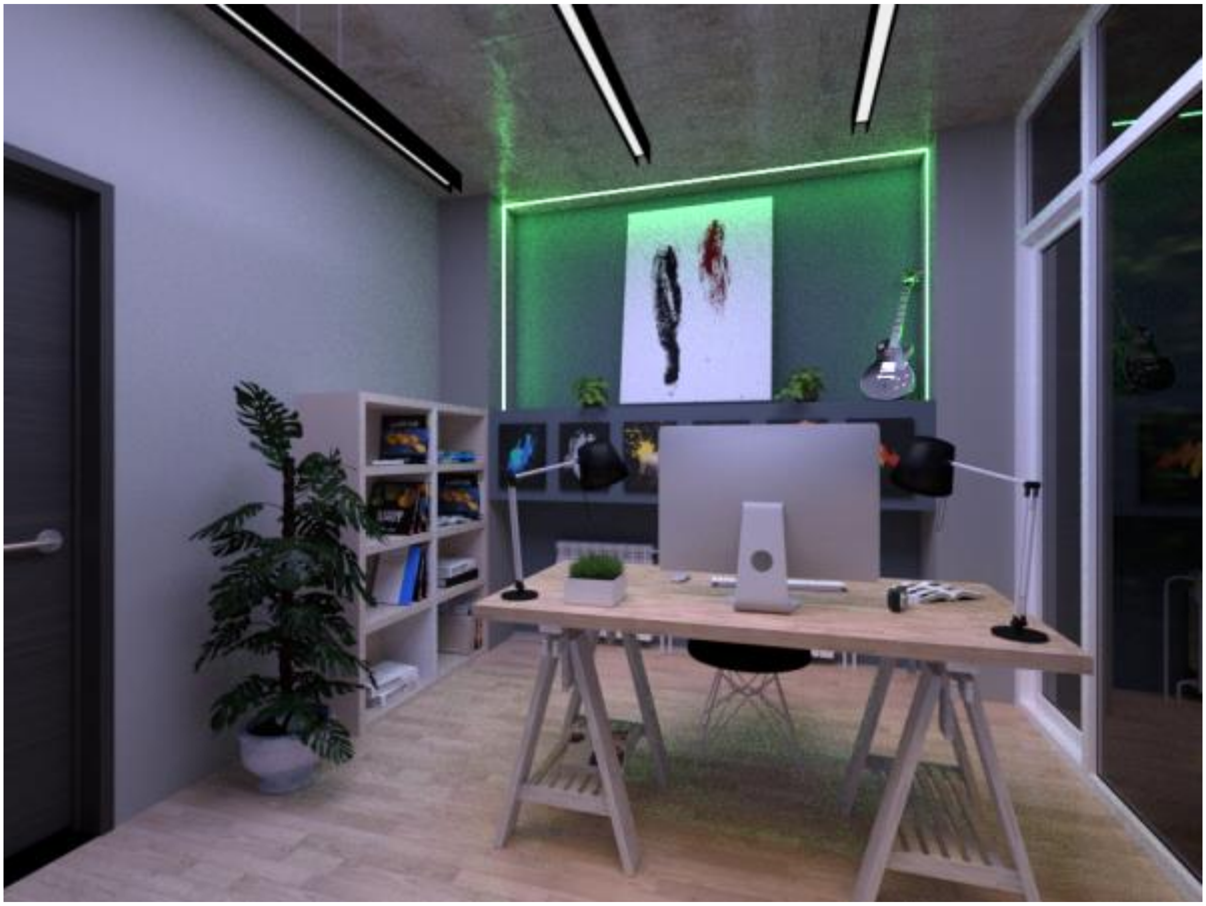
Concentrate

APPENDIX E. DYNAMIC LIGHTING SIMULATIONS

SCENE 1



SCENE 2



SCENE 3

APPENDIX F. MIXED LIGHTING SIMULATIONS

Morning

Clear

Cloudy

Overcast

Sunset

Evening

APPENDIX G. TRADITIONAL OFFICE LIGHTING SIMULATIONS

Incandescent Lighting - illuminance: 750 lux, CCT: 3200 Kelvin

Florescent Lighting - illuminance: 750 lux, CCT: 4100 Kelvin