UNIVERSITI PUTRA MALAYSIA

AN ARCHITECTURAL LIGHTING DESIGN TO ENHANCE INDIVIDUALS' WELLBEING INDICATORS IN WINDOWLESS, OPEN-PLAN WORKPLACE IN TROPICAL ENVIRONMENT

RATNAKALA A/P SITHRAVEL

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By

RATNAKALA A/P SITHRAVEL

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

April 2018

"I will give thanks to You, Lord, with all my heart;
I will tell of all Your wonderful deeds."
(Psalm 9:1, The New International Version).

To God the Almighty be the glory forever.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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Chairperson: **Prof. Hajah Rahinah Ibrahim, PhD**
Faculty: **Design and Architecture**

There is a need to identify supportive architectural lighting design concepts and conditions to enhance dayshift individuals' psychophysiological wellbeing indicators (IPWI), in a windowless open-plan workplace (WOPW) in tropical Malaysia. Studies from seasonal climates have evidenced the advantages of dynamic architectural lighting over constant (regular) lighting in enhancing IPWI especially in workplace with less natural daylight contribution. However, this has not been investigated in tropical Malaysia as yet. Hence, this thesis proposes the development of Integrated Tropical Architectural Lighting Design (ITALD) framework, to justify the need to develop supportive, dynamic architectural lighting configurations for WOPW in tropical Malaysia. For this purpose, an exploratory experimental study (mixed-group design with 45 healthy postgraduate males) was initiated in a computer laboratory in Universiti Putra Malaysia to mimic a realistic WOPW.

The immediate impact of a 2-hour morning exposure to overhead white LED (6500 K) ambient lighting on a number of IPWI such as urinary 6-sulfatoxymelatonin (aMT6s), alertness, positive affect, negative affect, visual comfort, cognitive and visual task performances were investigated. A few lighting configurations were also tested to identify potential threshold values and patterns that were more supportive of the morning boosting effect in tropical Malaysia. The light-settings included constant ($500_{constant}500$ lx) versus dynamic lighting with horizontal illuminance in decreasing oscillation ('$500_{decreasing\ to}250$ lx', '$750_{decreasing\ to}500$ lx', '$1000_{decreasing\ to}500$ lx'), and increasing oscillation ('$250_{increasing\ to}500$ lx', '$500_{increasing\ to}750$ lx', '$500_{increasing\ to}1000$ lx').

Results revealed each light-setting immediately impacted the measured indicators either positively or negatively. Not all of the light-settings contributed towards better morning boosting effect when compared to 'control' (visit 1: $500_{constant}500$ lx). Only

two specific configurations of dynamic lighting in increasing oscillation were identified as potentially more supportive than 'control'; while dynamic lighting in decreasing oscillation and follow-up constant lighting were less supportive. With illuminance-and-oscillation dependent responses, this thesis recommends oscillation effect as an additional lighting factor. It influenced the direction of the immediate impact and defined a supportive, dynamic architectural lighting pattern.

The two supportive light-settings were '$500_{\text{increased to}}$750 lx' and '$500_{\text{increased to}}$1000 lx'. They contributed towards a better morning boosting effect than 'control' as they supported most of the measured indicators. They therapeutically suppressed urinary aMT6s, improved alertness, cognitive task performance, positive affect, and visual comfort. These potential light-settings established a preliminary groundwork for defining supportive, dynamic architectural lighting configurations for a morning worktime period in WOPW in tropical Malaysia. Interestingly, an increasing oscillation lighting pattern was observed more beneficial in tropical Malaysia; while a reverse pattern (decreasing oscillation) was specified for the morning boosting effect by the 'human rhythmic' protocol developed by studies from the Netherlands.

These findings provided evidence that a supportive, dynamic architectural lighting has potentials to play an active role in enhancing IPWI during worktime, and act as an environmental therapeutic solution in minimizing light-induced circadian disruption in WOPW in tropical Malaysia. It could subsequently optimize work productivity; contribute towards better human capital performance, and positively impact an organization and the country's sustainable economic growth. Further investigations are recommended to develop the ITALD framework.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

REKABENTUK PENCAHAYAAN SENIBINA UNTUK MENYOKONG INDIKATOR-INDIKATOR KESEJAHTERAAN INDIVIDU YANG BEKERJA DI DALAM RUANG KERJA JENIS PELAN TERBUKA YANG TIDAK BERTINGKAP DI PERSEKITARAN TROPIKA

Oleh

RATNAKALA A/P SITHRAVEL

April 2018

Pengerusi: **Prof. Hajah Rahinah Ibrahim, PhD**
Fakulti: **Rekabentuk dan Senibina**

Kajian untuk mengenal pasti konsep dan keadaan rekabentuk pencahayaan senibina yang sesuai untuk menyokong indikator kesejahteraan psikofisiologi (IPWI) bagi individu yang bekerja di dalam ruang kerja jenis pelan terbuka yang tidak bertingkap (WOPW) di Malaysia amatlah diperlukan. Kajian penyelidikan dari negara-negara bermusim telah membuktikan keberkesanan pencahayaan senibina jenis dinamik daripada jenis yang tetap untuk menyokong IPWI terutamanya untuk ruang kerja yang kurang menerima penembusan cahaya semulajadi. Walaubagaimanapun, perkara ini masih belum disiasat dalam konteks Malaysia. Oleh yang demikian, rangka kerja Rekabentuk Pencahayaan Senibina Tropikal Bersepadu (ITALD) dicadangkan bagi menjustifikasikan pembangunan konfigurasi pencahayaan senibina dinamik yang sesuai untuk kegunaan di dalam WOPW di Malaysia. Bagi tujuan tersebut, satu eksperimen (melibatkan 45 pelajar lelaki pascasiswazah dalam rekabentuk kajian berteraskan kumpulan bercampur) telah dijalankan di dalam sebuah makmal komputer di Universiti Putra Malaysia yang menyerupai keadaan sebenar WOPW.

Impak segera akibat daripda pendedahan kepada 2-jam pencahayaan dari siling yang menggunakan lampu LED bewarna putih (6500 K) pada waktu pagi, telah disiasat ke atas beberapa IPWI seperti hormon melatonin, kewaspadaan, mood kesan positif dan negatif, keselesaan visual, dan prestasi tugas kognitif dan visual. Beberapa kombinasi pencahayaan juga dikaji untuk mengenal pasti nilai ambang dan corak pencahayaan yang mempunyai potensi untuk menyokong rangsangan pagi di Malaysia. Kombinasi tersebut terdiri daripada pencahayaan jenis tetap (500$_{tetap}$500 lx) dan jenis dinamik dengan iluminasi makmal yang menurun (‘500$_{menurun\ kepada}$250 lx’, ‘750$_{menurun\ kepada}$500 lx’, ‘1000$_{menurun\ kepada}$500 lx’); dan yang meningkat (‘250$_{meningkat\ kepada}$500 lx’, ‘500$_{meningkat\ kepada}$750 lx’, ‘500$_{meningkat\ kepada}$1000 lx’).

Keputusan kajian menunjukkan setiap kombinasi pencahayaan telah mengimpak indikator-indikator yang dikaji samada secara positif atau negatif. Bukan semua kombinasi pencahayaan menyumbang kepada impak rangsangan pagi yang lebih baik berbanding dengan pencahayaan kawalan (lawatan 1: 500_{tetap}500 lx). Hanya dua kombinasi pencahayaan jenis dinamik dengan iluminasi makmal yang meningkat dikenalpasti sebagai pencahayaan yang berpotensi dan lebih berkesan daripada pencahayaan kawalan; manakala pencahayaan jenis dinamik dengan iluminasi makmal yang menurun, dan susulan pencahayaan jenis tetap menunjukkan impak yang kurang berkesan. Dengan tindak balas yang bergangtung kepada iluminasi-dan-corak pencahayaan, tesis ini mengesyorkan corak pencahayaan sebagai faktor tambahan untuk pencahayaan. Ia telah menpengaruhi halatuju impak segera dan mendefinisikan suatu corak pencahayaan dinamik yang menyokong rangsangan pagi.

Dua kombinasi pencahayaan yang dimaklumkan adalah ‘$500_{meningkat\ kepada}$750 lx’ dan ‘$500_{meningkat\ kepada}$1000 lx’. Kombinasi-kombinasi tersebut telah menyumbang kepada impak rangsangan pagi yang lebih baik daripada pencahayaan kawalan, kerana mereka telah mengimpak kebanyakkan indikator yang dikaji. Mereka telah menunjukkan keadaan teraputik untuk menurunkan tahap hormon melatonin, dan meningkatkan kewaspadaan, prestasi tugas kognitif, mood kesan positif, dan keselesaan visual. Potensi kombinasi pencahayaan tersebut telah menubuhkan pangkalan awalan dalam mendefinisikan konfigurasi pencahayaan senibina dinamik yang sesuai untuk waktu kerja pagi di dalam WOPW di Malaysia. Corak pencahayaan dinamik dengan iluminasi makmal yang meningkat diperhatikan lebih menyokong impak rangsangan pagi di Malaysia, berbanding dengan corak yang menurun yang dispesifikasikan oleh kajian pencahayaan dinamik dari Belanda.

Penemuan-penemuan ini membuktikan bahawa pencahayaan senibina dinamik berpotensi untuk memainkan peranan yang aktif bagi menyokong IPWI semasa waktu bekerja, dan bertindak sebagai suatu penyelesaian alam sekitar yang berteraputik bagi meminimumkan gangguan sirkadian akibat daripada pencahayaan, di dalam WOPW di Malaysia. Pencahayaan senibina dinamik kemudiannya dapat mengoptimumkan produktiviti kerja; menyumbang ke arah prestasi modal insan yang lebih baik, dan memberi kesan positif kepada organisasi dan pertumbuhan ekonomi negara yang mampan. Siasatan lanjut untuk membangunkan rangka kerja ITALD adalah disyorkan.

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I am blessed to have this supportive multidisciplinary team. Their contributions played an important role in developing and strengthening my research.

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I thank you all once again. May God bless you and your families richly.

RatnaKala Sithravel
Universiti Putra Malaysia
April 2018

I certify that a Thesis Examination Committee has met on 27 April 2018 to conduct the final examination of RatnaKala a/p Sithravel on her thesis entitled "An Architectural Lighting Design to Enhance Individuals' Wellbeing Indicators in Windowless, Open-Plan Workplace in Tropical Environment" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Suhardi bin Maulan, PhD
Associate Professor LAr.
Faculty of Design and Architecture
Universiti Putra Malaysia
(Chairman)

Shamsul Bahri bin Hj. Mohd Tamrin, PhD
Professor
Faculty of Medicine and Health Sciences
Universiti Putra Malaysia
(Internal Examiner)

Cheng Hwee Ming, PhD
Professor
University of Malaya
Malaysia
(External Examiner)

Yvonne de Kort, PhD
Professor
Eindhoven University of Technology
Netherlands
(External Examiner)

NOR AINI AB. SHUKOR, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 28 June 2018

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Rahinah Ibrahim, PhD
Professor
Faculty of Design and Architecture
Universiti Putra Malaysia
(Chairperson)

Lye Munn Sann, MBBS, MPH, DrPH, FAMM
Professor Dato'
Faculty of Medicine and Health Sciences
Universiti Putra Malaysia
(Member)

Normala Ibrahim, MB.Bch.BAO, M.Med, PhD
Associate Professor
Faculty of Medicine and Health Sciences
Universiti Putra Malaysia
(Member)

Enoch Kumar a/l Perimal, PhD
Senior Lecturer
Faculty of Medicine and Health Sciences
Universiti Putra Malaysia
(Member)

Nur Dalilah binti Dahlan, PhD
Senior Lecturer
Faculty of Design and Architecture
Universiti Putra Malaysia
(Member)

____

ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by Graduate Student

I hereby confirm that:

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Declaration by Members of Supervisory Committee

This is to confirm that:

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Signature: ______________________________

Name of Chairperson of Supervisory Committee: Prof. Dr. Hajah Rahinah Ibrahim

Signature: ______________________________

Name of Member of Supervisory Committee: Prof. Dato' Dr. Lye Munn Sann

Signature: ______________________________

Name of Member of Supervisory Committee: Assoc. Prof. Dr. Normala Ibrahim

Signature: ______________________________

Name of Member of Supervisory Committee: Dr. Enoch Kumar Perimal

Signature: ______________________________

Name of Member of Supervisory Committee: Dr. Nur Dalilah Dahlan

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LIST OF ABBREVIATIONS

aMT6s	6-sulfatoxymelatonin
B	unstandardized coefficient
CCT	correlated color temperature
EEG	electroencephalogram
EMM	estimated marginal mean
E_H	horizontal illuminance
E_V	vertical illuminance
FFL	finished floor level
GLMM	Generalized Linear Mixed Model
IPWI	individuals' psychophysiological wellbeing indicators
ITALD	Integrated Tropical Architectural Lighting Design
K	Kelvin
KSS	Karolinska Sleepiness Scale
NA	Negative Affect
PA	Positive Affect
P_{acuity}	visual acuity task performance (in terms of speed)
P_{cog}	cognitive task performance (in terms of speed)
$P_{contrast}$	visual contrast task performance (in terms of speed)
WOPW	windowless open-plan workplace

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter provides a background on the research undertaken by this thesis. Its importance motivated the development of the research questions and objectives addressed in this thesis.

1.2 Background on Indoor Environment Affecting Individuals' Wellbeing at Workplace

Urban working individuals spend an increasing amount of time in their workplace (Vischer, 2008). On average, a dayshift working individual spends $\frac{1}{3}$ of a day ($\pm$8am - 6pm) in his/her workplace. Ample scholarly discussion and evidence reported the indoor environmental exposures in workplace have been inducing stress and threatening the individual's wellbeing while at work, and also radiating the effects to later times of the day(s) (Bluyssen et al., 2011; Danna & Griffin, 1999); despite compliance to design standards and guidelines in real-life practice (Al Horr et al., 2016; Bluyssen, 2008, 2009; Boubekri, 2008; Frontczak & Wargocki, 2011; Rashid & Zimring, 2008). This concern calls for innovative solutions to design a supportive workplace that optimizes the dayshift individual's wellbeing, which in turn could enhance organizational productivity.

1.3 Background on Indoor Lighting at Workplace

The design, construction, and maintenance of the indoor environmental conditions are crucial for individual's wellbeing (Bluyssen, 2009; Boyce, 2014). Lighting quality has been identified as one of the key indoor environmental parameters for workplace, besides other parameters like thermal, air quality, acoustics. According to Loftness et al. (1997) in Clements-Croome (2005), out of the 7 basic infrastructure requirements identified for people-friendly workplace design; 2 repeatedly covered aspects of lighting design and management.

Marans & Yan (1989), Kamaruzzaman et al. (2011), and Baird & Thompson (2012) have also highlighted that the overall lighting quality was an important factor in deciding the individuals' work environment satisfaction and comfort in conventional/historical/sustainable office buildings. Even for workplaces in Malaysia and Singapore (tropical context), dissatisfaction on lighting was mainly influenced by issues pertaining to electrical (architectural) lighting and overall lighting conditions (Baird & Thompson, 2012; Kamaruzzaman et al., 2011).

Many studies have contributed significantly to the improvement of workplace architectural lighting. They provided insight on the lighting conditions for aesthetic appreciation of a space and its content. They also contributed towards the necessary indoor lighting quality to support individual's visual comfort, which improved work environment satisfaction, task performance, and consequently impacting an organization's productivity and gains (Brainard, 1994; Danna & Griffin, 1999).

All these contributions were orientated towards complementing the individual's visual effects more than the non-visual effects. In general, visual effects relate to the individual's preference, comfort, and ease of sight (lighting for task performance); whereas non-visual effects relate to the individual's daily physiological responses and psychological behavior (lighting for wellbeing). Chapter 2 has further details.

1.3.1 Lighting For Non-Visual Effects

The discovery of the 3rd novel photoreceptor in the retina (see subsection 2.2.2.2) led the lighting research and practice to slowly shift from 'lighting for task performance' to 'lighting for wellbeing' (Bellia, Bisegna, & Spada, 2011; Bluyssen, 2008; Smolders, 2013). The awareness of light as an important stimulus influencing individual's circadian rhythm (Latin: *circa* = about; *dies* = day), encouraged workplace architectural lighting to complement the non-visual effects as well. Circadian rhythm refers to the 24-hour cycle of the individual's physiological responses and psychological behavior, which is regulated by the circadian pacemaker (biological clock). This internal clock runs in the background of the brain and manages the sleep-wake cycle, alertness, mood, etc. (non-visual responses) based on the environmental light signals (e.g., light-dark solar cycle).

1.3.2 Light-induced Disruption on Individual's Circadian Rhythm

An individual requires a daily vertical illuminance (E_V) of 1000 - 1500 lx to support daytime melatonin suppression and stimulate the non-visual responses during the day (Aries, 2005; Aries & Zonneveldt, 2004; van Bommel, 2006b). According to Wakamura and Tokura (2000), daytime light exposure of > 2500 lx is required to activate the biological clock and manage the non-visual responses. It was also emphasized that daytime light exposure between 50 - 300 lx is too dark, and could induce stress and upset a good night's sleep (Wakamura & Tokura, 2000). Hence, this thesis queries whether dayshift individuals in urban workplace have such high levels of daytime light exposure.

Insufficient Daytime Light Exposure: Prior studies highlighted that young, dayshift individuals in urban workplace lacked high levels of daytime light exposure.

i. Scheuermaier, Laffan, & Duffy (2010) reported young individuals only spent 9% of their day in illuminance of > 1000 lx across all seasons.

ii. Veitch (2008) observed individuals in San Diego only spent 4% of their day in illuminance of > 1000 lx. This finding is alarming because San Diego is typically known for outdoor life (experiencing sunshine which coincided with Veitch's data collection period, i.e., between August and September).

iii. Smolders et al. (2013) reported light exposure at work is mainly < 500 lx, whereas exposure to > 1000 lx occurs only for a few minutes every hour. Smolders et al. (2013) strengthen Rea, Figueiro, & Bullough (2002) concern that workplace lighting is unsupportive for the individuals' non-visual effects because the horizontal illuminance (E_H) is often designed with $\frac{1}{2}$ or $\frac{1}{3}$ of 1000 lx.

Obsolete Lighting Standards: Currently, workplace architectural lighting requirements as specified in the Lighting Standards (e.g., European (EN 12464-1), Malaysian (MS 1525:2014)) only recommended the minimum lighting conditions for the photopic vision (see subsection 2.2.3) and visual appearances. For general office design, a constant (regular) visual environment with an average E_H of 300 - 500 lx is recommended (Aries, 2005; Malaysian Standard: Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings - Code of Practice (MS 1525:2014), 2014; van Bommel & van den Beld, 2004). Specifically for MS 1525:2014, the requirements are of one-size-fits-all purpose for practical, energy-efficient lighting design.

Ill-conceived Daytime Architectural Lighting Design: Compliance of the standard's requirement and recommendations (discussed above) have resulted in workplace illuminance levels being relatively dim during the day, in comparison to the natural bright daylight levels.

i. Zain-Ahmed et al. (2002) reported outdoor illuminance levels were approximately 45,000 - 65,000 lx at ground level between 9am - 11am for January in tropical Malaysia.

ii. For countries experiencing seasonal climates, Rea, Figueiro, et al. (2002) reported the figures as being around 2000 - 10,000 lx during cloudy days. Boyce (2014) reported that it could stretch from 1000 lx on a heavily overcast day during winter, to 100,000 lx on a sunny day in summer.

Continuous exposure to the relatively dim indoor (during the day) was evidenced to have:

i. exposed the individuals to biological darkness (Begemann, 2002; Begemann, van den Beld, & Tenner, 1997; Canazei et al., 2014; "Circadian Lighting Supports Health and Wellbeing in the Office Environment," 2017; Kondo & Wakamura, 2012; van den Beld, 2002).

ii. decreased the individual's daily-required circadian light by 40 - 200 times (Bonmati-Carrion et al., 2014; van Bommel, 2006b). This deprived the individual of the light doses required to regulate the circadian rhythm, thus making it an initiator and underlying cause for a wide variety of health and performance-related problems (Begemann et al., 1997).

iii. increased the risk of individuals experiencing daytime fatigue and depleted mental resources while continuously engaged with demanding work-related tasks (although not sleep-deprived) (Huiberts et al., 2014; Smolders & de Kort, 2014).

Urban Lifestyle: An urban lifestyle increases the individual's exposure to indoor architectural (artificial) lighting that is significantly brighter than natural moonlight levels (Begemann, 2002; Verster, 2012). Bright evening light is known to suppress nocturnal melatonin levels and phase-delay its secretion pattern (Andersen, Mardaljevic, & Lockley, 2012; Morita et al., 2002; Park & Tokura, 1999; Takasu et al., 2006). This urban night glow (with brightness higher than the required non-visual baseline levels) increases the risk of disrupting the circadian rhythm (Verster, 2012).

A Global Concern: Research agencies working with the World Health Organization have reported concerns about the impact of light-induced circadian disruption (imbalanced rhythm) on disease occurrence and prognosis (Boubekri, 2008). These agencies evidenced that the combination of:

i. inadequate and inappropriate architectural bright light or natural daylight in the workplace during the day (due to ill-conceived daytime architectural lighting design); and

ii. too much light exposure at night (due to urban lifestyle),

have been associated with desynchronizing the circadian rhythm; and consequently initiating serious health problems and cancer risk in healthy individuals (Boubekri, 2008; Münch et al., 2016).

In order to reset and counteract a desynchronized rhythm, adequate and appropriate bright light exposure is required during the day. It entrains the circadian rhythm and stimulates the non-visual responses based on the local timing of 24-hour solar light-dark stimulus (Rajaratnam & Arendt, 2001; Rea, Bullough, & Figueiro, 2002; van Bommel, 2006b). The above findings call for more research to improve the workplace architectural lighting, so as to provide potential environmental therapeutic solutions that could minimize the light-induced circadian disruption.

1.3.3 High Reliance on Architectural (Artificial) Lighting in Workplace

Dayshift individuals are highly dependent on workplace architectural (artificial) lighting throughout the day (Aries, Aarts, & van Hoof, 2015; Boubekri, 2008; Boyce, 2014; Kamaruzzaman et al., 2011; Stebelová et al., 2015; Vischer, 2008). This is because the architectural lighting is more reliable and controllable. It is a necessary utility to support the workplace throughout the day, and across any weather conditions; as opposed to the unpredictable and uncontrollable nature of natural daylight (Vallenduuk, 1999). Besides that, some architectural features like deep-plan layouts, shallow floor to ceiling height, tinted glazing, shading elements (which helps to minimize internal heat gain and glare that causes discomfort) reduces the penetration of natural bright daylight into the workspace.

As an illustration, tropical Malaysia experiences a warm to hot and moist climate all year round. The sunshine detail of Kuala Lumpur (the national capital) is referred to illustrate her daylight properties. Located at coordinates 3°09'N, 101°42'E (www.timeanddate.com), Kuala Lumpur has sunshine throughout the year (see Figure 1.1), with an average daylight exposure of ±12 hours, i.e., between 7am - 7pm (www.gaisma.com; www.worlddata.info/asia/malaysia/sunset.php). Despite the abundance of natural daylight, Kamaruzzaman et al. (2011) reported office buildings in Malaysia still relied on the architectural lighting throughout the day, as the interior shades were kept drawn most of the time to avoid the glaring natural bright daylight. Glare, as defined by Illuminating Engineering Society of North America, is:

> *The sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort or loss in visual performance and visibility* (Xia et al., 2011, p. 888).

To further understand the current situation, the researcher conducted preliminary visits to 5 different workplaces around Kuala Lumpur, Selangor, and Johor. It was observed that regardless of the natural daylight conditions, these workplaces predominantly relied on architectural lighting throughout the worktime. Even with tinted glazing, the workplaces had the interior shades kept drawn all the time to avoid the glary natural bright daylight (see Appendix B - Figure 1.2).

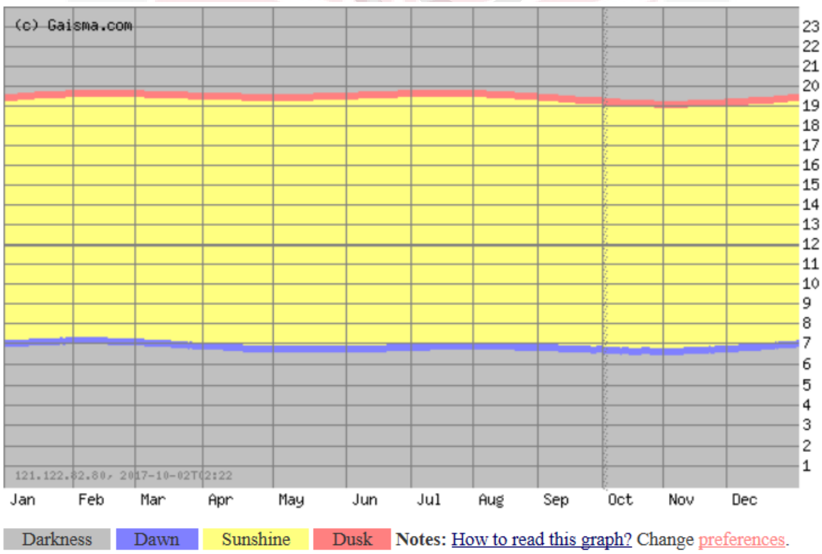


Figure 1.1: Average daylight hours in Kuala Lumpur, Malaysia.
(Source: https://www.gaisma.com/en/location/kuala-lumpur.html)

1.3.3.1 Workplaces With Minimal or No Natural Daylight Contribution

Interestingly, this thesis identified another critical situation in Malaysia - there are workplaces with minimal natural daylight contribution (see Appendix B - Figure 1.3) and located in a windowless context (see Figure 1.4). These are commonly observed in commercial developments, mainly in intermediate-lots of the corporate office towers and shop-lots.

Figure 1.4: Example of workplaces located in windowless contexts (mid-zone area with either minimal or no exposure to natural daylight).

Figure 1.5 presents a typical intermediate shop-lot layout plan and an example of a basic façade design. Its deep-plan (approximately 70 - 80 ft.) with tinted glazing at both ends provides minimal exposure to natural daylight, especially for the mid-zone area. More often than not, the manager's room, waiting area, meeting rooms, pantry, utility, and washrooms are practically zoned along the periphery for better view and natural ventilation; while the mid-zone (windowless context) as the workspace. This resulted in the high reliance on architectural lighting throughout the day in windowless workplace.

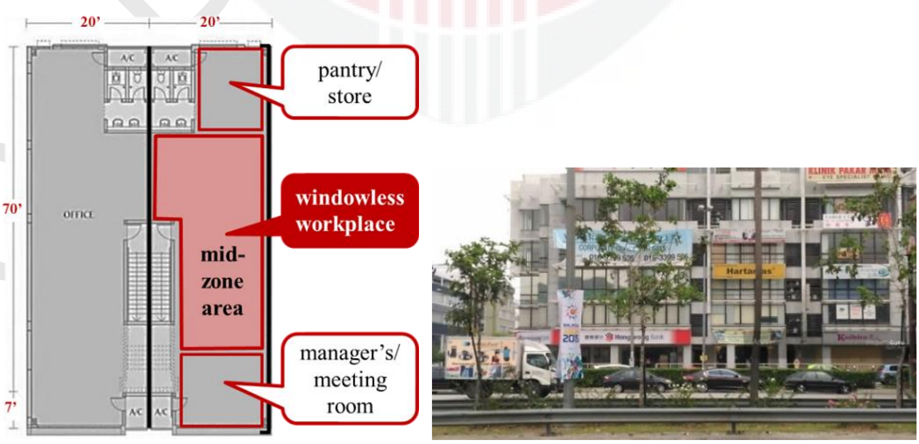


Figure 1.5: Example of Intermediate Shop-Lots in Malaysia - Typical Layout Plan (zoning of spaces) and Front Elevation (basic façade design).
(Source: www.crystalvillegroup.com and www.propertyguru.com.my)

1.4 Research Problem

This thesis raises concern for the wellbeing of the average Malaysian dayshift individual, especially those working in workplace designed with minimal natural daylight contribution or in a windowless context for 2 reasons:

i. They are exposed to prolonged workplace architectural lighting throughout the day. The lighting conditions could be biologically dim, hence negatively impacting their health, comfort, satisfaction, task performance; and consequently affecting an organization's productivity and gains (Aarts et al., 2009; Feige et al., 2013; Hoffmann et al., 2008; Veitch, 2001; Vischer, 2008).

ii. They are at risk of being deprived of the required natural daylight characteristics essential for their daily psychophysiological wellbeing. Pechacek, Andersen, & Lockley (2008) found that a room with windows for natural daylight contribution is no guarantee for exposure to adequate circadian illumination needed for the individual's daily physiological wellbeing. The tinted glazing and interior shades filter the blue light components of the natural daylight needed for circadian stimulus (Pechacek et al., 2008; van Bommel & van den Beld, 2004). As such, alternatives are needed to replenish the loss of the said blue light component.

Therefore, there is a need to identify supportive architectural lighting design concepts and conditions to enhance dayshift individuals' psychophysiological wellbeing indicators (IPWI), in a windowless open-plan workplace (WOPW) in tropical Malaysia.

1.5 Supportive Workplace Architectural Lighting for Individuals' Wellbeing

Human as a diurnal species are usually awake, active and cognitively engaged during the day, and seek rest and sleep at night (under entrained condition) (Vandewalle, Maquet, & Dijk, 2009). Similarly, light-sensitive psychophysiological indicators also depict a daily diurnal rhythm (see subsection 2.2.4). Hence, this thesis raises a few concerns, namely (1) is a constant workplace architectural lighting throughout worktime the only practical lighting solution; and (2) could a constant workplace architectural lighting support the IPWI when in reality the circadian rhythm (non-visual responses) has a diurnal rhythm.

Clements-Croome (2005) recommended the implementation of dynamic stimuli (multi-sensory experience) to stimulate the circadian rhythm appropriately over time. An example is the 'human rhythmic' dynamic lighting protocol (see Figure 1.6) developed by studies from the Netherlands for their application during worktime in winter. It specified timely exposures of changing illuminance and correlated color temperature (CCT) for the activation-relaxation of the IPWI during the day (van Bommel, 2006b, 2006a, van Bommel & van den Beld, 2003, 2004; van den Beld, 2002).

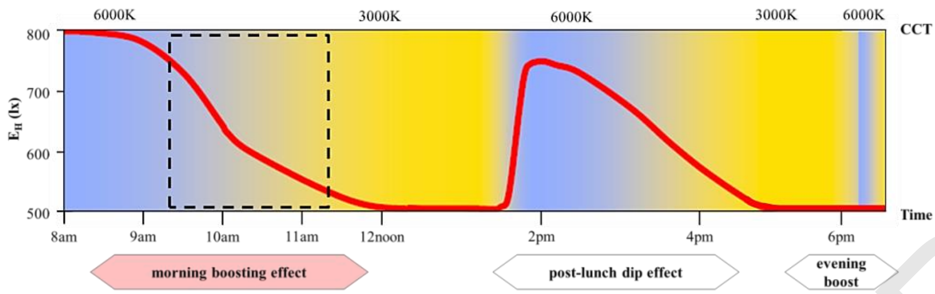


Figure 1.6: The 'human rhythmic' dynamic lighting protocol (changing illuminance and CCT levels). Red solid line represents gradual changes of E_H levels, Blue shaded area represents CCT 6000 K, Yellow shaded area 3000 K, Black dotted line focuses on the recommended luminous conditions for boosting effect during peak morning worktime period. (With permission from: van Bommel, 2006a)

According to de Kort & Smolders (2010) and van Bommel & van den Beld (2003), dynamic architectural lighting is most effective for supporting/enhancing the IPWI, in workplace with less natural daylight contribution. Workplaces with a high proportion of natural daylight contribution could undermine the dynamicity of the architectural lighting variations, hence making it less effective if applied (de Kort & Smolders, 2010). Besides that, a few studies that ventured into studying several other dynamic architectural lighting configurations found, dynamic lighting contributed towards better impacts in enhancing the psychological and physiological indicators than the constant lighting (Canazei et al., 2014; Hoffmann et al., 2008; Kondo et al., 2009; Vallenduuk, 1999).

Therefore, this thesis posits that the standard practice of implementing constant lighting may be less supportive towards sustaining/enhancing IPWI over time, especially for those working in windowless workplace. The changes in the circadian rhythm (non-visual responses) over time suggest constant lighting would not be able to provide the variation needed to support the diurnal rhythm. Implementing dynamic architectural lighting in windowless workplace was evidenced as more advantages, and thus will be referenced heavily in this thesis. It could be an alternative to compensate the deprivations faced by non-exposure to the changing light stimuli of natural daylight. This thesis is expecting the dynamic architectural lighting to play an active role in supporting/enhancing the IPWI during the day, and act as a potential environmental therapeutic solution in minimizing the light-induced circadian disruption in WOPW.

1.6 Research Gap

Three interrelated gaps have motivated this thesis:

i. The researcher discovered a dearth of literature regarding workplace architectural lighting requirements and its impact on IPWI, especially for tropical Malaysia. Most of the Malaysian architectural lighting studies have contributed significantly towards understanding the characteristics of constant lighting on individuals' visual responses. For example, Kamaruzzaman et al. (2011) and Baird & Thompson (2012) reported on the individuals' satisfaction and perception of the indoor lighting quality. Shamsul et al. (2013) and Sivaji, et al. (2013) identified the individuals' preferred CCT for visual comfort and task performance, with initial awareness opening up to support subjective alertness (non-visual effects).

It is still unknown whether dynamic architectural lighting will be of benefit to support/enhance the IPWI in WOPW in tropical Malaysia. From the thorough literature survey, this thesis found no local studies have ventured into investigating, defining or developing supportive, dynamic architectural lighting configurations as yet. Therefore, this thesis is a preliminary study in this research area, exploring the potential threshold values and patterns for a tropical Malaysian context, before any application can be recommended and further studied.

ii. This thesis found that most of the constant architectural lighting studies had significantly identified essential characteristics of lighting for wellbeing, by using incandescent, fluorescent, and light-emitting diodes (LED) lamps (see subsection 2.3.2). For dynamic architectural lighting, prior studies have only used fluorescent lamps, and not with white LED lamps as yet (see subsection 2.4.3). The lack of the above supports this thesis's motivation to investigate the effects of dynamic architectural lighting with white LED lamps on IPWI and more so for a tropical workplace. This attempt agrees with Rea (2010) and Hawes et al. (2012) that foresees LED lamps will be the future of general workplace lighting, replacing the commonly used incandescent and T8 fluorescent lamps. Hence, this thesis posits this approach is timely and reasonable.

iii. Workplace with an open-plan concept is emphasized because scholars such as de Bakker, Aries, Kort, & Rosemann (2016, 2017) have highlighted it as an upcoming trend and prevailing design strategy for commercial developments. A layout without any partitions separating the workstations helps to open up the whole workplace, especially when the built-up area is limited and set in a windowless context. Subsection 2.4.1 has further details. This thesis emphasized that in an open-plan workplace; ambient lighting becomes a shared commodity and has to relate to a group of individuals working in that shared space. Hence, this thesis posits that open-plan workplace architectural lighting would require its specific design strategy to support IPWI in a shared space, contrary to that which applies to private cubical-based layouts (where lighting could be individually personalized and controlled).

1.7 Research Inquiry: Research Questions and Research Objectives

This thesis follows Ibrahim (2008, 2011) in formulating the main research question, utilizing the one 'WHAT' and two 'HOW' constructs. Specific research constructs in relation to the research problem have been identified, which led to the formation of the research questions and research objectives.

i. The 'WHO' research question construct is defined as Workplace Architectural Lighting because it refers to the setting that will be impacted by the study.

ii. The 'WHAT' research question construct is defined as Human Psychophysiological Wellbeing because it forms the body of knowledge needed to solve the research inquiry.

iii. The two 'HOW' research question constructs are defined as Lighting for Wellbeing and Tropical Architectural Lighting Design because they refer to the action that has to be taken to solve the research inquiry.

Table 1.1 lists the way this thesis identified and formulated the main research question (an extraction of Appendix A_1). This has systematically guided the researcher achieve the respective research objectives based on the formulated sub-research questions.

Table 1.1: Identifying the Research Question Constructs, Formulating the Sub-Research Questions and Determining the Research Objectives
(Adapted from Ibrahim, 2011)

Research Question Construct	**Description of Research Question's Construct**	**Research Question**	**Research Objective**
WHO	Workplace Architectural Lighting	<u>Sub-Research Question 1:</u> Why is adequate and appropriate architectural lighting important for dayshift individuals' wellbeing, especially for those working in windowless workplaces?	<u>Research Objectives 1:</u> To understand the importance and characteristics of adequate and appropriate architectural lighting requirements for dayshift individuals' wellbeing in windowless workplaces.
WHAT	Human Psycho-physiological Wellbeing (HPW)	<u>Sub-Research Question 2:</u> What are the HPW routes and indicators that are affected by light?	<u>Research Objectives 2:</u> To identify HPW routes and indicators that are affected by light.
HOW 1	Lighting for Wellbeing	<u>Sub-Research Question 3:</u> What are the lighting factors, especially daytime lighting characteristics that influence dayshift IPWI?	<u>Research Objectives 3:</u> To identify the lighting factors, especially daytime lighting characteristics that influence dayshift IPWI.
HOW 2	Tropical Architectural Lighting Design	**<u>Main Research Question:</u>** **How to design architectural $_{[HOW\ 2]}$ lighting $_{[HOW\ 1]}$ that enhances dayshift individuals' psychophysiological wellbeing indicators $_{[WHAT]}$ in a windowless open-plan workplace $_{[WHO]}$ in tropical Malaysia?**	**<u>Main Research Objectives:</u>** **To identify potential architectural lighting design concepts and conditions that enhance dayshift IPWI in a WOPW in tropical Malaysia.**

1.8 Study Design: Experiment

This thesis conducted an experimental study design based on Yin's (Yin, 2014) recommended parameters of a suitable inquiry strategy (see Figure 1.7). The form of this thesis's main research question starts with 'HOW', requires control over the behavioral events (lighting conditions), and focuses on the light-setting's immediate impact on each of the measured IPWI within a close to real-life WOPW setting.

Strategy	Form of RQ	Requires Control of Behavioral Events	Focuses on Contemporary Events?
Experiment	how, why?	Yes	Yes
Survey	who, what, where, how many, how much?	No	Yes
Archival analysis	who, what, where, how many, how much?	No	Yes/No
History	how, why?	No	No
Case study	how, why?	No	Yes

Figure 1.7: Relevant situations for different research inquiry strategies.
(Source: Yin, 2014)

Therefore, this exploratory experimental study aimed to test whether a 2-hour morning exposure to dynamic, overhead white LED (6500 K) ambient lighting, installed in an experimental WOPW in tropical Malaysia, could

i. support the measured IPWI (in the direction needed for a supportive morning boosting effect), and hence

ii. contribute towards a better morning boosting effect than the 'control' (constant lighting).

A boosting effect is essential during the peak morning worktime period because it demands alertness and high work output. The IPWI that were investigated (based on the considerations discussed in subsection 2.2.7) included urinary 6-sulfatoxymelatonin (aMT6s), alertness, positive affect (PA), negative affect (NA), visual comfort, and task performance for cognitive (P_{cog}), visual acuity (P_{acuity}), and visual contrast ($P_{contrast}$).

A few dynamic architectural lighting configurations were also tested to identify the potential lighting threshold values and patterns that were more supportive of the morning boosting effect in tropical Malaysia. The predetermined E_H levels and lighting patterns were based on the considerations discussed in subsection 2.5. The light-settings included constant ($500_{constant}500$ lx) versus dynamic lighting with E_H in decreasing oscillation ('$500_{decreasing\ to}250$ lx', '$750_{decreasing\ to}500$ lx', '$1000_{decreasing\ to}500$ lx') and increasing oscillation ('$250_{increasing\ to}500$ lx', '$500_{increasing\ to}750$ lx', '$500_{increasing\ to}1000$ lx').

Results from this exploratory experimental study are expected to establish the preliminary groundwork (initiating the local data) for defining the potential supportive, dynamic architectural lighting configurations (threshold values and patterns) that are better for the morning boosting effect than the 'control'. The potential supportive light-settings are recommended if they support most of the measured IPWI (covering the 3 routes for individuals' psychophysiological wellbeing, and in the direction needed for a supportive morning boosting effect) during the peak morning worktime period in WOPW in tropical Malaysia. Identification of the potential supportive light-settings also serves to objectively validate the need to develop the proposed Integrated Tropical Architectural Lighting Design (ITALD) framework (see subsection 2.5), and justify its feasibility for further investigations and continued development.

1.8.1 Development of Experiment's Objectives

i. To identify the light-setting's immediate impact over time, on each of the measured IPWI.

ii. To compare the immediate impact of each light-setting with that of the 'control', for each of the measured IPWI.

iii. To recommend the potential supportive, dynamic architectural lighting configurations (threshold values and patterns) that are better for the morning boosting effect than the 'control'; hence worthwhile for larger and further investigations in developing the proposed ITALD framework.

1.8.2 Development of Hypotheses

Given the benefits of dynamic architectural lighting over constant lighting, this thesis hypothesizes the former would be more supportive than the latter for the morning boosting effect in WOPW in tropical Malaysia. However, it is predicted:

i. Not all of the dynamic light-settings would contribute towards better morning boosting effect when compared to the 'control'.

ii. The morning boosting effect would be greater with dynamic lighting in decreasing oscillation than its increasing counterpart.

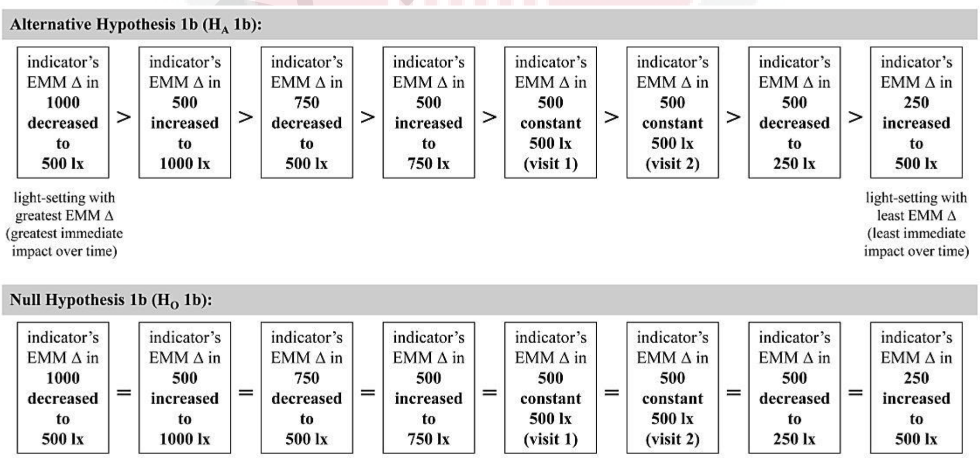
Subsection 2.5.1 has further details. In general, the formulated hypotheses were:

Hypothesis 1a: Prediction of the light-setting's immediate change over time, on each of the measured IPWI.

Predetermined light-setting	Immediate change in EMM over time (in the direction needed for a supportive morning boosting effect)	
	urinary aMT6s, alertness (KSS score), NA	PA, P_{cog}, P_{acuity}, $P_{contrast}$, visual comfort
$1000_{\text{decreased to}}500$ lx	H_A 1a: EMM $TP_1 > TP_2$ H_O 1a: EMM $TP_1 = TP_2$	H_A 1a: EMM $TP_1 < TP_2$ H_O 1a: EMM $TP_1 = TP_2$
$500_{\text{increased to}}1000$ lx		
$750_{\text{decreased to}}500$ lx		
$500_{\text{increased to}}750$ lx		
visit 1: $500_{\text{constant}}500$ lx		
visit 2: $500_{\text{constant}}500$ lx		
$500_{\text{decreased to}}250$ lx		
$250_{\text{increased to}}500$ lx		

Note. Alternative hypothesis (H_A), Null hypothesis (H_O), Estimated Marginal Mean (EMM), 1st time-point measurement (TP_1), 2nd time-point measurement (TP_2).

Hypothesis 1b: Prediction of the chronological order of the light-setting's immediate impact over time (based on its magnitude (EMM Δ) and direction of immediate change), for each of the measured IPWI.



Hypothesis 2: Prediction of the immediate impact of each light-setting in comparison to that of the 'control', for each of the measured IPWI.

Predetermined light-setting		Each light-setting's immediate impact (*B* estimate) relative to 'control' (in the direction needed for a supportive morning boosting effect)	
		urinary aMT6s, alertness (KSS score), NA	PA, P_{cog}, P_{acuity}, $P_{contrast}$, visual comfort
greatest impact (more supportive) ↑	$1000_{\text{decreased to}}500$ lx	H_A 2: *B* setting < 0 H_O 2: *B* setting = 0	H_A 2: *B* setting > 0 H_O 2: *B* setting = 0
	$500_{\text{increased to}}1000$ lx		
	$750_{\text{decreased to}}500$ lx		
'control'	$500_{\text{increased to}}750$ lx		
	visit 2: $500_{\text{constant}}500$ lx	H_A 2: *B* setting > 0 H_O 2: *B* setting = 0	H_A 2: *B* setting < 0 H_O 2: *B* setting = 0
	$500_{\text{decreased to}}250$ lx		
least impact (less supportive) ↓	$250_{\text{increased to}}500$ lx		

Note. Alternative hypothesis (H_A), Null hypothesis (H_O), hypothetical score for control (visit 1: $500_{\text{constant}}500$ lx) is set at 0.

1.9 Outline of Thesis

This thesis is presented in the following order:

i. Chapter 1 introduces the background problem and justifies the purpose of this thesis.

ii. Chapter 2 presents a comprehensive literature survey on the 3 research question constructs and concludes with the proposed ITALD framework.

iii. Chapter 3 discusses the applied research methodology. It explains the variables, participants, procedure, and materials of the exploratory experimental study.

iv. Chapter 4 reports the results of the light-setting's immediate impact over time, and relative to 'control', for each of the measured IPWI (for experimental objectives i & ii); and recommends the potential supportive, dynamic architectural lighting configurations (for experimental objectives iii).

v. Chapter 5 discusses the major findings of the light-setting's immediate impact over time, and relative to 'control', for each of the measured IPWI. It also discusses the recommended potential supportive, dynamic architectural lighting configurations that are better for the morning boosting effect than the 'control'. The differences identified from prior studies were presented to justify the feasibility of larger and further investigations.

vi. Chapter 6 presents the conclusion, novel knowledge claims, limitations, and strengths of this thesis, and concludes with recommendations for future studies.

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